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Evaluation of Personal $PM_{2.5}$ and O_3 Exposures by Season in Seoul Population

서울시 인구의 $PM_{2.5}$ 및 O_3 개인노출 평가

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이 논문을 보건학석사 학위논문으로 제출함

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Abstract

Evaluation of Personal $PM_{2.5}$ and O_3 Exposures by Season in Seoul Population

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Background: Personal exposures to particulate matter less than 2.5 μm ($PM_{2.5}$) and ozone (O_3) are associated with various health effects. To evaluate population exposures to $PM_{2.5}$ and O_3, levels of personal exposures to $PM_{2.5}$ and O_3 should be assessed for each individual in the population group. However, in most epidemiological studies to investigate the health effects caused by personal exposures to $PM_{2.5}$ and O_3 in the population group, ambient $PM_{2.5}$ and O_3 concentrations provided by air quality monitoring stations have been used as surrogates for personal exposure to $PM_{2.5}$ and O_3. This approach can be a bias within the epidemiological studies. Personal exposures to $PM_{2.5}$ and O_3 differ not only by the ambient concentrations of $PM_{2.5}$ and O_3 but also by some factors including season, indoor and outdoor locations where individuals stay, and the amount of their time spent in those locations.

Objectives: The objectives of this study were *1)* to identify differences in personal exposures and population-weighted exposures to $PM_{2.5}$ and O_3 by season and population group, *2)* to determine the relationship between personal exposures and corresponding ambient concentrations for $PM_{2.5}$ and O_3, and *3)* to evaluate the contribution of the microenvironment to personal exposures to $PM_{2.5}$ and O_3 in Seoul population.

Methods: Daily time-activity pattern scenarios for each of 10 population groups in Seoul were predefined by winter, summer, spring, and autumn using data from the Time Use Survey in 2014 by Statistics Korea. A field technician simulated a total of 10 time-activity pattern scenarios for each season by tracing spatial locations of microenvironments in each of the given scenarios. While simulating the scenario, the technician carried around a real-time aerosol monitor and a miniaturized O_3 monitor and directly measured one person-day of personal exposures to $PM_{2.5}$ and O_3. Personal exposure monitoring was conducted 40 person-days in winter, 50 person-days in spring, and 80 person-days in summer and autumn, respectively. To examine differences in personal exposures and population-weighted exposures to $PM_{2.5}$ and O_3 by season and population group, a one-way analysis of variance (ANOVA) was performed. Spearman's correlation analysis and simple linear regression analysis were conducted to determine the relationship between personal exposures and ambient concentrations for $PM_{2.5}$ and O_3. The population-weighted exposure and the contribution of the microenvironment were calculated using several products.

Results: The seasonal differences in personal $PM_{2.5}$ and O_3 exposures were significant. Personal exposure to $PM_{2.5}$ was significantly high in winter (22.2 ± 28.2 $\mu g/m^3$), and personal exposure to O_3 was significantly high in spring (11.6 ± 9.6 ppb). Personal exposure to $PM_{2.5}$ was high in worker groups, and personal exposure to O_3

was high in groups of office workers and housewives. In the Seoul population, population-weighted exposure to $PM_{2.5}$ was 21.5 μg/m^3 in winter, followed by 15.0 μg/m^3 in summer, and 14.7 μg/m^3 in autumn, and 14.0 μg/m^3 in spring. The population-weighted exposure to O_3 was 10.5 ppb in spring, followed by 3.9 ppb in autumn, 3.8 ppb in summer, and 3.2 ppb in winter. In winter, personal exposures to $PM_{2.5}$ and corresponding ambient concentrations were significantly correlated (r_s = 0.81) and had a linearity (R^2 = 0.57, slope = 0.45). In summer, personal exposures to O_3 and corresponding ambient concentrations had a weak correlation (r_s = 0.54) and a weak linearity (R^2 = 0.23, slope = 0.01). In all seasons, the residential indoors was the major contributor to personal exposures to $PM_{2.5}$ and O_3 although the highest $PM_{2.5}$ and O_3 exposures occurred in barbeque restaurants.

Conclusions: This study provided a seasonal variation of personal exposures to $PM_{2.5}$ and O_3 in the Seoul population. Population exposures to $PM_{2.5}$ and O_3 were high in winter and spring, respectively. $PM_{2.5}$ had a significant relationship between personal exposures and ambient concentrations in winter. O_3 had a weak relationship between personal exposures and ambient concentrations in all seasons. In Seoul, ambient $PM_{2.5}$ concentration could be a surrogate of personal $PM_{2.5}$ exposure in winter. However, ambient O_3 concentration could not be a surrogate for personal O_3 exposure in all seasons. The management of $PM_{2.5}$ and O_3 levels in the residential indoors, barbeque restaurants, and restaurants is important to mitigate personal exposures to $PM_{2.5}$ and O_3 in the Seoul population.

Keywords: personal exposure, population exposure, $PM_{2.5}$, O_3, ambient, correlation, time-activity pattern, microenvironment

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I. Introduction

Personal exposure to particulate matter less than 2.5 μm ($PM_{2.5}$) has been associated with several notable health effects, including lung inflammation, lung function reduction, cardiovascular problems, and premature mortality (Carey et al., 2013; Du and Li, 2016; Yunesian et al., 2019). $PM_{2.5}$ can readily be transported to bronchioles and alveoli of the lungs via the upper respiratory tract such as the nasal cavity. $PM_{2.5}$ in alveoli can deposit in the lungs and enter the main organ system.

Ozone (O_3) has consistently attracted the public's attention due to its detrimental health effects. O_3 is a secondary air pollutant generated by photochemical reactions of oxides of nitrogen (NOx) and volatile organic compounds (VOCs). Precedent researches have documented that O_3 exposure contributes to both morbidity and mortality, and a risk of death from respiratory and cardiovascular diseases, such as emphysema and chronic obstructive disease (Bell et al., 2005; Zhao et al., 2021). In Korea, an annual average O_3 concentration in the atmosphere increased from 35.8 ppb in 2010 to 45.0 ppb in 2019. Due to the increased O_3 concentration level in the atmosphere, the excess mortality has been estimated to have doubled over the past 10 years (2010-2019) (KDCA, 2022).

Epidemiological studies on $PM_{2.5}$ (Carey et al., 2013; Kim et al., 2018; Thurston et al., 2016) and O_3 (Byun et al., 2022; Carey et al., 2013; Jerrett et al., 2009; Wen et al., 2022) have shown an association between population exposure to $PM_{2.5}$ and O_3 and their health effects by using data of ambient concentrations of $PM_{2.5}$ and O_3. The ambient concentration data of $PM_{2.5}$ and O_3 were provided by national air quality monitoring stations. This approach assumes that ambient concentrations of $PM_{2.5}$ and O_3 can be a surrogate for $PM_{2.5}$ and O_3 exposures of individuals in the population group. However, the assumption that was not able to contain information about personal exposures to $PM_{2.5}$ and O_3 can be a confounding factor, which is a potential bias within the epidemiological studies. Personal exposures to $PM_{2.5}$ and O_3 differ not only by the ambient concentrations of $PM_{2.5}$ and O_3 but also by many factors including season and time-activity pattern (U.S. EPA, 2019, 2020). Therefore, to identify whether the ambient concentrations of $PM_{2.5}$ and O_3 can be a surrogate for personal exposures to $PM_{2.5}$ and O_3, it is necessary to evaluate a relationship between personal exposures to $PM_{2.5}$ and O_3 and corresponding ambient concentrations.

The exposure assessment study has evolved significantly with a myriad of methods for assessing population exposure to air pollutants (Branco et al., 2014; Lioy, 2010). Two alternative approaches, direct and indirect, have been taken to assess population exposure to air pollutants. The direct approach is a method of personal monitoring and biomonitoring (Ott, 1982). In particular, personal monitoring is the field measurements of air pollutant concentrations using portable equipment worn by a study subject. Personal monitoring is advantageous in the simplicity of study design and the freedom from modeling assumptions. However, as the number of subjects increases, there is a burden that direct measurements of personal exposures are expensive and time-consuming (Branco et al., 2014; Lioy, 1995).

The indirect approach is a method of exposure modeling. Exposure modeling is recently classified into statistical regression models and microenvironmental models (Branco et al., 2014). Among the classification, microenvironmental models typically estimate population exposures derived from time-activity patterns in parallel with personal monitoring. The personal monitoring in the model is conducted with quantitative measurements of air pollutant concentrations within microenvironments (Branco et al., 2014; Jungers et al., 1985; Ott, 1982). The microenvironmental models can be more cost-effective and time-saving than direct personal monitoring of the population. In addition, the microenvironmental models are appropriate for reflecting changes in movement over time of individuals, rather than the regression models.

Population exposure by an indirect estimation was compared with the directly measured personal exposure. These examples were the Korea Simulation Exposure Model Version 2 for $PM_{2.5}$ (KoSEM II-$PM_{2.5}$), and the Air Pollution Exposure Distributions of Adult Urban Populations in Europe (EXPOLIS) study. The KoSEM II-$PM_{2.5}$ was developed based on three types of input data: a repeated simulation of ten time-activity pattern scenarios for each season in summer, autumn, and winter; outdoor $PM_{2.5}$ concentration; and direct measurement of $PM_{2.5}$ concentrations in microenvironments (Guak et al., 2021). The time-activity pattern scenarios were derived from a national time-use survey of Seoul population. Outdoor $PM_{2.5}$ concentration was obtained from a national air quality monitoring station (AQMS). The $PM_{2.5}$ concentration was directly measured in seven microenvironments: home; workplace or school; other indoor locations; restaurant; walking; car; and subway or bus. A total of 140 person-days of exposure data were collected by repeating four to five times at each of the simulation of the ten time-activity patterns, with 50 person-days in summer; 40 person-days in autumn; and 50 person-days in winter. The KoSEM II-$PM_{2.5}$ was developed by using the input data and a probabilistic approach.

The EXPOLIS study was conducted between 1996 and 2000 during weekdays in six cities of Europe: Athens, Basel, Grenoble, Helsinki, Milan, and

Prague (Jantunen et al., 1998). Personal exposures to $PM_{2.5}$, CO, 30 volatile organic compounds (VOCs), and NO_2 were measured to identify the frequency distribution of exposure to air pollutants for European adult urban populations. Microenvironments were defined as home indoors, work indoors, and other places. The participants kept a time–microenvironment–activity diary every 15 min for 48 consecutive hours. Then, the EXPOLIS simulation model was developed using a probabilistic approach and simulated frequency distribution of population $PM_{2.5}$ exposures (Kruize et al., 2003). Input data in the EXPOLIS simulation model were the spatial location of the population, time-location data, and calculated spatial pollutant concentration distributions.

Personal exposures to $PM_{2.5}$ and O_3 can differ by season. Personal $PM_{2.5}$ exposure was greater during winter than other seasons, as were indoor and outdoor $PM_{2.5}$ concentrations (Liu et al., 2003). A panel study reported that high exposure to $PM_{2.5}$ was observed during a heating season compared to a non-heating season due to a heating fuel combustion and smoking status in a household (Lee et al., 2021). The longitudinal study confirmed that personal exposure to O_3 was higher in the warmer season than the non-warmer season (Geyh et al., 2000). In addition, other studies presented that higher personal O_3 exposures occurred in summer than in winter (Chang et al., 2000; Sarnat et al., 2001).

Attention should continue to be paid to ambient air quality and its influence on human health. However, people spend up to 90% of their time indoors (U.S. EPA, 2011; Yang et al., 2011), making indoor air quality more important than before. Exposures to many air pollutants indoors are often higher than those typically encountered outdoors due to an emanation of air pollutants from a range of indoor sources (Jones, 1999). Therefore, research on personal exposure to air pollutants needs to consider both outdoor and indoor concentrations.

The microenvironment was defined as “a chunk of air space with homogeneous pollutant concentration” (Duan, 1982). Such microenvironments can include either outdoors or indoors where personal exposure takes place. As time-activity patterns varied with the subjects of exposure studies, personal exposure to air pollutants differed by microenvironmental concentration and time spent in various microenvironments (Hwang and Lee, 2018; Lim et al., 2012).

In several substantial studies, results have been reported for the influence of the microenvironment on personal exposure to $PM_{2.5}$ and O_3. The residential indoors accounted for a significant proportion of daily $PM_{2.5}$ exposure in each study case (Burke et al., 2001). In addition, the distribution of daily personal $PM_{2.5}$ exposures of ambient origin was less variable across the population than the distribution of daily total $PM_{2.5}$ exposures (Hwang and Lee, 2018; Lim et al., 2012). O_3 concentrations were generally higher outdoors than those indoors including residential indoors, offices, and schools (Bozkurt et al., 2015; Che et al., 2021; Geyh et al., 2000). Despite the distribution of O_3 concentration, a substantial proportion of O_3 inhaled on a time-averaged basis is inhaled indoors (Weschler, 2006).

The overall aim of this study was to evaluate personal exposures to $PM_{2.5}$ and O_3 by season in the Seoul population using time-activity patterns from Korean Time Use Survey. Accordingly, the three objectives of this study were *1)* to identify differences in personal exposures and population-weighted exposures to $PM_{2.5}$ and O_3 by season and population group, *2)* to determine the relationship between personal exposures and corresponding ambient concentrations for $PM_{2.5}$ and O_3, and *3)* to evaluate the contribution of the microenvironment to personal exposures to $PM_{2.5}$ and O_3 in Seoul population. The 24-hour personal exposures to $PM_{2.5}$ and O_3

were directly measured for four seasons. Field technicians carried a real-time aerosol monitor and a miniaturized O_3 monitor, and traced locations of microenvironments in predefined ten time-activity pattern scenarios.

II. Methods

2.1. Time-activity pattern scenarios

Daily time-activity pattern scenarios for Seoul population in this study were predefined in a precedent study (Lee, 2017). The precedent study classified time-activity patterns in Seoul population using data of the Time Use Survey in 2014 by Statistics Korea (KOSTAT). The survey was conducted in summer (18th to 27th July), autumn (19th September to 1st October), and winter (28th November to 7th December) in 2014. A total of 3,981 person-days weekday data of Seoul population were extracted from the survey data. All the person-days data were stratified into summer, autumn, and winter. The survey data were transformed into a matrix dataset of four-digit time-activity codes. The four-digit codes were constructed by combining a one-digit location code and a three-digit activity code every 10 minutes. For each season in summer, autumn, and winter, 1,000 person-days data were randomly selected from the matrix and classified into 10 population groups based on similarities in their time-activity patterns. According to the classification of population groups in the precedent study, 10 time-activity pattern scenarios were generated for each season in summer, autumn, and winter.

The microenvironments consisting time-activity pattern scenarios in this study were categorized into 7 main categories and 22 sub-categories: *Residential indoor*; *Workplace/school* consisted of office, school, self-employment, shopping mall, and security office; *Other locations* were composed of café, study café, pub, PC room, bookstore, senior citizens hall, department store, supermarket, private educational facility, and traditional market; *Restaurant/bar* was made up of general restaurant and Korean style barbeque restaurant; *Walking*; *Private transportation* consisted of using either a taxi or an own car; and *Public transportation* composed of subway and bus.

There was no raw data to generate time-activity pattern scenarios for spring because the Time Use Survey in 2014 was only conducted during summer, autumn, and winter. Hence, the time-activity pattern scenarios for spring were generated via assuming that the time-activity patterns in autumn were the same as spring. In total, 40 time-activity pattern scenarios in four seasons were used to monitor personal exposures to $PM_{2.5}$ and O_3 (**Table S1**, **Table S2**, **Table S3**, and **Table S4**).

The 10 population groups showed different characteristics: *Group 1*, shopping mall night workers; *Group 2*, office workers 1; *Group 3*, office workers 2; *Group 4*, senior citizens; *Group 5*, university students; *Group 6*, middle and high school students; *Group 7*, self-employed workers; *Group 8*, housewives; *Group 9*, office workers 3; and *Group 10*, security office night workers. A total population number constituting 10 population groups was 955 in winter, 956 in summer, and 980 in spring and autumn, respectively. For each season, the population proportion of each population group ranged from 2.2% to 28.2% (**Table 1**).

Table 1. The number of people and population proportion of 10 population groups by season based on data from Seoul.

Group	Description	Season: Winter Number	Winter Population proportion (%)	Spring and Autumn Number	Spring and Autumn Population proportion (%)	Summer Number	Summer Population proportion (%)
1	Shopping mall night workers	202	21.2	137	14.0	270	28.2
2	Office workers 1	169	17.7	27	2.8	63	6.6
3	Office workers 2	115	12.0	111	11.3	75	7.8
4	Senior citizens	105	11.0	145	14.8	48	5.0
5	University students	88	9.2	22	2.2	41	4.3
6	Middle and high school students	66	6.9	214	21.8	143	15.0
7	Self-employed workers	61	6.4	47	4.8	69	7.2
8	Housewives	60	6.3	177	18.1	25	2.6
9	Office workers 3	57	6.0	18	1.8	24	2.5
10	Security office night workers	32	3.4	82	8.4	198	20.7
Total		955	100.0	980	100.0	956	100.0

2.2. Monitoring of personal exposures to $PM_{2.5}$ and O_3

Monitoring of personal exposures to $PM_{2.5}$ and O_3 was performed from December 2021 to October 2022. Seasonal categories of the monitoring were winter (Dec 2021 to Feb 2022), spring (Mar 2022 to May 2022), summer (Jun 2022 to Aug 2022), and autumn (Sep 2022 to Oct 2022). A field technician simulated the predefined 10 time-activity pattern scenarios for each season by tracing locations in each of the given scenario. While simulating the scenario, the technician carried around a bag packaged with real-time monitors of $PM_{2.5}$, O_3, temperature, and relative humidity (RH) (**Figure 1**). One person-day of personal exposures to $PM_{2.5}$ and O_3, temperature, and RH were directly measured for 24 hours through one simulation of the scenario. Five technicians took part in the measurements of personal exposures in winter and spring, and eight technicians in summer and autumn. A total of 250 person-days of personal exposure data were collected during the year, with 40 person-days in winter; 50 person-days in spring; 80 person-days in summer and autumn, respectively.

Personal exposures to $PM_{2.5}$ and O_3, temperature, and RH were measured using real-time monitors. Personal exposure to $PM_{2.5}$ was measured using a real-time laser photometer (SidePak AM520, TSI, USA) (**Figure 2**). The aerosol monitor was set to record measurements of $PM_{2.5}$ mass concentration at a 1-min average. The manufacturer-specified flow rate of 1.7 L/min was used. Personal exposure to O_3 was measured using a miniaturized O_3 monitor (Personal Ozone Monitor; POM, 2B Technologies, USA), which is a designated Federal Equivalent Method by U.S.EPA (**Figure 3**). During personal monitoring, POM was set to acquire 1-min average O_3 data at a flow rate of 0.8 L/min. The temperature and RH were measured using a HOBO data logger (Onset Corporation, USA) in a 1-min interval. All personal exposure measurement devices were factory calibrated. The $PM_{2.5}$ and O_3 monitors, together with a rechargeable battery, were carried by the technicians while the inlet of the monitor was positioned as close to the breathing zone as possible.

Figure 1. A packaged bag with real-time monitors of $PM_{2.5}$, O_3, temperature, and RH.

Figure 2. A real-time laser photometer (SidePak AM520, TSI, MN, USA).

Figure 3. A miniaturized O_3 monitor (Personal Ozone Monitor, 2B technologies, USA).

A real-time laser photometer, SidePak AM520, was continuously checked for each personal exposure monitoring of one person-day for quality assurance and quality control (QA/QC) of $PM_{2.5}$ concentration data. Before each monitoring, zero calibration was performed, and the internal impactor disk of the instrument was cleaned according to the guideline of the manufactural manual. The flow rate of 1.7 L/min was maintained during entire study periods by calibrating before and after each monitoring.

The SidePak AM520 was factory calibrated with the respirable fraction of standard ISO 12103-1, A1 Test Dust (Arizona Test Dust). Since the optical mass measurement of the dust depends on actual urban particle sizes, shapes, and other material properties, an additional calibration of the SidePak was required to obtain the actual $PM_{2.5}$ mass concentration. The aerosol monitors with the light scattering method showed measurements about 2.6 to 3.1 times higher than those of the gravimetric method (Jenkins et al., 2004). Therefore, the $PM_{2.5}$ concentration data measured by the SidePak AM520 in this study were adjusted by the correction factor of 0.3 (Lim et al., 2012).

POM is a miniaturized O_3 monitor with a low weight (340 g) and small size (10.1 × 7.6 × 3.8 cm). The monitor has been designated as Federal Equivalent Method by U.S.EPA (FEM: EQOA-0815-227). POM measures O_3 concentrations based on ultraviolet (UV) absorption at the wavelength of 254 nm. The O_3 molecule has an absorption maximum of 254 nm, coincident with the principal emission wavelength of a low-pressure mercury lamp. Although substances absorbed at 254 nm in the atmosphere are rarely found at significant, the interruption can occur in POM with the absorption of the wavelength by substances such as organic compounds containing aromatic rings in highly polluted air. Compared with passive samplers, POM has a much quicker response to abrupt changes in the O_3 level. This advantage enables the collection of more reliable real-time measured data in personal exposure studies.

A limit of detection (LOD) of $PM_{2.5}$ and O_3 monitors was considered during the data preprocessing in this study. The LOD of the aerosol monitor, SidePak AM520, was 1 μg/m^3 to an upper limit of 100 mg/m^3. The LOD of the O_3 monitor, POM, was 3 ppb to an upper limit of 10 ppm. The values of measured $PM_{2.5}$ and O_3 concentration data that were less than their respective LODs were assigned values of half of the LODs for statistical analysis. Half of the LOD was 0.5 μg/m^3 for $PM_{2.5}$ and 1.5 ppb for O_3.

2.3. Population-weighted exposures to $PM_{2.5}$ and O_3 in Seoul

Population-weighted exposures to $PM_{2.5}$ and O_3 were calculated to assess exposures to $PM_{2.5}$ and O_3 in the Seoul population. The measured personal exposures to $PM_{2.5}$ and O_3 were weighted by the number of each population group in each season, as shown in Equation (1):

$$PWE_i = \frac{\sum_{j=1}^{10}\left(P_{ij} \times PE_{ij}\right)}{\sum_{j=1}^{10} P_{ij}} \quad \textbf{(1)}$$

where i refers to the season, j refers to the population group in season i, PWE_i is the daily population-weighted exposure in season i, P_{ij} is the population proportion of the population group j in season i, and PE_{ij} is the personal exposure to $PM_{2.5}$ or O_3 of the population group j in season i.

2.4. Correspondences from ambient concentration data to personal exposure data for $PM_{2.5}$ and O_3

Ambient $PM_{2.5}$ and O_3 concentration were provided by AQMSs. The ambient $PM_{2.5}$ concentrations in the AQMS were measured by a beta-ray absorption principle. The detection limit for $PM_{2.5}$ in the AQMS was 5 μg/m^3 and the measurement range was from 0 μg/m^3 to 1,000 μg/m^3. The ambient O_3 concentrations in the AQMS were measured by a UV photometric method. The detection limit for O_3 in the AQMS was 2 ppb (https://www.airkorea.or.kr/web/board/3/267/?pMENU_NO=145). The ambient $PM_{2.5}$ and O_3 concentration data of the AQMSs were obtained from a website called AirKorea, operated by the Korea Environment Corporation (KECO) (https://www.airkorea.or.kr/web/realSearch?pMENU_NO=97).

The ambient $PM_{2.5}$ and O_3 concentration data were derived from AirKorea over the same period with the measured personal exposure data of $PM_{2.5}$ and O_3. The personal exposure monitors, SidePak AM520 and POM, were co-located with the national AQMSs from 40 to 80 days for each season. As the ambient $PM_{2.5}$ and O_3 concentration data were an hourly average, the measured personal exposure data of

$PM_{2.5}$ and O_3 were hourly averaged. For each personal $PM_{2.5}$ and O_3 exposure data point in an hourly average, ambient $PM_{2.5}$ and O_3 concentrations were extracted from AirKorea by inputting the address of the location where the personal exposure concentrations of $PM_{2.5}$ and O_3 was measured. The measured personal exposure data of $PM_{2.5}$ and O_3 corresponded to the ambient $PM_{2.5}$ and O_3 concentration data every hour.

2.5. Contributions of the microenvironment to personal exposures to $PM_{2.5}$ and O_3

Contributions of each of 22 microenvironments to personal exposures to $PM_{2.5}$ and O_3 were calculated using the equation derived from (Hwang and Lee, 2018). $PM_{2.5}$ and O_3 data from all seasons were used to apportion personal $PM_{2.5}$ and O_3 exposures by microenvironments. Seoul population data were used to determine the population proportions of each group. The average time spent in each microenvironment per group was determined from the scenario of the time-activity pattern of each group. The products of the population proportion, average time spent, and mean concentrations of $PM_{2.5}$ and O_3 were used to evaluate the contribution of each microenvironment. The apportionment of each microenvironment was calculated as the product of the microenvironment divided by the sum of all products, as shown in Equation (2):

$$Contribution_m = \frac{\mathrm{C}_m \times \sum_{n=1}^{10} (Population\ proportion_n \times T_{(m,n)})}{\sum_{m=1}^{22} \sum_{n=1}^{10} (C_m \times Population\ proportion_n \times T_{(m,n)})} \quad \textbf{(2)}$$

where $Contribution_m$ is the contribution of the microenvironment m (%) to $PM_{2.5}$ and O_3 exposures, C_m is the mean concentrations of $PM_{2.5}$ and O_3, $Population\ proportion_n$ is the population proportion of time-activity pattern group n from total population data, and $T_{(m,n)}$ is the average time spent in microenvironment *m* of time-activity pattern group *n*.

2.6. Data analysis

Personal exposure data of $PM_{2.5}$ and O_3 were analyzed on a daily average for descriptive statistics. All personal exposure data were stratified by season and population group. Differences in daily personal exposures to $PM_{2.5}$ and O_3 by season and population group were examined through a one-way analysis of variance (ANOVA) and Bonferroni's test in the post-hoc comparison. A p-value less than 0.05 was considered statistically significant.

Comparisons of ambient concentrations and personal exposures to $PM_{2.5}$ and O_3 were conducted by season and population group using Spearman's correlation coefficient (r_s) was used to investigate the correlation between ambient concentrations and personal exposures to $PM_{2.5}$ and O_3, respectively. To determine the relationship, simple linear regression analysis was performed for ambient concentration data as explanatory variables with personal exposure data as dependent variables. A p-value less than 0.05 was considered statistically significant. All statistical analyses were performed using R software (version 3.6.3; R Core Development Team, Vienna, Austria).

III. Results

3.1. Daily personal exposures to $PM_{2.5}$ and O_3 by season and population group

A total of 250 person-days of daily average personal exposure data were collected. Descriptive statistics for the measured personal exposures to $PM_{2.5}$ and O_3 were evaluated and stratified by population group and by season (**Table 2** and **Table 3**). Overall, daily personal exposures to $PM_{2.5}$ and O_3 differed by season and population group.

Daily personal $PM_{2.5}$ exposure was highest in winter among the four seasons (**Figure 4a**). The average personal $PM_{2.5}$ exposures were 22.2 ± 28.2 μg/m^3 in winter, followed by 16.7 ± 32.3 μg/m^3 in autumn, 16.2 ± 35.1 μg/m^3 in spring, and 16.0 ± 46.0 μg/m^3 in summer. The mean of personal $PM_{2.5}$ exposure differed significantly between winter and other seasons ($p < 0.0001$). Except for winter, there was no difference in personal $PM_{2.5}$ exposures between spring, summer, and autumn.

Daily personal O_3 exposure was highest in spring (**Figure 4b**). The average personal O_3 exposures were 11.6 ± 9.6 ppb in spring, followed by 4.8 ± 3.1 ppb in summer, 4.0 ± 2.3 ppb in winter, and 3.1 ± 1.8 ppb in autumn. In spring, the mean of daily personal O_3 exposure for all groups was more than three times higher than in winter. The mean of personal O_3 exposure differed significantly between spring and other seasons ($p < 0.0001$). Except for spring, there was no difference in personal O_3 exposures between winter, summer, and autumn.

By population group, in winter, the highest $PM_{2.5}$ exposure was 28.2 ± 24.0 μg/m^3 in group 1 (shopping mall night workers), which $PM_{2.5}$ level was not different from group 6, 8, 7, 9, and 10 ($p < 0.0001$). The lowest $PM_{2.5}$ exposure was 13.3 ± 8.2 μg/m^3 in group 4 (senior citizens). In spring, the highest $PM_{2.5}$ exposure was 24.5 ± 37.8 μg/m^3 in group 10 (security office night workers), and the lowest $PM_{2.5}$ exposure was 4.8 ± 4.0 μg/m^3 in group 6 (middle and high school students). In summer, the highest $PM_{2.5}$ exposure was 22.3 ± 115.9 μg/m^3 in group 9 (office workers 3). Group 9 experienced the second highest $PM_{2.5}$ exposure in spring. The lowest $PM_{2.5}$ exposure was 9.3 ± 8.0 μg/m^3 in group 6 (middle and high school students). Group 6 was also the lowest $PM_{2.5}$ exposure group in spring. In autumn, the highest $PM_{2.5}$ exposure was 30.1 ± 86.2 μg/m^3 in group 7 (self-employed workers), and the lowest $PM_{2.5}$ exposure was 8.7 ± 8.5 μg/m^3 in group 8 (housewives).

By population group, in winter, the highest O_3 exposure was 4.2 ± 3.9 ppb in group 1 (shopping mall night workers) and the lowest O_3 exposure was 2.1 ± 1.7 ppb in group 4 (senior citizens). In spring, the highest O_3 exposures were 13.8 ± 11.9 ppb in group 3 (office workers 2) and 13.8 ± 15.9 ppb in group 8 (housewives). The lowest O_3 exposures were 7.5 ± 9.3 ppb in group 1 (shopping mall night workers) and 7.5 ± 8.1 ppb in group 2 (office workers 1). In summer, the highest O_3 exposure was 7.4 ± 10.3 ppb in group 8 (housewives) and the lowest O_3 exposure was 2.9 ± 4.1 ppb in group 10 (security office night workers). In autumn, the highest O_3 exposure was 5.3 ± 6.4 ppb in group 7 (self-employed workers). The lowest O_3 exposure was observed in groups of workers with a mean of 3.6 ppb: group 1 (shopping mall night workers); group 3 (office workers 2); and group 10 (security office night workers).

Table 2. Daily personal $PM_{2.5}$ exposures (μg/m^3) in 10 population groups by season (mean ± standard deviation).

Population groups	Winter (n = 40)	Spring (n = 50)	Summer (n = 80)	Autumn (n = 80)
1	28.2 ± 24.0	18.2 ± 14.5	14.5 ± 12.1	13.4 ± 11.3
2	16.3 ± 10.0	15.7 ± 9.5	11.9 ± 8.5	15.6 ± 18.3
3	17.6 ± 13	12.3 ± 9.7	12.1 ± 9.6	13.7 ± 11.7
4	13.3 ± 8.2	13.5 ± 27.8	18.5 ± 46.6	15.6 ± 19
5	16.4 ± 15.4	13.9 ± 39.1	16.5 ± 29.3	13.0 ± 10.5
6	26.9 ± 21.2	4.8 ± 4.0	9.3 ± 8.0	12.3 ± 12.5
7	26.2 ± 36.0	19.2 ± 52.2	19.4 ± 35.5	30.1 ± 86.2
8	26.7 ± 18.3	15.8 ± 12.2	17.2 ± 16.2	8.7 ± 8.5
9	25.3 ± 47.2	24.4 ± 71.0	22.3 ± 115.9	18.6 ± 23.6
10	25.4 ± 47.3	24.5 ± 37.8	17.8 ± 50.9	25.9 ± 27.6
Total	22.2 ± 28.2	16.2 ± 35.1	16.0 ± 46.0	16.7 ± 32.3

Table 3. Daily personal O_3 exposures (ppb) in 10 population groups by season (mean ± standard deviation).

Population groups	Winter (n = 40)	Spring (n = 50)	Summer (n = 80)	Autumn (n = 80)
1	4.2 ± 3.9	7.5 ± 9.3	3.1 ± 3.3	3.6 ± 4.6
2	2.4 ± 1.9	7.5 ± 8.1	4.0 ± 5.1	3.8 ± 4.8
3	3.9 ± 3.1	13.8 ± 11.9	5.1 ± 6.8	3.6 ± 4.5
4	2.1 ± 1.7	11.3 ± 12.3	5.0 ± 11.9	3.7 ± 4.4
5	2.5 ± 2.6	8.6 ± 10.0	7.3 ± 10.7	4.3 ± 5.5
6	3.2 ± 4.0	8.0 ± 6.5	3.4 ± 5.4	4.2 ± 5.0
7	3.9 ± 5.1	9.7 ± 9.0	4.0 ± 5.2	5.3 ± 6.4
8	2.6 ± 3.4	13.8 ± 15.9	7.4 ± 10.3	3.8 ± 5.6
9	3.5 ± 9.5	19.7 ± 23.0	5.1 ± 9.3	4.5 ± 5.5
10	2.7 ± 3.5	8.5 ± 9.8	2.9 ± 4.1	3.6 ± 4.4
Total	3.1 ± 4.5	10.9 ± 13.0	4.8 ± 8.0	4.0 ± 5.1

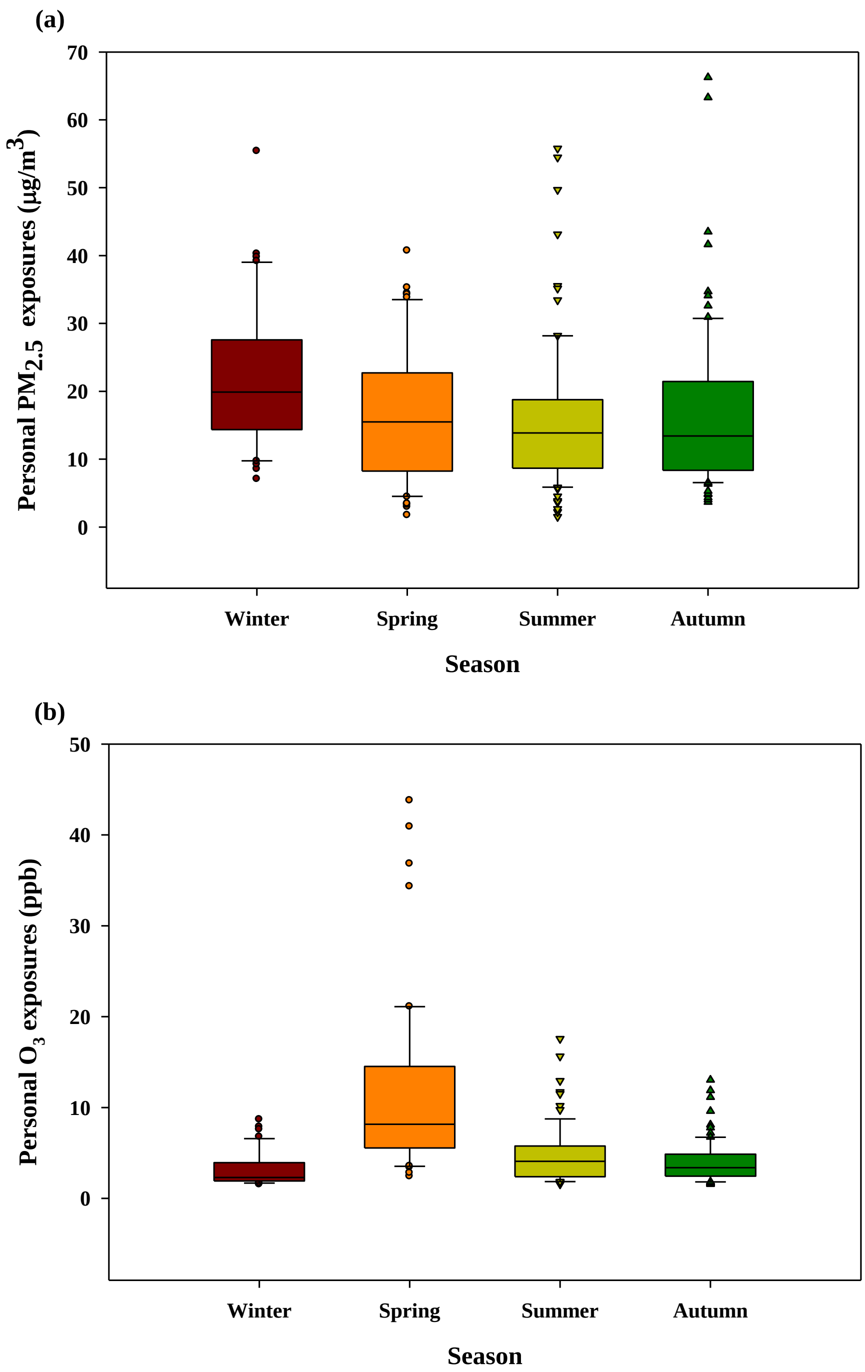


Figure 4. (a) Personal $PM_{2.5}$ exposures in winter, spring, summer, and autumn; (b) Personal O_3 exposures in winter, spring, summer, and autumn.

3.2. Population exposures to $PM_{2.5}$ and O_3 in Seoul

Daily population-weighted exposures to $PM_{2.5}$ and O_3 in Seoul were assessed by season and population group (**Figure S1**). The population-weighted exposure to $PM_{2.5}$ of the Seoul population was 21.5 μg/m^3 in winter, followed by 15.0 μg/m^3 in summer, and 14.7 μg/m^3 in autumn, and 14.0 μg/m^3 in spring. The population-weighted exposure to $PM_{2.5}$ was higher in winter than other three seasons. The population-weighted exposure to O_3 of the Seoul population was 10.5 ppb in spring, followed by 3.9 ppb in autumn, 3.8 ppb in summer, and 3.2 ppb in winter. The population-weighted exposure to O_3 was higher in spring than other three seasons.

3.3. Relationships between personal exposures and corresponding ambient concentrations for $PM_{2.5}$ and O_3

Relationships between personal exposures to $PM_{2.5}$ and O_3 and corresponding ambient concentrations were evaluated using a total of 250 person-days of personal exposure data and corresponding ambient concentration data. The mean of ambient $PM_{2.5}$ concentrations were 31.6 ± 21.6 μg/m^3 in winter, 15.6 ± 9.7 μg/m^3 in spring, 12.7 ± 8.3 μg/m^3 in summer, and 14.3 ± 10.9 μg/m^3 in autumn. The mean of ambient O_3 concentrations were 46.3 ± 21.0 ppb in spring, 33.2 ± 19.2 ppb in summer, 22.0 ± 15.8 ppb in autumn, and 12.3 ± 10.1 ppb in winter (**Table 4** and **Figure S3**). The ambient O_3 concentrations were between 3.1 and 6.9 times higher than personal O_3 exposures in all seasons.

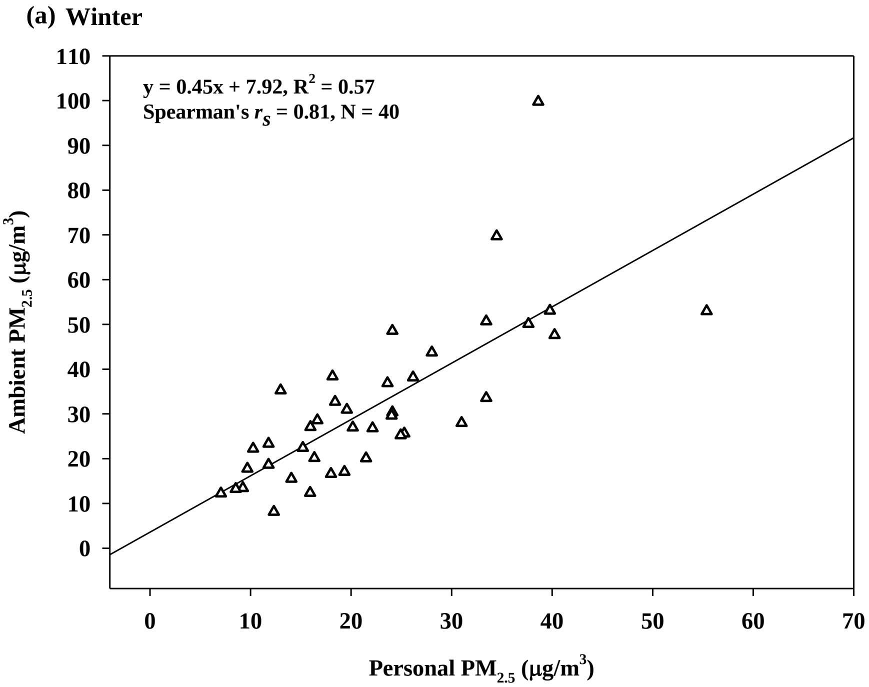
Table 4. Personal exposures to $PM_{2.5}$ and O_3 and corresponded ambient concentrations by season (mean ± standard deviation).

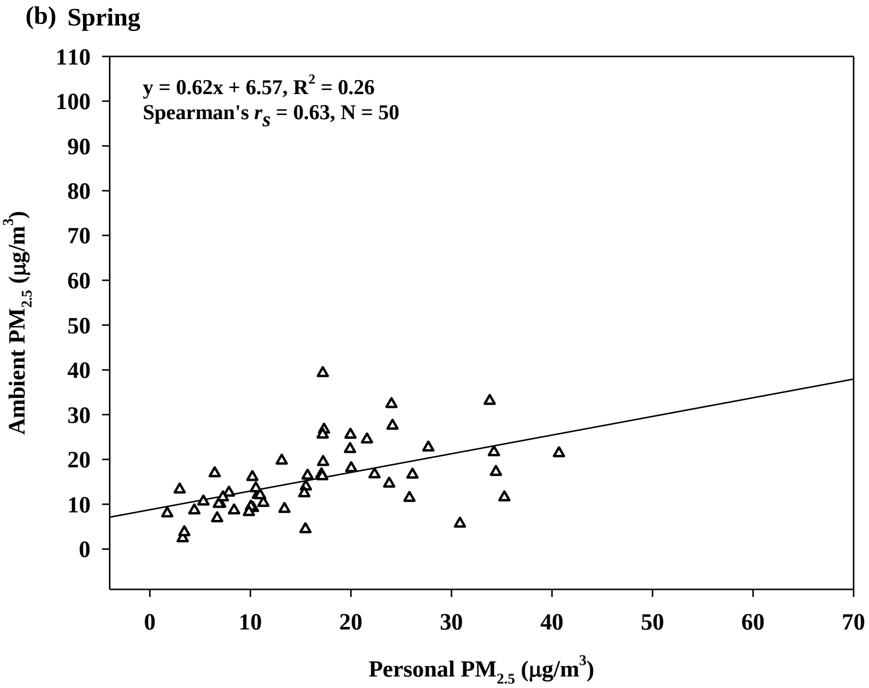
Season	$PM_{2.5}$ (μg/m^3)		O_3 (ppb)	
	Personal exposure	Ambient concentration	Personal exposure	Ambient concentration
Winter	22.2 ± 28.2	31.6 ± 21.6	3.1 ± 4.5	46.3 ± 21.0
Spring	16.2 ± 35.1	15.6 ± 9.7	10.9 ± 13.0	33.2 ± 19.2
Summer	16.0 ± 46.0	12.7 ± 8.3	4.8 ± 8.0	22.0 ± 15.8
Autumn	16.7 ± 32.3	14.3 ± 10.9	4.0 ± 5.1	12.3 ± 10.1

Over in four seasons, personal $PM_{2.5}$ exposures and ambient $PM_{2.5}$ concentrations were strongly correlated (Spearman's $r_s = 0.71$, $p < 0.0001$). As a result of the simple linear regression analysis, the R^2 value between personal $PM_{2.5}$ exposures and ambient $PM_{2.5}$ concentrations was 0.32 ($p < 0.0001$). The slope was 0.53, and the intercept was 8.47 (**Figure S2a**). Ambient O_3 concentrations and personal O_3 exposures showed a significant correlation (Spearman's $r_s = 0.57$, $p <$ 0.0001). As a result of the simple linear regression analysis, the R^2 value between personal O_3 exposures and ambient O_3 concentrations was 0.29 ($p < 0.0001$). The slope was 0.21, and the intercept was -0.43 (**Figure S2b**).

The correlation and the linearity between personal $PM_{2.5}$ exposures and corresponding ambient $PM_{2.5}$ concentrations were evaluated by season (**Figure 5**). Personal $PM_{2.5}$ exposures and ambient $PM_{2.5}$ exposures were significantly correlated for each season. Spearman's correlation coefficients were 0.81 in winter ($p < 0.0001$), 0.63 in spring ($p < 0.0001$), 0.77 in summer ($p < 0.0001$), and 0.67 in autumn ($p < 0.0001$). As a result of the simple linear regression analysis, personal $PM_{2.5}$ exposures and corresponding ambient $PM_{2.5}$ concentrations had a significant linearity in winter (p < 0.0001), and had a weak linearity in spring (p < 0.0001), summer (p < 0.0001), and autumn (p < 0.0001). The R^2 values were 0.57 in winter, 0.26 in spring, 0.34 in summer, and 0.29 in autumn. The slopes of the regression line were 0.45 in winter, 0.62 in spring, 0.99 in summer, and 0.69 in autumn.

The correlation and the linearity between personal O_3 exposures and corresponding ambient O_3 concentrations were evaluated by season (**Figure 6**). Personal O_3 exposures and ambient O_3 concentrations were significantly correlated in summer (Spearman's $r_s = 0.54$, $p < 0.0001$), and in autumn (Spearman's $r_s = 0.36$, $p < 0.05$). However, personal O_3 exposures and ambient O_3 concentrations were not correlated in winter ($p = 0.36$) and spring ($p = 0.27$). As a result of the simple linear regression analysis, personal O_3 exposures and ambient O_3 concentrations had a weak linearity in summer ($p < 0.0001$), autumn ($p < 0.001$), and spring ($p < 0.05$). The R^2 values were 0.23 in summer, 0.14 in autumn, and 0.11 in spring. The slopes of the regression line were 0.15 in summer, 0.12 in autumn, and 0.26 in spring. In contrast, in winter, the linearity between personal O_3 exposures and ambient O_3 concentrations was not significant ($p = 0.71$).


(a) Winter
y = 0.45x + 7.92, R2 = 0.57
Spearman's rS = 0.81, N = 40
Ambient PM2.5 (μg/m3)
Personal PM2.5 (μg/m3)
0
10
20
30
40
50
60
70
80
90
100
110


(b) Spring
y = 0.62x + 6.57, R2 = 0.26
Spearman's rS = 0.63, N = 50
Ambient PM2.5 (μg/m3)
Personal PM2.5 (μg/m3)
0
10
20
30
40
50
60
70
80
90
100
110

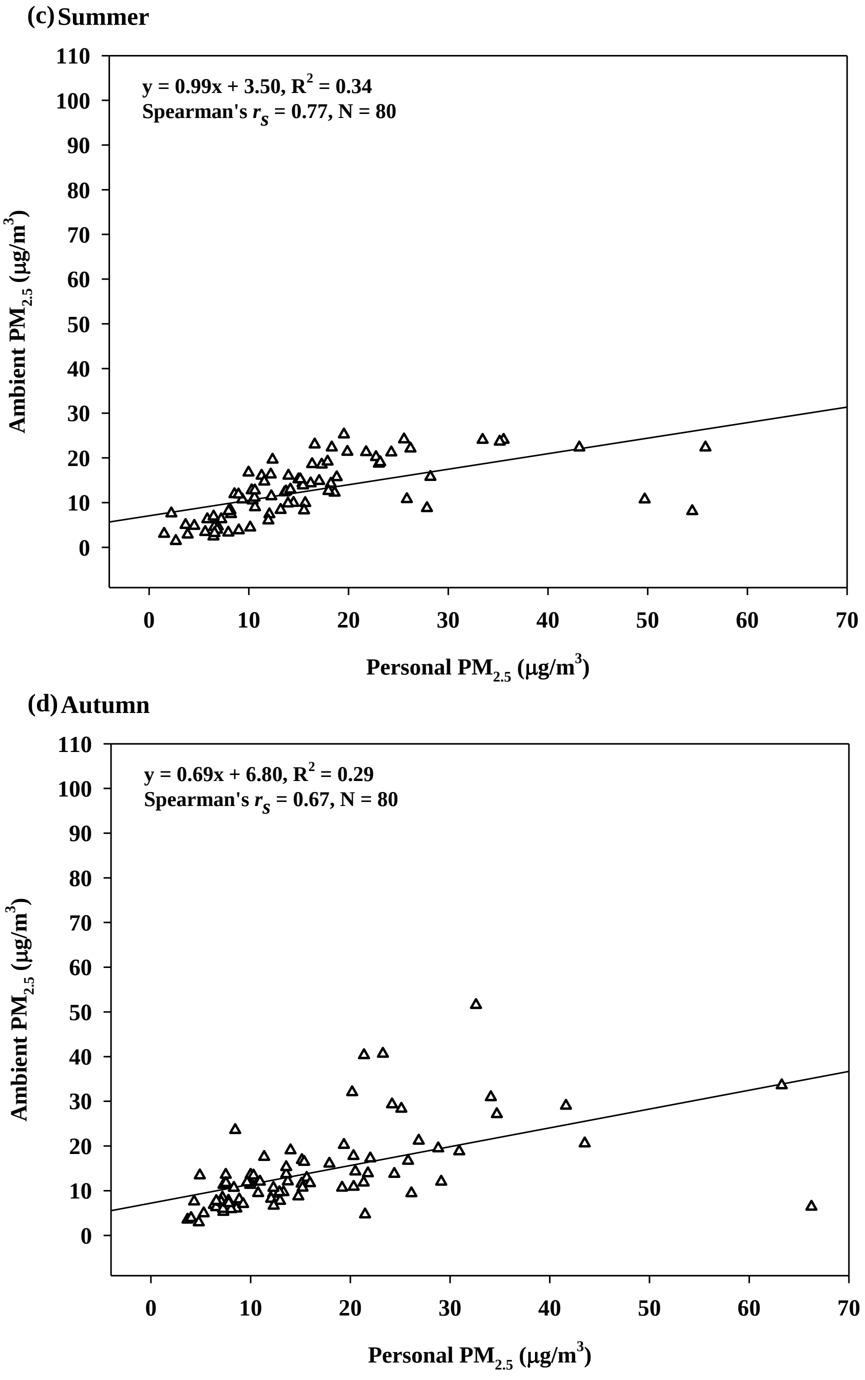
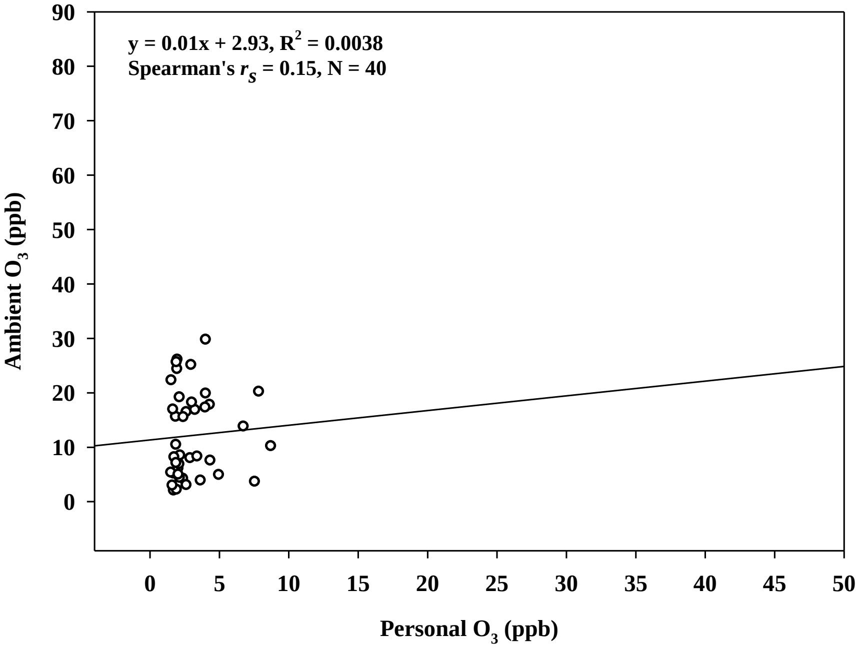
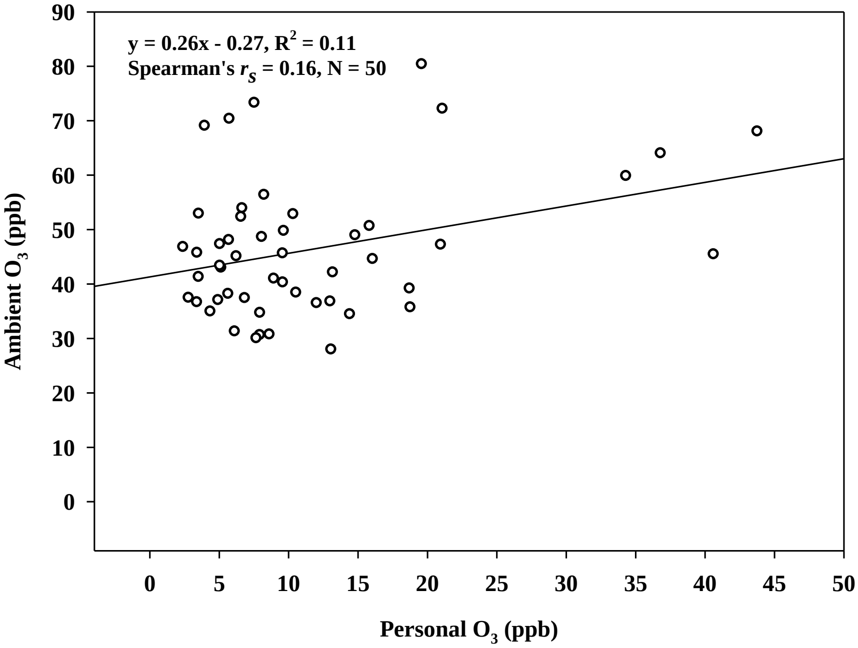


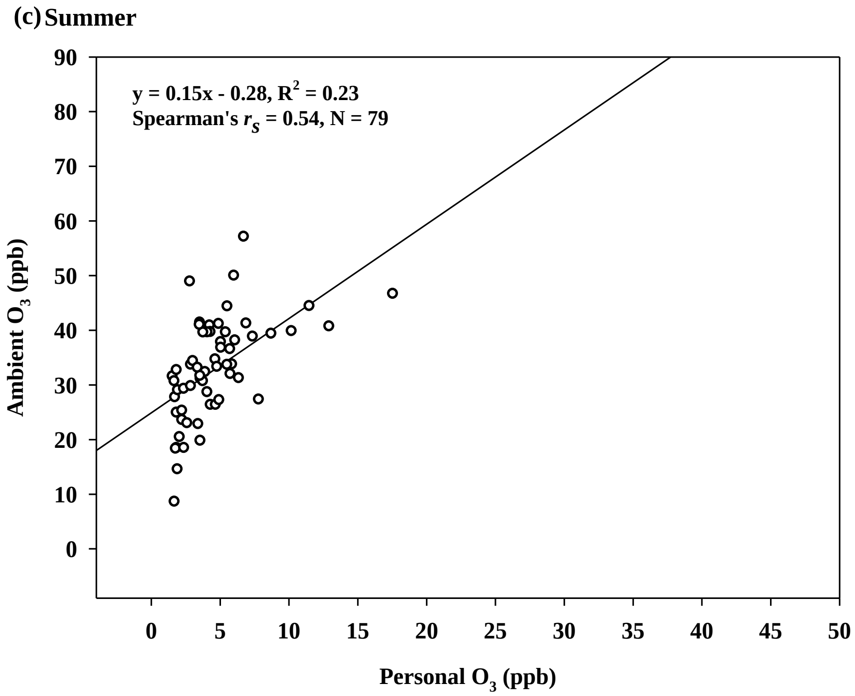
Figure 5. Relationships between personal $PM_{2.5}$ exposures and corresponding ambient $PM_{2.5}$ concentrations on a daily average during (a) winter, (b) spring, (c) summer, and (d) autumn.

(a) Winter



(b) Spring





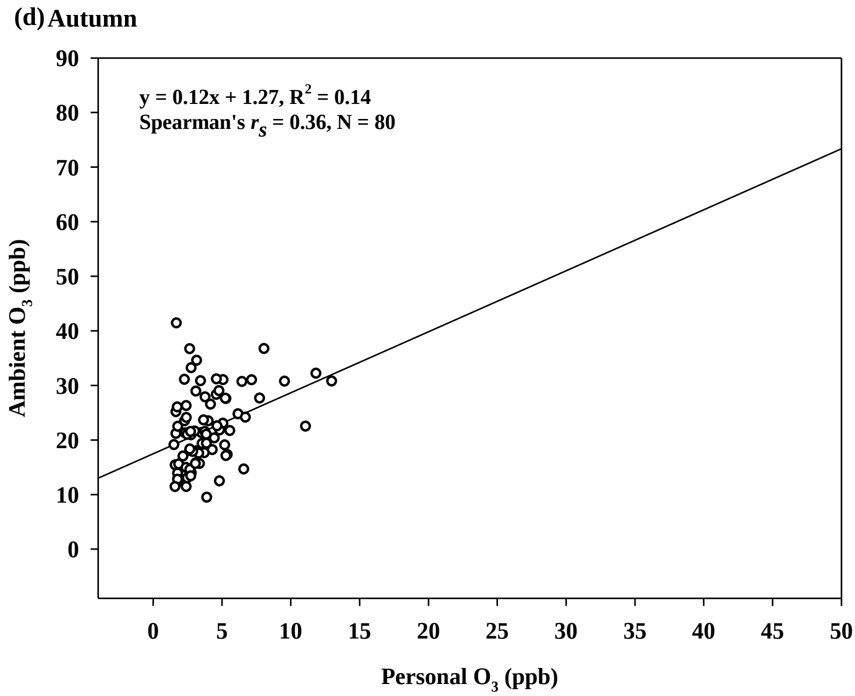


Figure 6. Relationships between personal O_3 exposures and corresponding ambient O_3 concentrations on a daily average during (a) winter, (b) spring, (c) summer, and (d) autumn.

3.4. Concentrations of $PM_{2.5}$ and O_3 in each microenvironment by season

The microenvironmental concentrations of $PM_{2.5}$ and O_3 were evaluated in winter, spring, summer, and autumn. Overall, $PM_{2.5}$ concentrations were high in locations where food could be consumed, including pubs, restaurants, and barbeque restaurants. The total mean for four seasons of $PM_{2.5}$ concentrations was 66.2 ± 128.1 $\mu g/m^3$ in pubs; 46.4 ± 99.1 $\mu g/m^3$ in restaurants; and 159.0 ± 261.6 $\mu g/m^3$ in barbeque restaurants. $PM_{2.5}$ concentrations in residential indoors and offices were below 20 $\mu g/m^3$ in all seasons (**Table 5**).

O_3 concentrations were high in locations where food could be consumed, including pubs, restaurants, and barbeque restaurants. The total mean for four seasons of $PM_{2.5}$ concentrations was 5.8 ± 6.5 ppb in pubs; 6.1 ± 7.6 ppb in restaurants; and 21.0 ± 30.1 ppb in barbeque restaurants. In winter, summer, and autumn, O_3 concentrations tended to be higher in barbeque restaurants, restaurants, traditional markets, and walking. The highest O_3 concentration was observed in barbeque restaurants, where the O_3 concentration was 21.0 ± 30.1 ppb in winter; 37.3 ± 52.7 ppb in spring; and 16.8 ± 24.4 ppb in summer. In spring, O_3 concentrations tended to be higher than other seasons in every microenvironment. In autumn, the highest O_3 concentration was 14.5 ± 12.1 ppb in traditional market (**Table 6**).

Table 5. $PM_{2.5}$ concentrations ($\mu g/m^3$) in each microenvironment by season (mean ± standard deviation).

Microenvironment	Season				
Category	Winter	Spring	Summer	Autumn	Total
Residential indoor	15.2 ± 9.3	12.1 ± 8.4	12.8 ± 14.4	12.0 ± 13.1	12.8 ± 12.2
Workplace/school					
Office	16.9 ± 9.3	15.8 ± 9.2	10.4 ± 8.3	13.9 ± 10.5	13.7 ± 9.7
School	31.2 ± 26.1	7.4 ± 9.0	9.5 ± 7.3	11.9 ± 11.4	13.3 ± 15.8
Self-employment	32.4 ± 9.5	16.0 ± 8.6	17.7 ± 9.6	31.1 ± 33.1	23.5 ± 18.6
Shopping mall	37.7 ± 30.0	22.5 ± 24.0	11.2 ± 9.5	11.8 ± 7.2	17.7 ± 19.6
Security office	22.7 ± 22.9	21.6 ± 15.5	14.4 ± 19.0	22.1 ± 15.8	19.8 ± 18.3
Other locations					
Café	33.4 ± 16.2	13.6 ± 7.9	14.8 ± 10.3	13.9 ± 8.3	16.2 ± 11.7
Study café	39.7 ± 21.0	22.1 ± 27.2	11.5 ± 6.0	13.1 ± 9.3	16.7 ± 17.6
Pub	71.1 ± 74.1	24.6 ± 17.5	61.3 ± 97.1	93.6 ± 174.9	66.2 ± 128.1
PC room	41.6 ± 26.2	32.3 ± 24.5	34.2 ± 18.9	21.0 ± 16.3	30.7 ± 21.7
Bookstore	14.0 ± 7.2	10.2 ± 14.1	10.9 ± 8.0	11.2 ± 7.2	11.4 ± 9.2
Senior citizens hall	15.6 ± 9.9	12.4 ± 7.5	17.9 ± 10.4	22.8 ± 19.7	18.1 ± 14.4
Department store	21.4 ± 11.6	12.4 ± 5.4	16.4 ± 16.3	14.1 ± 12.3	15.8 ± 13.1
Supermarket	44.7 ± 7.8	15.9 ± 12.7	17.3 ± 10.5	12.7 ± 13.4	20.8 ± 16.5
Private educational facility	31.9 ± 19.9	3.1 ± 1.9	7.3 ± 5.3	12.3 ± 8.5	11.4 ± 12.8
Traditional market	47.3 ± 9.5	27.8 ± 18.4	32.0 ± 42.7	8.1 ± 6.3	27.8 ± 34.1
Restaurant/bar					
Restaurant	53.2 ± 64.7	62.2 ± 141.2	48.4 ± 119	31.2 ± 45.7	46.4 ± 99.1
Barbeque restaurant	172.0 ± 163.7	158.0 ± 237.2	223.1 ± 390.9	88.3 ± 72.9	159.0 ± 261.6
Walking	38.4 ± 24.1	18.2 ± 13.3	17.9 ± 14.5	22.8 ± 20.8	21.9 ± 18.9
Private transportation					
Taxi/Car	24.3 ± 17.4	14.8 ± 11.5	7.8 ± 10.6	18.6 ± 21.1	15.4 ± 17
Public transportation					
Subway	32.8 ± 19.2	19.0 ± 12.4	17.2 ± 9.8	22.1 ± 11.4	21.9 ± 14.1
Bus	29.3 ± 20.8	15.5 ± 13.0	11.7 ± 9.3	23.2 ± 19.6	18.4 ± 16.8

Table 6. O_3 concentrations (ppb) in each microenvironment by season (mean ± standard deviation).

Microenvironment	Season				
Category	Winter	Spring	Summer	Autumn	Total
Residential indoor	2.6 ± 2.8	8.6 ± 10.6	4.2 ± 6.4	2.8 ± 3.3	4.3 ± 6.6
Workplace/school					
Office	2.2 ± 1.7	15.3 ± 13.4	4.1 ± 4.5	5.7 ± 5.6	6.6 ± 8.6
School	2.2 ± 1.0	12.5 ± 10.3	5.5 ± 7.7	7.2 ± 7.5	7.2 ± 8.4
Self-employment	4.1 ± 3.7	8.3 ± 9.0	3.6 ± 2.6	3.8 ± 3.3	4.3 ± 4.5
Shopping mall	4.2 ± 3.4	8.0 ± 5.8	2.1 ± 1.5	3.4 ± 4.1	4.1 ± 4.4
Security office	2.9 ± 1.9	8.1 ± 7.3	2.3 ± 1.7	2.5 ± 2.6	3.7 ± 4.5
Other locations					
Café	2.9 ± 1.9	9.9 ± 7.6	2.4 ± 1.9	5.0 ± 5.0	5.1 ± 5.7
Study café	4.3 ± 1.9	7.9 ± 7.3	5.8 ± 7.3	4.2 ± 4.5	5.6 ± 6.2
Pub	5.8 ± 6.5	18.0 ± 20.7	6.8 ± 8.5	8.4 ± 10.8	10.4 ± 14.3
PC room	5.1 ± 2.2	12.8 ± 8.5	4.9 ± 3.0	5.6 ± 3.5	6.3 ± 4.9
Bookstore	3.5 ± 3.6	10.1 ± 11.2	2.8 ± 2.0	4.2 ± 5.1	4.8 ± 6.6
Senior citizens hall	1.8 ± 1.0	21.1 ± 18.7	7.2 ± 8.8	4.4 ± 4.4	8 ± 11.7
Department store	1.8 ± 0.6	13.9 ± 16.2	9.0 ± 9.6	6.6 ± 5.2	8.2 ± 10.3
Supermarket	3.4 ± 1.8	13.1 ± 14.2	2.1 ± 2.4	3.6 ± 3.1	5 ± 7.8
Private educational facility	3.0 ± 3.6	10.5 ± 6.6	3.1 ± 4.1	2.7 ± 3.5	4.5 ± 5.4
Traditional market	10.2 ± 9.7	18.8 ± 22.2	16.8 ± 17.2	14.5 ± 12.1	15.9 ± 16.4
Restaurant/bar					
Restaurant	6.1 ± 7.6	16.8 ± 13.2	11.2 ± 23.8	7.2 ± 6.4	10.1 ± 15.6
Barbeque restaurant	21.0 ± 30.1	37.3 ± 52.7	16.8 ± 24.4	10.9 ± 9.8	20.1 ± 32.3
Walking	7.8 ± 7.0	21.5 ± 16.8	13.5 ± 13.5	11.7 ± 10.2	13.7 ± 13.3
Private transportation					
Taxi/Car	2.8 ± 2.7	11.8 ± 13.4	3.9 ± 4.8	3.8 ± 4.0	5.3 ± 7.8
Public transportation					
Subway	3.0 ± 2.7	10.3 ± 9.5	3.4 ± 3.7	2.8 ± 2.6	4.7 ± 6
Bus	3.2 ± 2.3	12.0 ± 10.8	4.1 ± 4.3	4.4 ± 4.4	5.4 ± 6.5

3.5. Contributions of the microenvironment to personal exposures to $PM_{2.5}$ and O_3

Contributions of 22 microenvironments to personal $PM_{2.5}$ and O_3 exposures were calculated (**Table 7**). The mean time spent considering the population-weighted value in each microenvironment was presented as the product of the population proportion and mean time spent in each microenvironment. The highest time spent showed in the residential indoors, ranging from 13.3 to 14.3 hours per day. The lowest time spent showed in a department store, ranging from 0.05 to 0.07 hours.

$PM_{2.5}$ exposures in the residential indoors contributed the most to overall personal $PM_{2.5}$ exposures, accounting for 42.2% in winter, 46.7% in spring, 44.0% in summer, and 45.4% in autumn. $PM_{2.5}$ exposures in the office accounted for 5.3% to 9.5%, primary contributing to personal $PM_{2.5}$ exposures in all seasons. The restaurant and the barbeque restaurant showed personal $PM_{2.5}$ exposure to high concentrations, with contributions ranging from 3.7% to 7.6% and 2.5% to 13.9%, respectively.

O_3 exposures in the residential indoor contributed the most to overall personal O_3 exposures, accounting for 50.3% in winter, 47.0% in spring, 50.6% in summer, and 40.7% in autumn. In spring and autumn, O_3 exposures in the school accounted for 9.0% and 14.0%, respectively. O_3 exposures in the office continued to contribute to personal O_3 exposures across all seasons, accounting for 8.3% to 13.4%. Unlike $PM_{2.5}$ exposures, walking contributed highly to personal O_3 exposures in all seasons, ranging from 5.9% to 8.2%

Table 7. Contributions of 22 microenvironments to personal $PM_{2.5}$ and O_3 exposures for the Seoul population.

Season	Microenvironment / Category	Population x mean time (h)	Mean $PM_{2.5}$ ($\mu g/m^3$)	Contribution of $PM_{2.5}$ personal exposure (%)	Mean O_3 (ppb)	Contribution of O_3 personal exposure (%)
Winter	*Residential indoor*	14.26	15.2	**42.2**	2.6	**50.3**
(n=40)	*Workplace/school*					
	Office	2.89	16.9	**9.5**	2.2	**8.4**
	School	0.77	31.2	4.7	2.2	2.3
	Self-employment	0.54	38.6	4.1	6.9	5.0
	Shopping mall	0.74	37.7	**5.4**	4.2	4.2
	Security office	0.32	22.7	1.4	2.9	1.2
	Other locations					
	Café	0.30	33.4	2.0	2.9	1.2
	Study café	0.12	39.7	0.9	4.3	0.7
	Pub	0.10	71.1	1.4	5.8	0.8
	PC room	0.42	41.6	3.4	5.1	2.9
	Bookstore	0.22	14.0	0.6	3.5	1.0
	Senior citizens hall	0.27	15.6	0.8	1.8	0.7
	Department store	0.05	21.4	0.2	1.8	0.1
	Supermarket	0.17	44.7	1.5	3.4	0.7
	Private educational facility	0.10	31.9	0.6	3.0	0.4
	Traditional market	0.05	47.3	0.5	10.2	0.7
	Restaurant/bar					
	Restaurant	0.70	53.2	**7.2**	6.1	**5.7**
	Barbeque restaurant	0.09	172.0	3.1	21.0	2.6

	Walking	0.57	38.4	4.2	7.8	**5.9**
	Private transportation					
	Taxi/Car	0.45	14.8	1.3	2.8	1.7
	Public transportation					
	Subway	0.57	30.3	3.4	3.1	2.4
	Bus	0.28	29.3	1.6	3.2	1.2
Spring	*Residential indoor*	13.90	12.1	**46.7**	8.6	**47.0**
(n=50)	*Workplace/school*					
	Office	1.38	15.8	**6.0**	15.3	**8.3**
	School	1.83	7.4	3.7	12.5	**9.0**
	Self-employment	0.39	22.7	2.5	6.8	1.1
	Shopping mall	0.65	22.5	4.1	8.0	2.1
	Security office	0.93	21.6	**5.6**	8.1	3.0
	Other locations					
	Café	0.31	13.6	1.2	9.9	1.2
	Study café	0.08	22.1	0.5	7.9	0.2
	Pub	0.21	24.6	1.4	18.0	1.5
	PC room	0.16	32.3	1.5	12.8	0.8
	Bookstore	0.19	10.2	0.5	10.1	0.8
	Senior citizens hall	0.54	12.4	1.9	21.1	4.5
	Department store	0.07	12.4	0.3	13.9	0.4
	Supermarket	0.39	15.9	1.7	13.1	2.0
	Private educational facility	0.36	3.1	0.3	10.5	1.5

	Traditional market	0.15	27.8	1.2	18.8	1.1
	Restaurant/bar					
	Restaurant	0.44	62.2	**7.6**	16.8	2.9
	Barbeque restaurant	0.10	158.0	4.5	37.3	1.5
	Walking	0.66	18.2	3.3	21.5	**5.6**
	Private transportation					
	Taxi/Car	0.46	14.8	1.9	11.8	2.1
	Public transportation					
	Subway	0.52	19.0	2.7	10.3	2.1
	Bus	0.27	15.5	1.1	12.0	1.3
Summer (n=80)	*Residential indoor*	13.26	12.8	**44.0**	4.2	**50.6**
	Workplace/school					
	Office	3.61	10.4	**9.8**	4.1	**13.4**
	School	0.54	9.5	1.3	5.5	2.7
	Self-employment	0.39	17.7	1.8	3.6	1.3
	Shopping mall	1.04	11.2	3.0	2.1	2.0
	Security office	0.63	14.4	2.3	2.3	1.3
	Other locations					
	Café	0.49	14.8	1.9	2.4	1.1
	Study café	0.07	11.5	0.2	5.8	0.4
	Pub	0.21	61.3	3.3	6.8	1.3
	PC room	0.28	34.2	2.5	4.9	1.3
	Bookstore	0.08	10.9	0.2	2.8	0.2
	Senior citizens hall	0.26	17.9	1.2	7.2	1.7

	Department store	0.06	16.4	0.3	9.0	0.5
	Supermarket	0.05	17.3	0.2	2.1	0.1
	Private educational facility	0.16	7.3	0.3	3.1	0.4
	Traditional market	0.05	32.0	0.4	16.8	0.8
	Restaurant/bar					
	Restaurant	0.42	48.4	**5.3**	11.2	**4.3**
	Barbeque restaurant	0.24	223.1	**13.8**	16.8	3.7
	Walking	0.64	17.9	3.0	13.5	**7.8**
	Private transportation					
	Taxi/Car	0.50	7.8	1.0	3.9	1.8
	Public transportation					
	Subway	0.61	17.2	2.7	3.4	1.9
	Bus	0.40	11.7	1.2	4.1	1.5
Autumn (n=80)	*Residential indoor*	13.90	12.0	**45.4**	2.8	**40.6**
	Workplace/school					
	Office	1.38	13.9	**5.3**	5.7	**8.3**
	School	1.83	11.9	**5.9**	7.2	**14.0**
	Self-employment	0.39	31.1	3.3	3.8	1.6
	Shopping mall	0.65	11.8	2.1	3.4	2.3
	Security office	0.93	22.1	**5.6**	2.5	2.4
	Other locations					
	Café	0.31	13.9	1.2	5.0	1.6
	Study café	0.08	13.1	0.3	4.2	0.3
	Pub	0.21	93.6	5.4	8.4	1.9

PC room	0.16	21.0	0.9	5.6	1.0
Bookstore	0.19	11.2	0.6	4.2	0.8
Senior citizens hall	0.54	22.8	3.4	4.4	2.5
Department store	0.07	14.1	0.3	6.6	0.5
Supermarket	0.39	12.7	1.4	3.6	1.5
Private educational facility	0.36	12.3	1.2	2.7	1.0
Traditional market	0.15	8.1	0.3	14.5	2.3
Restaurant/bar					
Restaurant	0.44	31.2	3.7	7.2	3.3
Barbeque restaurant	0.10	88.3	2.5	10.9	1.2
Walking	0.66	22.8	4.1	11.7	**8.2**
Private transportation					
Taxi/Car	0.46	18.6	2.3	3.8	1.9
Public transportation					
Subway	0.52	22.1	3.1	2.8	1.5
Bus	0.27	23.2	1.7	4.4	1.2

IV. Discussion

4.1. Seasonal differences in personal exposure to $PM_{2.5}$ and O_3

Personal exposure to $PM_{2.5}$ was highest in winter, followed by spring, summer, and autumn. In summer and autumn, similar level of personal exposure to $PM_{2.5}$ was observed in the Seoul population. This seasonal difference in personal $PM_{2.5}$ exposure was similar to the tendency of ambient $PM_{2.5}$ concentrations of this study. In this study, the ambient $PM_{2.5}$ concentration was also highest in winter, followed by spring, autumn, and summer ($p < 0.0001$) (**Figure S3**). A similar seasonal tendency between personal exposures and ambient concentrations for $PM_{2.5}$ could be explained by an association between personal exposure, indoor levels, and outdoor levels of $PM_{2.5}$. Since the Seoul population spent much of their time indoors (Yang et al., 2011), personal $PM_{2.5}$ exposure usually occurred in indoor environments (Hwang and Lee, 2018). The indoor $PM_{2.5}$ level, which was the main factor for personal $PM_{2.5}$ exposures, was commonly associated with the ambient $PM_{2.5}$ level. According to previous studies, indoor $PM_{2.5}$ levels were significantly associated with outdoor levels (Su et al., 2022; Zahed et al., 2022), and the outdoor $PM_{2.5}$ was designated as the major factor of indoor $PM_{2.5}$ (Nishihama et al., 2021).

Personal O_3 exposure was highest in spring, followed by summer, winter, and autumn. Despite the same time-activity pattern scenario in spring and autumn, the mean of personal exposure to O_3 in autumn was significantly lower than in spring. The difference inferred that personal exposure to O_3 may be affected by the ambient concentrations. In Seoul, ozone seasons were in spring and summer, and non-ozone seasons were in autumn and winter. Hence, in the Seoul population, personal exposure to O_3 was higher in ozone seasons than in non-ozone seasons. The result was consistent with previous works (Chang et al., 2000; Geyh et al., 2000; Sarnat et al., 2001). Personal exposure to O_3 was usually higher in warmer seasons (ozone seasons) than in cooler seasons (non-ozone seasons). As the O_3 is a secondary air pollutant formed by photochemical reactions among precursors in the presence of sunlight, ambient O_3 levels are generally high in sun-lighting seasons (Monks et al., 2015). The seasonal characteristics of ambient O_3 could be related to the seasonal difference in personal O_3 exposures. From 2021 winter to 2022 autumn, according to the Seoul Metropolitan Government, the average ambient O_3 concentration in Seoul was highest in spring (40 ppb), followed by summer (34 ppb), autumn (23 ppb), and winter (21 ppb) (https://cleanair.seoul.go.kr/statistics/seasonAverage).

4.2. Personal exposures to $PM_{2.5}$ and O_3 between population groups

Overall, in all seasons, personal exposure to $PM_{2.5}$ was high in group 9 (office workers 3), group 10 (security office night workers), and group 7 (self-employed workers) among ten time-activity pattern groups. In time-activity patterns of group 9 and group 10, they included barbeque restaurants and pubs. The high $PM_{2.5}$ level of barbecue restaurants and pubs may affect the average of personal exposure to $PM_{2.5}$. For group 7, self-employments in this study included microenvironments where cooking was occurred, such as bakeries and cafes. The high personal exposure to $PM_{2.5}$ in group 7 may be explained by the cooking indoors.

In spring, summer, and autumn, there were three- to five-fold differences in personal $PM_{2.5}$ exposures between population groups. The personal $PM_{2.5}$ exposure levels were low in the group of school students and high among groups of working population. In contrast, in winter, there were no differences in the average of personal $PM_{2.5}$ exposure between six population groups, including groups of workers and housewives. The mean of personal exposures to $PM_{2.5}$ of six groups were 1.5 to 2.0 times higher than other groups. This was because of high outdoor levels of $PM_{2.5}$ in winter, and a significant correlation between outdoor levels and personal exposure to $PM_{2.5}$.

In a previous study conducted in Seoul in 2013, personal exposures to $PM_{2.5}$ of nine population groups were monitored by simulating nine time-activity pattern scenarios of the Seoul population in winter and summer (Hwang and Lee, 2018). In winter, personal exposure to $PM_{2.5}$ was high in working population and low in housewives population. This result had partially consistency with this study only for the working population. In the previous study, the mean of daily personal exposure to $PM_{2.5}$ of nine population groups was 36.9 ± 28.7 μg/m^3 in winter, and 27.8 ± 21.4 μg/m^3 in summer. Compared with this study, the $PM_{2.5}$ exposure level of the previous study was 1.7 times higher in winter and summer, respectively. The mitigation of personal exposures to $PM_{2.5}$ in this study might be due to the mitigation of the ambient $PM_{2.5}$ concentrations in Korea during COVID-19 with the effects of social distancing (Seo et al., 2020). In particular, compared to the same period of 2017 to 2019, $PM_{2.5}$ concentration in the atmosphere in March 2020 reduced 36% in Seoul and 30% in Daegu. According to the Seoul Metropolitan Government, in 2022, the average ambient $PM_{2.5}$ concentration in Seoul was 20.0 μg/m^3 in spring, 13.0 μg/m^3 in summer, 16.0 μg/m^3 in autumn, and 25 μg/m^3 in winter. However, in 2013, , the average ambient $PM_{2.5}$ concentration in Seoul was 28.0 μg/m^3 in spring, 23.0 μg/m^3 in summer, 18.0 μg/m^3 in autumn, and 31.0 μg/m^3 in winter (https://cleanair.seoul.go.kr/statistics/seasonAverage).

Personal exposures to O_3 had no great difference between population groups in winter, summer, and autumn. In winter, summer, and autumn, personal exposure to O_3 in 10 population groups was one-twentieth lower than the Korean national ambient air standard of 100 ppb. In spring, personal exposure to O_3 was significantly higher than other three seasons. The O_3 exposure level was high in group 9 (office worker 3), followed by group 3 (office workers 2) and group 8 (housewives). The higher exposure may be explained by human activities such as outdoor activities, using transportation and ventilations in indoors. In a children panel study in Greece, the determinant of personal exposure to O_3 was time spent in transportation and duration of opening windows (Dimakopoulou et al., 2017). In European offices, it was reported that more than halves of the mean of occupant exposure to O_3 decreased while the ventilation of offices was reduced from 1.5 to 0.5 ach^{-1} (Terry et al., 2014). However, there is a limit to managing of indoor air quality in offices in considering only O_3 exposure as complex air pollutants, such as particulate matters and gaseous matter, was in the office environment.

4.3. Population-weighted exposures to $PM_{2.5}$ in Seoul

Population-weighted exposure to $PM_{2.5}$ in Seoul was highest in winter, and the other three seasons had no differences. In a previous study, the Korea simulation exposure model was developed with a probabilistic approach, and the Seoul population exposure to $PM_{2.5}$ was estimated as 29.9 ± 10.6 μg/m^3 in winter, 21.3 ± 4.0 μg/m^3 in summer, and 9.8 ± 2.7 μg/m^3 in autumn (Guak et al., 2021). In both this study and the previous work, population exposure to $PM_{2.5}$ in Seoul was highest in winter. High population exposure in winter may be associated with high ambient $PM_{2.5}$ concentrations. In Korea, high ambient $PM_{2.5}$ levels were typically observed during winter (Kim et al., 2020). To mitigate the population exposure to $PM_{2.5}$ in Seoul, policies on atmospheric air quality management during winter will be important.

4.4. Relationship between personal exposure and corresponding ambient concentration for $PM_{2.5}$ and O_3

Personal $PM_{2.5}$ exposure was closely related with ambient concentration. The results of this study were similar with other previous studies. The meta-analysis study documented the correlation coefficient of $PM_{2.5}$ by season, country, urbanicity, and other factors. By season, the coefficient was 0.52 in overall, 0.57 in summer, and 0.44 in winter. By the type of correlation analysis, the Spearman's coefficient was 0.56 and Pearson's coefficient was 0.67 (Boomhower et al., 2022). In Boston, USA, Spearman's coefficient of $PM_{2.5}$ was 0.61 in summer and 0.35 in winter. The slope of the regression line of $PM_{2.5}$ was 0.77 in summer and 0.33 in winter (Sarnat et al., 2005). In Guangzhou, China, Spearman's coefficient of $PM_{2.5}$ was 0.70 and the slope of the regression line was 0.49 in winter (Chen et al., 2017).

The significant relationship between personal exposures to $PM_{2.5}$ and corresponding ambient concentrations could be explained along with a high infiltration rate of $PM_{2.5}$. A review paper summarized that the median of infiltrations of $PM_{2.5}$ was 0.55, ranging from 0.35 to 0.85, in indoors without apparent sources (Chen and Zhao, 2011). In all seasons, personal $PM_{2.5}$ exposures in every season were lower than ambient $PM_{2.5}$ concentrations. This is because indoor $PM_{2.5}$ concentrations were lower than outdoor $PM_{2.5}$ concentrations during monitoring periods of this study due to a lack of indoor sources. In addition, as the Seoul population remained much of their time indoors, especially 60% of their time in residences (Yang et al., 2011), time-spent indoors accounted for a higher proportion of personal $PM_{2.5}$ exposure.

In this study, the relationship between personal O_3 exposures and ambient O_3 concentrations was weak in summer, and other seasons were indistinct despite the similarity of seasonal differences between personal exposures and ambient concentrations of O_3. This weak relationship between personal exposures and ambient concentrations of O_3 is consistent in previous studies. In Shanghai, China, the associations between personal O_3 exposures and ambient O_3 concentrations were weak. The R^2 value of ranged from 0.23 to 0.26, and the slopes ranged from 0.28 to 0.35 during summer and autumn (Niu et al., 2018). In Ohio, USA, the associations between personal O_3 exposures and ambient O_3 concentrations were reported according to the ventilation status of indoors. In summer, the R^2 value was 0.19 and the slope was 0.08 at low ventilation status. The R^2 value was 0.27 and the slope was 0.18 at high ventilation status. The R^2 value and the slope slightly were elevated as ventilation increased (Sarnat et al., 2006).

The weak relationship between personal exposures to O_3 and ambient concentrations may reflect the indoor loss processes of O_3. The correlations between personal O_3 exposures and ambient O_3 exposures could depend on outdoor-indoor transport of O_3 (Brown et al., 2009). Indoor O_3 concentrations commonly tracked outdoor concentrations and entered buildings along with ventilation air (Dimakopoulou et al., 2017; Weschler, 2000). However, during outdoor to indoor exchange, indoor O_3 concentrations could attenuate rapidly due to its high reactivity with the indoor surface (Lee et al., 1999; Weschler, 2000), resulting in low O_3 concentrations indoors. Due to the O_3 attenuation indoors, personal exposure to O_3 could also be attenuated as the majority of personal exposure to O_3 occurred in indoor environments. Decreased personal O_3 exposure could be associated with a weak correlation with ambient O_3 concentrations.

4.5. Concentrations of $PM_{2.5}$ and O_3 in each microenvironment

Microenvironmental concentrations of $PM_{2.5}$ were significantly higher in barbeque restaurants, restaurants, and pubs than in other locations. The higher concentrations of $PM_{2.5}$ in locations where food can be consumed were due to certain indoor sources such as cooking and fuel combustion. Cooking has often been a significant indoor sources of indoor $PM_{2.5}$ peaks (Buonanno et al., 2013). In a previous study conducted in Seoul, personal $PM_{2.5}$ exposures were higher in restaurants (188.5 ± 306.8 μg/m^3) and bars (69.4 ± 100.3 μg/m^3) than other microenvironments due to cooking and smoking (Lim et al., 2012). Another Korean study reported $PM_{2.5}$ concentrations in several microenvironments in summer and winter. The highest $PM_{2.5}$ concentrations were observed in restaurants, 96.1 ± 165.8 μg/m^3 in summer and 85.4 ± 103.3 μg/m^3 in winter. The lowest $PM_{2.5}$ concentrations were observed in private educational facilities in summer (8.0 ± 2.7 μg/m^3), and senior citizen centers in winter (15.2 ± 9.7 μg/m^3) (Hwang and Lee, 2018).

Microenvironmental concentrations of O_3 were lower in indoors than outdoors. The result was consistent with some previous studies. In residential indoors, O_3 concentrations ranged from 1.3 to 21.4 ppb while outdoor concentrations ranged from 9 to 109 ppb (Lee et al., 2004; Liu et al., 1995; Liu et al., 1993; Stock et al., 1985). In offices, O_3 concentrations ranged from 2.1 to 8.0 ppb while outdoor concentrations ranged from 16.8 to 35 ppb (Bozkurt et al., 2015; Norgaard et al., 2014; Othman et al., 2020). In schools, kindergartens, and childcare centers, O_3 concentrations ranged from 1.6 to 31 ppb while outdoor concentrations ranged from

9 to 109 ppb (Jovanović et al., 2014; Karthikeyan et al., 2007; Romieu et al., 1998; Verriele et al., 2016; Zuraimi et al., 2007). The lower concentration in indoor environments may be due to a high reactivity of O_3 (Lee et al., 1999).

4.6. Contributions of the microenvironment to personal exposures to $PM_{2.5}$ and O_3 for Seoul population

The major microenvironmental contributor of personal exposures to $PM_{2.5}$ and O_3 was residential indoors. Although $PM_{2.5}$ and O_3 concentrations were higher in barbeque restaurants or restaurants than in other microenvironments, their contributions to personal exposures were low. In previous studies, personal exposure to $PM_{2.5}$ in residences had the largest contribution to total $PM_{2.5}$ exposure in both summer and winter in Seoul (Hwang and Lee, 2018; Lim et al., 2012); in Canada (Kim et al., 2005); in Italy (Buonanno et al., 2015); and in USA (Burke et al., 2001). These results may be associated with time activity patterns. Among the microenvironments, people spent the longest time spent in residential indoors, which accounted for more than 60% of the day (U.S. EPA, 2011; Yang et al., 2011).

Indoor $PM_{2.5}$ levels in restaurants, especially in Korean style barbeque restaurants, are significantly higher than other indoor environments. Despite the low contribution to personal $PM_{2.5}$ exposure in this study, $PM_{2.5}$ levels in barbeque restaurants was prominent. Korean barbeque restaurants typically use ignition fuels such as charcoal, briquettes, and gas. The combustion of fuels and grilling meats emitted substantial levels of particulate matters to the indoor air of barbeque restaurants. In this study, $PM_{2.5}$ concentration was measured 46 times repeatedly for 1 hour at a time in barbeque restaurants during study periods. The seasonal maximum range of $PM_{2.5}$ concentration in barbeque restaurants was from 625.8 to 1729.8 $\mu g/m^3$.

In a previous study, the indoor $PM_{2.5}$ levels in Korean restaurants with using charcoal during cooking had the mean of 388.1 μg/m^3, ranging from 17.9 to 1989.4 μg/m^3. In contrast, with using gas during cooking, the indoor $PM_{2.5}$ levels had the mean of 49.4 μg/m^3, ranging from 9.5 to 231.0 μg/m^3 (Lim et al., 2012). In Korea, exhaust particulate matters and gases emitted from barbeque restaurants are emerging problems especially in urban cities where residences and stores are concentrated. $PM_{2.5}$ caused by the combustion of fuels and meats in restaurants are often emitted to the atmosphere by ventilation and local exhaust. Policies for management on an emission of particulate matters from barbeque restaurants should be considerable.

4.7. Limitations

This study was based on time-activity patterns of 3,981 person-days from Seoul surveyed in 2014. The time-activity patterns used in personal exposure monitoring could be representative of the Seoul population. However, time-activity pattern data from KOSTAT was not surveyed in spring. The assumption that time-activity patterns in spring was same in autumn can be an error in estimating population exposures. In addition, the representative categories of the microenvironment may be limited to reflect all locations where the entire Seoul population frequently visited. Time-activity patterns of this study included the microenvironments with 22 sub-categories.

The study period of this study was from 2021 to 2022, but the time-activity pattern scenarios used in this study were developed based on the 2014 survey. Due to COVID-19, the time-activity patterns of the Seoul population may be different between 2021 tot 2021 and those of 2014. Therefore, there was a limitation to reflecting personal exposure to $PM_{2.5}$ and O_3 of the Seoul population in 2021 and

2022. Recently in 2021, the data of the Time Use Survey in 2019 of KOSTAT was freely available to the public. The survey in 2019 has 13 categories of microenvironments. A follow-up study would be improved with estimation of population exposure through simulations of personal exposure monitoring reflecting the updated time-activity patterns.

V. Conclusions

This study provided a seasonal variation of personal exposures to $PM_{2.5}$ and O_3 in the Seoul population. Population exposures to $PM_{2.5}$ and O_3 were high in winter and spring, respectively. $PM_{2.5}$ had a significant relationship between personal exposures and ambient concentrations in winter. O_3 had a weak relationship between personal exposures and ambient concentrations in all seasons. In Seoul, ambient $PM_{2.5}$ concentration could be a surrogate of personal $PM_{2.5}$ exposure in winter. However, ambient O_3 concentration could not be a surrogate for personal O_3 exposure in all seasons. The management of $PM_{2.5}$ and O_3 levels in the residential indoors, barbeque restaurants, and restaurants is important to mitigate personal exposures to $PM_{2.5}$ and O_3 in the Seoul population.

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Supplements

Table S1. Ten time-activity pattern scenarios of the Seoul population in winter.

Season	Group	Descriptive	Time			Microenvironment	
			Start		End	Category	Subcategory
Winter	1	Shopping mall night workers	0:00	~	0:30	Public transportation	Subway/Bus
			0:30	~	0:50	Private transportation	Taxi/Own car
			0:50	~	15:50	Residential indoor	Residential indoor
			15:50	~	16:00	Walking	Walking
			16:00	~	18:00	Other locations	PC room
			18:00	~	18:10	Walking	Walking
			18:10	~	19:10	Restaurant/bar	Restaurant/bar
			19:10	~	19:20	Walking	Walking
			19:20	~	20:20	Other locations	Café
			20:20	~	20:30	Walking	Walking
			20:30	~	0:00	Workplace/school	Shopping mall
	2	Office workers 1	0:00	~	8:00	Residential indoor	Residential indoor
			8:00	~	8:20	Private transportation	Taxi/Own car
			8:20	~	8:50	Public transportation	Subway
			8:50	~	9:00	Walking	Walking
			9:00	~	12:00	Workplace/school	Office
			12:00	~	12:10	Walking	Walking
			12:10	~	13:00	Restaurant/bar	Restaurant/bar
			13:00	~	13:10	Walking	Walking
			13:10	~	19:30	Workplace/school	Office
			19:30	~	19:50	Public transportation	Bus
			19:50	~	20:10	Other locations	Café
			20:10	~	20:30	Private transportation	Taxi/Own car
			20:30	~	0:00	Residential indoor	Residential indoor
	3	Office workers 2	0:00	~	9:00	Residential indoor	Residential indoor
			9:00	~	9:50	Public transportation	Subway
			9:50	~	10:00	Private transportation	Taxi/Own car
			10:00	~	12:50	Workplace/school	Office
			12:50	~	13:00	Walking	Walking
			13:00	~	14:00	Restaurant/bar	Restaurant/bar
			14:00	~	14:10	Walking	Walking
			14:10	~	16:50	Workplace/school	Office
			16:50	~	17:00	Walking	Walking
			17:00	~	18:50	Other locations	Bookstore

		18:50	~	19:20	Public transportation	Bus
		19:20	~	19:50	Private transportation	Taxi/Own car
		19:50	~	20:00	Walking	Walking
		20:00	~	0:00	Residential indoor	Residential indoor
4	Senior citizens	0:00	~	12:30	Residential indoor	Residential indoor
		12:30	~	12:40	Walking	Walking
		12:40	~	13:10	Restaurant/bar	Restaurant/bar
		13:10	~	13:20	Private transportation	Taxi/Own car
		13:20	~	15:50	Other locations	Senior citizens hall
		15:50	~	16:00	Walking	Walking
		16:00	~	16:30	Public transportation	Subway
		16:30	~	17:00	Other locations	Department store
		17:00	~	17:10	Walking	Walking
		17:10	~	0:00	Residential indoor	Residential indoor
5	University students	0:00	~	12:20	Residential indoor	Residential indoor
		12:20	~	12:40	Public transportation	Subway
		12:40	~	13:40	Restaurant/bar	Restaurant/bar
		13:40	~	14:00	Walking	Walking
		14:00	~	16:20	Workplace/school	Lecture room of univercity
		16:20	~	16:40	Public transportation	Subway
		16:40	~	18:00	Workplace/school	Study café/Library
		18:00	~	18:20	Walking	Walking
		18:20	~	18:50	Public transportation	Bus
		18:50	~	0:00	Residential indoor	Residential indoor
6	Middle and high school students	0:00	~	8:00	Residential indoor	Residential indoor
		8:00	~	8:20	Public transportation	Subway
		8:20	~	8:40	Walking	Walking
		8:40	~	16:40	Workplace/school	School
		16:40	~	17:10	Walking	Walking
		17:10	~	18:40	Other locations	Private educational facility
		18:40	~	19:10	Public transportation	Bus
		19:10	~	0:00	Residential indoor	Residential indoor
7	Self-employed workers	0:00	~	10:50	Residential indoor	Residential indoor
		10:50	~	11:20	Public transportation	Bus
		11:20	~	11:30	Walking	Walking
		11:30	~	12:10	Restaurant/bar	Restaurant/bar
		12:10	~	12:30	Private transportation	Taxi/Own car
		12:30	~	21:00	Workplace/school	Self-employment
		21:00	~	21:30	Other locations	Pub
		21:30	~	22:10	Public transportation	Subway

		22:10	~	22:20	Walking	Walking
		22:20	~	0:00	Residential indoor	Residential indoor
8	Housewives	0:00	~	11:00	Residential indoor	Residential indoor
		11:00	~	11:10	Walking	Walking
		11:10	~	11:40	Other locations	Café
		11:40	~	12:10	Private transportation	Taxi/Own car
		12:10	~	12:40	Restaurant/bar	Restaurant/bar
		12:40	~	13:00	Private transportation	Taxi/Own car
		13:00	~	15:40	Other locations	Supermarket
		15:40	~	16:30	Other locations	Traditional market
		16:30	~	17:00	Public transportation	Subway
		17:00	~	17:10	Walking	Walking
		17:10	~	0:00	Residential indoor	Residential indoor
9	Office workers 3	0:00	~	7:20	Residential indoor	Residential indoor
		7:20	~	8:00	Public transportation	Subway
		8:00	~	17:40	Workplace/school	Office
		17:40	~	17:50	Walking	Walking
		17:50	~	19:00	Restaurant/bar	Barbeque restaurant
		19:00	~	19:40	Private transportation	Taxi/Own car
		19:40	~	20:20	Other locations	Pub
		20:20	~	20:50	Public transportation	Bus
		20:50	~	21:10	Walking	Walking
		21:10	~	0:00	Residential indoor	Residential indoor
10	Security office night workers	0:00	~	6:50	Workplace/school	Night security office
		6:50	~	7:50	Private transportation	Taxi/Own car
		7:50	~	8:00	Walking	Walking
		8:00	~	18:00	Residential indoor	Residential indoor
		18:00	~	18:20	Private transportation	Taxi/Own car
		18:20	~	19:00	Public transportation	Subway
		19:00	~	19:40	Restaurant/bar	Barbeque restaurant
		19:40	~	19:50	Walking	Walking
		19:50	~	20:40	Other locations	Pub
		20:40	~	21:10	Public transportation	Bus
		21:10	~	0:00	Workplace/school	Night security office

Table S2. Ten time-activity pattern scenarios of the Seoul population in spring and autumn.

Season	Group	Descriptive	Time			Microenvironment	
			Start		End	Category	Subcategory
Winter	1	Shopping mall night workers	0:00	~	0:20	Workplace/school	Shopping mall
			0:20	~	0:40	Public transportation	Bus
			0:40	~	14:00	Residential indoor	Residential indoor
			14:00	~	14:20	Walking	Walking
			14:20	~	15:10	Restaurant/bar	Restaurant/bar
			15:10	~	15:20	Walking	Walking
			15:20	~	16:30	Other locations	PC room
			16:30	~	16:40	Walking	Walking
			16:40	~	18:20	Other locations	Café
			18:20	~	18:50	Private transportation	Taxi/Own car
			18:50	~	19:00	Walking	Walking
			19:00	~	19:30	Public transportation	Subway
			19:30	~	19:40	Walking	Walking
			19:40	~	0:00	Workplace/school	Shopping mall
	2	Office workers 1	0:00	~	7:30	Residential indoor	Residential indoor
			7:30	~	8:30	Public transportation	Bus + Subway
			8:30	~	12:00	Workplace/school	Office
			12:00	~	12:10	Walking	Walking
			12:10	~	13:00	Restaurant/bar	Restaurant/bar
			13:00	~	13:10	Walking	Walking
			13:10	~	18:50	Workplace/school	Office
			18:50	~	19:00	Walking	Walking
			19:00	~	19:30	Other locations	Café
			19:30	~	20:00	Private transportation	Taxi/Own car
			20:00	~	0:00	Residential indoor	Residential indoor
	3	Office workers 2	0:00	~	7:30	Residential indoor	Residential indoor
			7:30	~	8:10	Public transportation	Subway
			8:10	~	12:00	Workplace/school	Office
			12:00	~	12:10	Walking	Walking
			12:10	~	13:00	Restaurant/bar	Restaurant/bar
			13:00	~	13:10	Walking	Walking
			13:10	~	18:00	Workplace/school	Office
			18:00	~	18:30	Public transportation	Bus
			18:30	~	20:10	Other locations	Bookstore
			20:10	~	20:40	Private transportation	Taxi/Own car
			20:40	~	21:00	Walking	Walking
			21:00	~	0:00	Residential indoor	Residential indoor

4	Senior citizens	0:00	~	10:00	Residential indoor	Residential indoor
		10:00	~	10:10	Walking	Walking
		10:10	~	10:30	Public transportation	Bus
		10:30	~	11:50	Other locations	Senior citizens hall
		11:50	~	12:00	Walking	Walking
		12:00	~	12:30	Restaurant/bar	Restaurant/bar
		12:30	~	12:40	Walking	Walking
		12:40	~	15:00	Other locations	Senior citizens hall
		15:00		15:10	Walking	Walking
		15:10		15:30	Public transportation	Subway
		15:30		16:00	Other locations	Department store
		16:00		16:30	Private transportation	Taxi/Own car
		16:30	~	16:40	Walking	Walking
		16:40	~	0:00	Residential indoor	Residential indoor
5	University students	0:00	~	12:00	Residential indoor	Residential indoor
		12:00	~	12:40	Public transportation	Bus
		12:40	~	16:20	Workplace/school	Lecture room of univercity
		16:20	~	16:30	Walking	Walking
		16:30	~	17:20	Public transportation	Subway
		17:20	~	18:00	Restaurant/bar	Restaurant/bar
		18:00	~	18:10	Walking	Walking
		18:10	~	21:40	Workplace/school	Study café/Library
		21:40	~	21:50	Walking	Walking
		21:50	~	0:00	Residential indoor	Residential indoor
6	Middle and high school students	0:00	~	8:00	Residential indoor	Residential indoor
		8:00	~	8:30	Public transportation	Subway
		8:30	~	16:30	Workplace/school	School
		16:30	~	16:40	Walking	Walking
		16:40	~	16:50	Private transportation	Taxi/Own car
		16:50	~	17:10	Public transportation	Bus
		17:10		17:20	Walking	Walking
		17:20		19:00	Other locations	Private educational facility
		19:00	~	19:20	Walking	Walking
		19:20	~	0:00	Residential indoor	Residential indoor
7	Self-employed workers	0:00	~	9:30	Residential indoor	Residential indoor
		9:30	~	9:40	Walking	Walking
		9:40	~	10:10	Public transportation	Subway
		10:10	~	10:20	Walking	Walking
		10:20	~	12:20	Workplace/school	Self-employment
		12:20	~	13:30	Restaurant/bar	Restaurant/bar

		13:30	~	19:40	Workplace/school	Self-employment
		19:40	~	20:00	Public transportation	Bus
		20:00		22:00	Other locations	Pub
		22:00	~	23:00	Private transportation	Taxi/Own car
		23:00	~	0:00	Residential indoor	Residential indoor
8	Housewives	0:00	~	11:00	Residential indoor	Residential indoor
		11:00	~	11:30	Public transportation	Bus + Subway
		11:30	~	11:50	Other locations	Café
		11:50	~	12:00	Walking	Walking
		12:00	~	12:20	Restaurant/bar	Restaurant/bar
		12:20	~	12:30	Walking	Walking
		12:30	~	14:40	Other locations	Supermarket
		14:40	~	14:50	Walking	Walking
		14:50	~	15:40	Other locations	Traditional market
		15:40	~	16:00	Private transportation	Taxi/Own car
		16:00	~	0:00	Residential indoor	Residential indoor
9	Office workers 3	0:00	~	8:10	Residential indoor	Residential indoor
		8:10	~	8:40	Public transportation	Subway
		8:40	~	9:10	Public transportation	Bus
		9:10	~	17:10	Workplace/school	Office
		17:10	~	17:20	Walking	Walking
		17:20	~	18:20	Restaurant/bar	Barbeque restaurant
		18:20	~	18:50	Private transportation	Taxi/Own car
		18:50	~	20:30	Other locations	Pub
		20:30		20:50	Private transportation	Taxi/Own car
		20:50	~	21:00	Walking	Walking
		21:00	~	0:00	Residential indoor	Residential indoor
10	Security office night workers	0:00	~	9:00	Workplace/school	Night security office
		9:00	~	9:10	Walking	Walking
		9:10	~	9:40	Public transportation	Subway
		9:40	~	18:30	Residential indoor	Residential indoor
		18:30	~	18:40	Walking	Walking
		18:40	~	19:40	Restaurant/bar	Barbeque restaurant
		19:40	~	20:10	Private transportation	Taxi/Own car
		20:10	~	21:10	Other locations	Pub
		21:10	~	21:20	Walking	Walking
		21:20	~	21:50	Private transportation	Taxi/Own car
		21:50	~	0:00	Workplace/school	Night security office

Table S3. Ten time-activity pattern scenarios of the Seoul population in summer.

Season	Group	Descriptive	Time			Microenvironment	
			Start		End	Category	Subcategory
Winter	1	Shopping mall	0:00	~	1:30	Workplace/school	Shopping mall
		night workers	1:30	~	2:00	Private transportation	Taxi/Own car
			2:00	~	17:20	Residential indoor	Residential indoor
			17:20	~	18:20	Other locations	Café
			18:20	~	19:00	Public transportation	Subway
			19:00	~	19:40	Restaurant/bar	Restaurant/bar
			19:40	~	20:00	Walking	Walking
			20:00	~	20:20	Public transportation	Bus
			20:20	~	21:20	Other locations	PC room
			21:20	~	21:50	Walking	Walking
			21:50	~	0:00	Workplace/school	Shopping mall
	2	Office workers 1	0:00	~	6:30	Residential indoor	Residential indoor
			6:30	~	7:00	Private transportation	Taxi/Own car
			7:00	~	8:00	Other locations	Café
			8:00	~	8:30	Public transportation	Subway
			8:30	~	17:50	Workplace/school	Office
			17:50	~	18:00	Walking	Walking
			18:00	~	18:40	Public transportation	Bus
			18:40	~	19:10	Restaurant/bar	Restaurant/bar
			19:10	~	19:30	Private transportation	Taxi/Own car
			19:30	~	19:50	Walking	Walking
			19:50	~	0:00	Residential indoor	Residential indoor
	3	Office workers 2	0:00	~	8:40	Residential indoor	Residential indoor
			8:40	~	9:10	Private transportation	Taxi/Own car
			9:10	~	9:30	Public transportation	Bus
			9:30	~	11:50	Workplace/school	Office
			11:50	~	12:10	Walking	Walking
			12:10	~	13:10	Restaurant/bar	Restaurant/bar
			13:10	~	13:30	Walking	Walking
			13:30	~	16:50	Workplace/school	Office
			16:50	~	17:10	Private transportation	Taxi/Own car
			17:10	~	18:50	Other locations	Bookstore
			18:50		19:10	Walking	Walking
			19:10	~	20:00	Public transportation	Subway
			20:00	~	0:00	Residential indoor	Residential indoor
	4	Senior citizens	0:00	~	9:50	Residential indoor	Residential indoor
			9:50	~	10:00	Walking	Walking
			10:00	~	12:00	Other locations	Senior citizens hall

		12:00	~	12:10	Walking	Walking
		12:10	~	12:40	Restaurant/bar	Restaurant/bar
		12:40	~	12:50	Walking	Walking
		12:50	~	14:30	Other locations	Senior citizens hall
		14:30	~	15:00	Private transportation	Taxi/Own car
		15:00		15:50	Other locations	Department store
		15:50		16:20	Public transportation	Bus + Subway
		16:20	~	0:00	Residential indoor	Residential indoor
5	University students	0:00	~	13:00	Residential indoor	Residential indoor
		13:00	~	13:10	Walking	Walking
		13:10	~	14:10	Restaurant/bar	Restaurant/bar
		14:10	~	14:20	Walking	Walking
		14:20	~	17:10	Workplace/school	Study café/Library
		17:10	~	17:30	Private transportation	Taxi/Own car
		17:30	~	20:15	Workplace/school	Lecture room of univercity
		20:15	~	20:40	Walking	Walking
		20:40	~	21:30	Public transportation	Bus + Subway
		21:30	~	0:00	Residential indoor	Residential indoor
6	Middle and high school students	0:00	~	8:30	Residential indoor	Residential indoor
		8:30	~	8:40	Walking	Walking
		8:40	~	9:00	Public transportation	Subway
		9:00	~	15:00	Workplace/school	School
		15:00	~	15:20	Walking	Walking
		15:20	~	17:20	Other locations	Private educational facility
		17:20	~	17:50	Public transportation	Bus
		17:50	~	0:00	Residential indoor	Residential indoor
7	Self-employed workers	0:00	~	9:00	Residential indoor	Residential indoor
		9:00	~	9:50	Public transportation	Subway
		9:50	~	11:50	Workplace/school	Self-employment
		11:50	~	12:00	Walking	Walking
		12:00	~	12:50	Restaurant/bar	Restaurant/bar
		12:50	~	13:00	Walking	Walking
		13:00	~	20:00	Workplace/school	Self-employment
		20:00	~	20:20	Public transportation	Bus
		20:20		21:10	Other locations	Pub
		21:10		21:30	Private transportation	Taxi/Own car
		21:30	~	22:00	Walking	Walking
		22:00	~	0:00	Residential indoor	Residential indoor
8	Housewives	0:00	~	7:00	Residential indoor	Residential indoor
		7:00	~	7:40	Public transportation	Subway

		7:40	~	10:00	Other locations	Café
		10:00	~	10:10	Walking	Walking
		10:10	~	12:10	Other locations	Supermarket
		12:10	~	12:20	Walking	Walking
		12:20	~	12:50	Restaurant/bar	Restaurant/bar
		12:50	~	13:10	Walking	Walking
		13:10		15:10	Other locations	Traditional market
		15:10	~	15:30	Private transportation	Taxi/Own car
		15:30	~	16:00	Public transportation	Bus
		16:00	~	0:00	Residential indoor	Residential indoor
9	Office workers 3	0:00	~	8:10	Residential indoor	Residential indoor
		8:10	~	8:40	Walking	Walking
		8:40	~	9:10	Public transportation	Subway
		9:10	~	17:10	Workplace/school	Office
		17:10	~	17:20	Public transportation	Bus
		17:20	~	18:20	Walking	Walking
		18:20	~	18:50	Restaurant/bar	Barbeque restaurant
		18:50	~	20:30	Walking	Walking
		20:30		20:50	Other locations	Pub
		20:50	~	21:00	Private transportation	Taxi/Own car
		21:00	~	0:00	Residential indoor	Residential indoor
10	Security office night workers	0:00	~	9:30	Workplace/school	Night security office
		9:30	~	9:40	Walking	Walking
		9:40	~	10:10	Private transportation	Taxi/Own car
		10:10	~	20:30	Residential indoor	Residential indoor
		20:30	~	20:55	Private transportation	Taxi/Own car
		20:55	~	21:55	Restaurant/bar	Barbeque restaurant
		21:55	~	22:10	Walking	Walking
		22:10	~	23:10	Other locations	Pub
		23:10	~	0:00	Workplace/school	Night security office

Table S4. Daily average time spent in 22 microenvironments of 10 population groups in four seasons.

Microenvironment	Daily average time spent in each microenvironment (hr)									
	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8	Group 9	Group 10
(a) Winter										
Residential indoor	**15.00**	**11.50**	**13.00**	**19.33**	**17.50**	**12.83**	**12.50**	**17.83**	**10.17**	**10.00**
Office	0.00	**9.33**	**5.50**	0.00	0.00	0.00	0.00	0.00	**9.67**	0.00
School	0.00	0.00	0.00	0.00	**2.33**	**8.00**	0.00	0.00	0.00	0.00
Self-employment	0.00	0.00	0.00	0.00	0.00	0.00	**8.50**	0.00	0.00	0.00
Shopping mall	**3.50**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Night security office	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**9.67**
Café	**1.00**	**0.33**	0.00	0.00	0.00	0.00	0.00	**0.50**	0.00	0.00
Study café	0.00	0.00	0.00	0.00	**1.33**	0.00	0.00	0.00	0.00	0.00
Pub	0.00	0.00	0.00	0.00	0.00	0.00	**0.50**	0.00	**0.67**	**0.83**
PC room	**2.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Bookstore	0.00	0.00	**1.83**	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Senior citizens hall	0.00	0.00	0.00	**2.50**	0.00	0.00	0.00	0.00	0.00	0.00
Department store	0.00	0.00	0.00	**0.50**	0.00	0.00	0.00	0.00	0.00	0.00
Supermarket	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**2.67**	0.00	0.00
Private educational facility	0.00	0.00	0.00	0.00	0.00	**1.50**	0.00	0.00	0.00	0.00
Traditional market	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.83**	0.00	0.00
Restaurant	**1.00**	**0.83**	**1.00**	**0.50**	**1.00**	0.00	**0.67**	**0.50**	0.00	0.00
Barbeque restaurant	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.17**	**0.67**
Walking	**0.67**	**0.50**	**0.67**	**0.50**	**0.67**	**0.83**	**0.33**	**0.33**	**0.50**	**0.33**
Taxi/Car	**0.33**	**0.67**	**0.67**	**0.17**	0.00	0.00	**0.33**	**0.83**	**0.67**	**1.33**
Subway	**0.50**	**0.50**	**0.83**	**0.50**	**0.67**	**0.33**	**0.67**	**0.50**	**0.67**	**0.67**
Bus	0.00	**0.33**	**0.50**	0.00	**0.50**	**0.50**	**0.50**	0.00	**0.50**	**0.50**
(b) Spring and Autumn										
Residential indoor	**15.00**	**11.50**	**13.00**	**19.33**	**17.50**	**12.83**	**12.50**	**17.83**	**10.17**	**10.00**
Office	0.00	**9.33**	**5.50**	0.00	0.00	0.00	0.00	0.00	**9.67**	0.00
School	0.00	0.00	0.00	0.00	**2.33**	**8.00**	0.00	0.00	0.00	0.00
Self-employment	0.00	0.00	0.00	0.00	0.00	0.00	**8.50**	0.00	0.00	0.00
Shopping mall	**3.50**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Night security office	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**9.67**

Café	**1.00**	**0.33**	0.00	0.00	0.00	0.00	0.00	**0.50**	0.00	0.00
Study café	0.00	0.00	0.00	0.00	**1.33**	0.00	0.00	0.00	0.00	0.00
Pub	0.00	0.00	0.00	0.00	0.00	0.00	**0.50**	0.00	**0.67**	**0.83**
PC room	**2.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Bookstore	0.00	0.00	**1.83**	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Senior citizens hall	0.00	0.00	0.00	**2.50**	0.00	0.00	0.00	0.00	0.00	0.00
Department store	0.00	0.00	0.00	**0.50**	0.00	0.00	0.00	0.00	0.00	0.00
Supermarket	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**2.67**	0.00	0.00
Private educational facility	0.00	0.00	0.00	0.00	0.00	**1.50**	0.00	0.00	0.00	0.00
Traditional market	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.83**	0.00	0.00
Restaurant	**1.00**	**0.83**	**1.00**	**0.50**	**1.00**	0.00	**0.67**	**0.50**	0.00	0.00
Barbeque restaurant	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**1.17**	**0.67**
Walking	**0.67**	**0.50**	**0.67**	**0.50**	**0.67**	**0.83**	**0.33**	**0.33**	**0.50**	**0.33**
Taxi/Car	**0.33**	**0.67**	**0.67**	**0.17**	0.00	0.00	**0.33**	**0.83**	**0.67**	**1.33**
Subway	**0.50**	**0.50**	**0.83**	**0.50**	**0.67**	**0.33**	**0.67**	**0.50**	**0.67**	**0.67**
Bus	0.00	**0.33**	**0.50**	0.00	**0.50**	**0.50**	**0.50**	0.00	**0.50**	**0.50**

(d) Summer

Residential indoor	**15.33**	**10.33**	**14.67**	**12.67**	**11.00**	**10.67**	**17.50**	**15.50**	**15.00**	**11.33**
Office	0.00	0.00	0.00	**5.67**	0.00	**9.33**	0.00	0.00	0.00	**9.33**
School	0.00	0.00	**6.00**	0.00	0.00	0.00	0.00	**2.75**	0.00	0.00
Self-employment	0.00	0.00	0.00	0.00	**9.00**	0.00	0.00	0.00	0.00	0.00
Shopping mall	**3.67**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Night security office	0.00	**9.50**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Café	**1.00**	0.00	0.00	0.00	0.00	**1.00**	0.00	0.00	**2.33**	0.00
Study café	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**2.83**	0.00	0.00
Pub	0.00	**1.00**	0.00	0.00	**0.83**	0.00	0.00	0.00	0.00	**0.50**
PC room	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Bookstore	0.00	0.00	0.00	**1.67**	0.00	0.00	0.00	0.00	0.00	0.00
Senior citizens hall	0.00	0.00	0.00	0.00	0.00	0.00	**3.67**	0.00	0.00	0.00
Department store	0.00	0.00	0.00	0.00	0.00	0.00	**0.83**	0.00	0.00	0.00
Supermarket	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**2.00**	0.00
Private educational facility	0.00	0.00	**2.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Traditional market	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**2.00**	0.00

Restaurant	**0.67**	0.00	0.00	**1.00**	**0.83**	**0.50**	**0.50**	**1.00**	**0.50**	0.00
Barbeque restaurant	0.00	**1.00**	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.83**
Walking	**0.83**	**0.42**	**0.50**	**1.00**	**0.83**	**0.50**	**0.50**	**0.75**	**0.67**	**0.50**
Taxi/Car	**0.50**	**0.92**	0.00	**0.83**	**0.33**	**0.83**	**0.50**	**0.33**	**0.33**	**0.33**
Subway	**0.67**	**0.83**	**0.33**	**0.83**	**0.83**	**0.50**	**0.50**	0.00	**0.67**	**0.67**
Bus	**0.33**	0.00	**0.50**	**0.33**	**0.33**	**0.67**	0.00	**0.83**	**0.50**	**0.50**

*Group description: Group 1 for shopping mall night workers; Group 2 for office workers 1; Group 3 for office workers 2; Group 4 for senior citizens; Group 5 for university students; Group 6 for middle and high school students; Group 7 for self-employed workers; Group 8 for housewives; Group 9 for office workers 3; Group 10 for security office night workers.

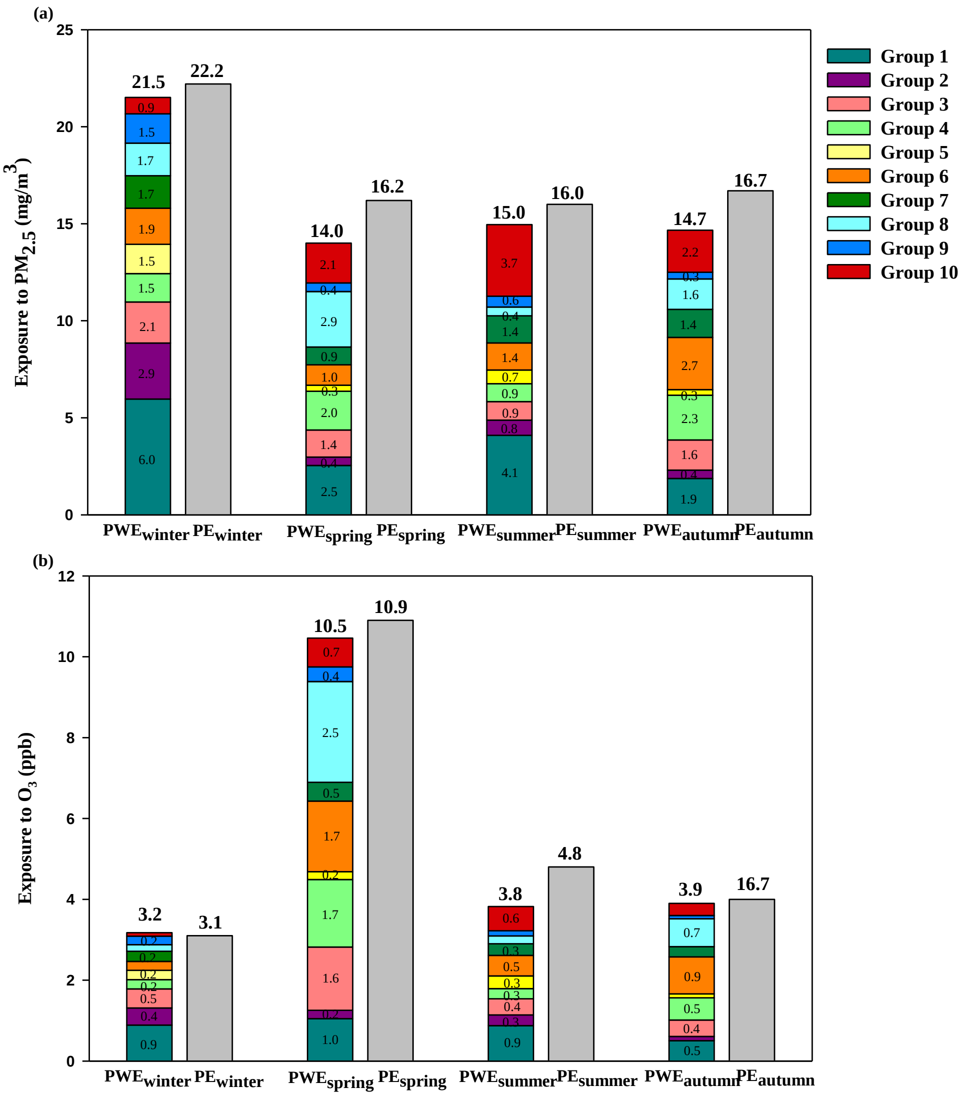

Figure S1. (a) Daily population-weighted exposure (PWE) and personal exposure (PE) to $PM_{2.5}$ of the Seoul population by season; (b) Daily population-weighted exposure (PWE) and personal exposure (PE) to O_3 of the Seoul population by season.

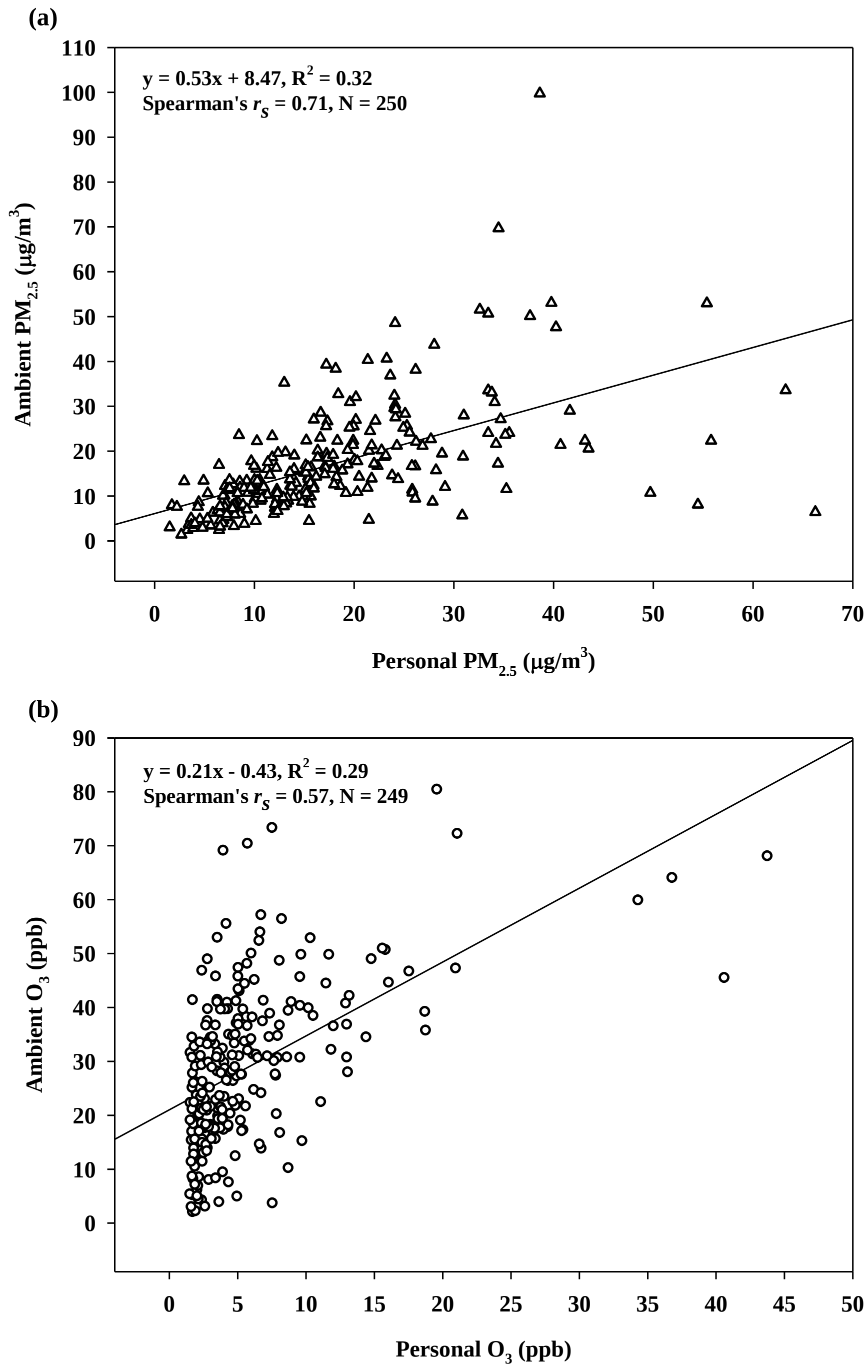

Figure S2. (a) Relationship between personal exposure and corresponding ambient concentration of $PM_{2.5}$ on a daily average in four seasons; (b) Relationship between personal exposure and corresponding ambient concentration of O_3 on a daily average in four seasons.

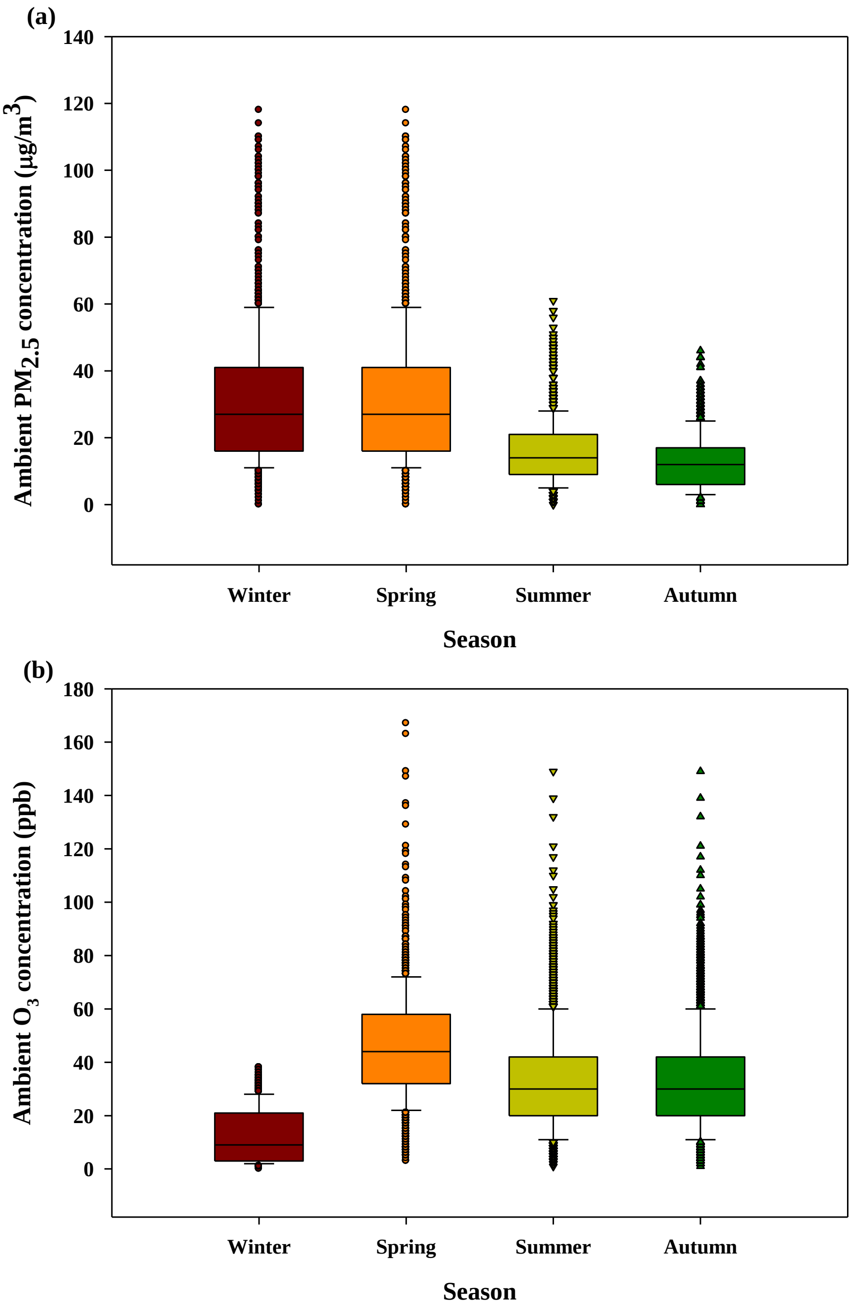

Figure S3. (a) Ambient $PM_{2.5}$ concentrations in winter, spring, summer, and autumn; (b) Ambient O_3 concentrations in winter, spring, summer, and autumn.

국문 초록

서울시 인구의 $PM_{2.5}$ 및 O_3 개인노출 평가

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연구 배경: $PM_{2.5}$ 및 O_3에 대한 노출은 공중 보건학적으로 지속적인 우려 사항이다. 여러 역학 연구에서 $PM_{2.5}$와 O_3에 대한 노출과 건강영향의 관계를 추정함에 있어, 대기 농도가 인구집단 노출을 대용하여 사용되었다. 그러나 개인노출과 대기 농도의 상관관계는 다양하며, 개인노출은 시간 활동 양상, 계절, 그리고 미소 환경 등 여러 요인에 영향받을 수 있다.

연구 목적: 본 연구의 목적은 1) $PM_{2.5}$와 O_3에 대한 개인노출과 인구가중노출의 계절 및 인구집단 간 차이를 파악하는 것, 2) $PM_{2.5}$와 O_3에 대한 개인노출과 대기농도 사이의 관계를 파악하는 것, 그리고 3) 미소환경 종류별 서울시 인구의 $PM_{2.5}$와 O_3에 대한 개인노출 기여도를 평가하는 것이다.

연구 방법: 통계청의 2014년 생활시간조사 자료를 바탕으로 10개 인구집단의 일일 시간활동양상 시나리오가 겨울, 봄, 여름, 가을 등 사계절에 각각 형성되었다. 이를 바탕으로 연구자가 실시간 에어로졸

모니터와 소형 오존 모니터를 휴대하여 24시간 동안 시간 활동 패턴 노출 시나리오를 시뮬레이션 하였다. 총 250명/일의 개인노출 모니터링 데이터가 수집되었으며 계절별로는 겨울에 40명/일, 봄에 50명/일, 여름과 가을에 각각 80명/일이었다. $PM_{2.5}$와 O_3에 대한 개인노출의 계절 및 인구집단에 따른 차이를 식별하기 위해 일원 분산 분석을 수행했다. $PM_{2.5}$와 O_3에 대한 개인노출과 대기 농도 사이의 관계를 파악하기 위해 Spearman의 상관관계 분석과 단순 선형 회귀 분석을 수행했다. 미소환경 종류별 개인노출 기여도 및 인구가중노출이 계산되었다.

연구 결과: $PM_{2.5}$와 O_3에 대한 개인노출의 계절적 차이는 유의하게 나타났다. $PM_{2.5}$와 O_3에 대한 개인노출은 각각 겨울(22.2 ± 28.2 μg/m^3) 그리고 봄(11.6 ± 9.6 ppb)에 높았다. $PM_{2.5}$에 대한 개인노출은 근로자 인구집단에서 일반적으로 높았고, O_3에 대한 개인노출은 직장인과 가정주부 인구집단에서 일반적으로 높았다. $PM_{2.5}$에 대한 인구가중노출은 겨울에 21.5 μg/m^3, 봄에 14.0 μg/m^3, 여름에 15.0 μg/m^3, 그리고 가을에 14.7 μg/m^3 이었다. O_3에 대한 인구가중노출은 겨울에 2.3 ppb, 봄에 10.5 Ppb, 여름에 3.8 ppb, 그리고 가을에 3.9 ppb 이었다. 겨울철 $PM_{2.5}$에 대한 개인노출과 대기농도는 유의한 상관관계가 있었다 (r_s = 0.81, R^2 = 0.57). O_3에 대한 개인노출과 대기 농도는 여름에 약한 상관관계가 있었다 (r_s = 0.54, R^2 = 0.23). 모든 계절에, $PM_{2.5}$와 O_3의 농도는 고기집에서 가장 높았음에도, 실내 주거환경이 $PM_{2.5}$와 O_3에 대한 개인노출에 가장 주요하게 기여하는 것으로 나타났다.

결론: 본 연구는 서울시 인구의 $PM_{2.5}$와 O_3에 대한 개인노출의 계절적 차이를 평가했다. $PM_{2.5}$와 O_3에 대한 개인노출은 각각 겨울과 봄에 더

높았다. $PM_{2.5}$는 겨울철에 개인노출과 대기 농도 사이에 유의한 관계성이 있었다. O_3는 모든 계절에서 개인노출과 대기 농도 사이에 약한 관계성이 있었다. 서울시를 대상으로는 겨울철 $PM_{2.5}$에 대하여 대기 농도가 개인노출을 대체할 수 있었다. 그러나 O_3에 대해서는 모든 계절에서 대기 농도가 개인노출을 대체할 수 없었다. 서울시 인구의 $PM_{2.5}$와 O_3에 대한 개인노출을 줄이기 위해서는 실내 주거환경, 식당, 그리고 고기집에서의 $PM_{2.5}$ 및 O_3 농도 관리가 중요하다.

주요어: 개인노출, 인구집단 노출, $PM_{2.5}$, O_3, 대기농도, 상관관계, 시간활동양상, 미소환경, 초미세먼지, 오존

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