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The associations of real-time and perceived air pollution exposure with episode-level subjective wellbeing: a case study of a suburban community in Beijing

Wenbo Guo [a,*], Tim Schwanen [a], Christian Brand [a], Yanwei Chai [b]

[a] Transport Studies Unit, School of Geography and the Environment, University of Oxford, OX1 3QY, UK
[b] College of Urban and Environmental Sciences, Peking University, 100871, China

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ABSTRACT

Background: The dynamics of everyday life and mobility patterns are often neglected in studies examining the association between air pollution and subjective wellbeing (SWB). We investigated the association between air pollution exposure, both by ambient and perceived measurement, and subjective wellbeing for individuals' activity episodes and trips in Beijing.
Methods: Data on 1688 activities and 573 trips were obtained from the activity-travel diary survey in the Meiheyuan residential community, Beijing, from November 2017 to January 2018. Real-time exposure to ambient air pollution (AAP) in the form of fine particulate matter ($PM_{2.5}$) was collected using portable air pollution sensors, and perceived air pollution (PAP) and SWB at the episode level were acquired through activity-travel diaries. Multi-level structural equation modelling (ML-SEM) was used to investigate the associations between air pollution and SWB separately for daily activity episodes and trips.
Results: PAP is not only directly associated with SWB at both activity and trip episodes but also mediates between AAP and SWB for activities. A time-lagged effect of AAP on SWB is observed for trips, where AAP of the preceding episode is directly linked to SWB at the current episode. Location plays a fundamental role in shaping individuals' AAP, PAP and SWB at activity episodes. The effects of start time, location, activity type and duration are primarily mediated by location and location-PAP. life circumstances shape their exposure to and perceptions of air pollution, as well as their SWB during activity and trip episodes.
Conclusion: People's perception of air pollution bears a more pronounced relationship with their satisfaction with individual activities and trips compared to the objective measurements of ambient $PM_{2.5}$ exposure. It also highlights that ambient $PM_{2.5}$ exposure during the preceding activity episode has a time-lagged effect on satisfaction with the current trip episode.

1. Introduction

Ambient air pollution (AAP) is one of the major environmental and health stressors, which poses a threat to human psychological and physiological health (World Health Organization, 2021a). Air pollution can not only directly lead to respiratory diseases, cardiovascular diseases and impaired cognitive functioning, but also deteriorate mental health and subjective wellbeing (SWB), the latter of which is less frequently explored (Li et al., 2018; Bakolis et al., 2021). $PM_{2.5}$, referring to fine particulate matter with a diameter of 2.5 μm or smaller, is a particularly harmful pollutant that significantly impacts health and subjective wellbeing. However, its invisible nature makes it challenging for individuals to perceive without specialized equipment (World Health Organization, 2021b; Hong et al., 2022). Given the similar conscious nature shared by human environmental perception and subjective wellbeing (Li et al., 2018), perceived air pollution (PAP) is increasingly understood as a factor mediating the relationship between ambient air pollution and subjective wellbeing (Chen et al., 2020; Ma et al., 2020).

Within the strand of literature that investigates the relationships among ambient air pollution, perceived air pollution and subjective wellbeing, it has been common to utilise population-level analysis based on census data and large-scale survey data in the last two decades

* Corresponding author.
E-mail addresses: wenbo.guo@ouce.ox.ac.uk (W. Guo), tim.schwanen@ouce.ox.ac.uk (T. Schwanen), christian.brand@ouce.ox.ac.uk (C. Brand), chyw@pku.edu.cn (Y. Chai).

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(Welsch, 2006; Menz, 2011; Orru et al., 2016). The negative effect of long-term air pollution on self-reported life satisfaction has been validated at the national and subnational levels through large-scale surveys (Luechinger, 2009; Frey et al., 2010; Claeson et al., 2013). The effects of air pollution on life satisfaction have also been differentiated by gender, income, age, residence, marital status, or job market status in discussing inequality issues (Ferreira et al., 2013; Yang and Liu, 2018; Pu et al., 2019).

However, both ambient and perceived air pollution are localised phenomena and may vary by not only individuals' sociodemographic background but also their different geographical contexts. People's ambient and perceived exposure to air pollution and its relationship with subjective wellbeing may well vary across the activity and travel episodes people undertake in different spatial locations over the course of a day. Here, by one 'episode', we mean a continuous time-span devoted to a single type of activity (e.g., work, sleep, shopping) or a trip from one place to another that occurs with the sequence of activities and trips on a whole day (0–24 h).

With the development of portable air pollution monitoring devices, it is possible to gauge episode-level exposure to ambient air pollution with high space-time resolution. Together with the activity-travel diaries that collect the perceived levels of air pollution and subjective wellbeing, the association between AAP, PAP, and SWB can be investigated for individual activity-travel episodes. Among the few empirical studies quantifying the effects of ambient and perceived air pollution on subjective wellbeing at the episode level, Ma et al. (2020, 2021) have explained the association for different activity types and transport modes. However, their study did not consider the lagged effects of ambient and perceived air pollution on subjective wellbeing. Such effects may be important as the ambient and perceived air pollution of preceding activities or trips may continue to be related to an individual's subjective wellbeing later. Besides, other characteristics of activity-travel episodes than those considered by Ma and colleagues may also be associated with AAP, PAP and SWB.

This study aims to examine the relationships among four sets of variables – various indicators of air pollution exposure, subjective wellbeing, characteristics of activity/travel episodes, and life circumstances. The air pollution variables included ambient $PM_{2.5}$ exposure during the activity/travel episode of interest, perceived exposure during that episode, and ambient $PM_{2.5}$ exposure during the preceding episode. The analysis is conducted separately for activity and travel episodes as the set of episode characteristics differs substantially for each category. Multi-level structural equation modelling (ML-SEM) is applied to data obtained from real-time, mobility-based measurement of $PM_{2.5}$ air pollution and activity-travel diaries involving episode-level valuation of air pollution and satisfaction for a sample of residents of a suburb in Beijing.

The remainder of this paper is organised into four sections. Section 2 reviews four categories of relevant research articles and highlights the research gaps to be addressed. Section 3 introduces the study area and dataset together with the SEM deployed in this research. Section 4 provides the results of the SEM while Section 5 discusses the main findings, research limitations and future directions.

2. Literature review

2.1. *Ambient air pollution, perceived air pollution and subjective wellbeing at the day level or longer timescales of the month and the year*

Preceding studies investigating the association of ambient air pollution with subjective wellbeing largely focused on the national and sub-national level on timescales such as the year or the month. They have demonstrated a clear negative relationship between air pollution and life satisfaction (e.g., Welsch, 2007; Smyth et al., 2008; Luechinger, 2009). Although there are few research articles exploring air pollution exposure and subjective wellbeing on a daily scale, Levinson (2012) showed that people report lower levels of happiness on days with worse local air pollution by using the air pollution data from the EPA's Air Quality System (AQS) and the subjective wellbeing information from the General Social Survey (GSS) in the US. Big data is playing an increasingly important role in exploring the relationship between ambient air pollution and subjective wellbeing. For instance, Zheng et al. (2019) verified that the local air quality index and $PM_{2.5}$ concentrations lower happiness at the daily level based on the sentiment information of 144 cities obtained from geotagged tweets on the Chinese largest microblog platform Sina Weibo.

Preceding studies have also chosen perceived air pollution as a convenient way to explore the relationship between air pollution and subjective wellbeing. Air pollution can be associated with people's thoughts and experiences of their lives directly by visual perceptions and reduces people's subjective wellbeing to a significant degree (Li et al., 2018). Thus, visually perceived air pollution is a key sensation of environmental exposure situations and can potentially be related to subjective wellbeing, which has been reported in multiple studies investigating the association (e.g., Kirk, 2006; Hyslop, 2009).

Studies examining the association between perceived air pollution and subjective wellbeing often use single Likert-scale items asking respondents' perceptions of air pollution together with the subjective wellbeing level. Li et al. (2014) measured perceived air pollution intensity and hazard level of pollutants as well as subjective wellbeing for a stratified random sample of 800 participants living in a mining area of China. Their results indicate that both types of perceived air pollution are negatively associated with people's happiness, although their combined effect is less than the (positive) effect of having a higher income and education. However, in a study of 288 working adults in Beijing by Gu et al. (2015), perceived air pollution was not significantly associated with general subjective wellbeing but improved their sense of purpose and meaning in life (i.e., eudaimonic wellbeing). There may also be geographical variations in people's risk perception and attitude toward air pollution among different regions once confounding factors are controlled. For instance, Pu et al. (2019) found that the respondents in the northeast region, northern coastal region, eastern coastal region and Middle Yellow River region perceived higher air pollution risk and had lower levels of satisfaction with air quality than among participants from other regions in China.

While the majority of previous studies have addressed the association between ambient air pollution, perceived air pollution and subjective wellbeing at the national or regional levels, there are still some empirical studies exploring the associations at the individual level. Within the few new studies investigating the association of air pollution with subjective wellbeing within a day, it is hard to find robust evidence that greater exposure to air pollution is associated with lower subjective wellbeing. Zhang et al. (2017), using a nationally representative survey in China, found that bad air quality on a given day is not associated with overall life satisfaction but it reduces momentary emotions and affection and increases the prevalence of depressive symptoms.

2.2. *Ambient air pollution, perceived air pollution and subjective wellbeing at the level of individual activity-travel episodes*

A wide range of activity-travel variables has been discussed in relation to episode-level subjective wellbeing. Examples include the timing, duration and location of trips or activities; the type of activity or trip purpose, and the transport mode used (e.g., De Vos and Witlox, 2017). Satisfaction is commonly found to be highest for walking, followed by cycling, and lowest for public transport in most travel behaviour studies (Bergstad et al., 2011; Susilo and Cats, 2014; De Vos et al., 2015; Ettema et al., 2016). Life circumstances such as age, gender and income play a significant role in shaping an individual's travel-related satisfaction (De Vos et al., 2016; Ettema et al., 2017; Ye and Titheridge, 2017) Social contacts during daily travel increase subjective wellbeing (Zhu and Fan, 2018; De Vos, 2019), However, air pollution as an indicator of geographical context has rarely been considered in previous studies.

Air pollution exposure during daily activity-travel episodes has often been assessed using a combination of air pollution diffusion maps generated based on air pollution monitor stations and trajectory information obtained from activity-travel diary surveys (e.g., Gulliver and Briggs, 2005; Kwan et al., 2015). Not until the development and implication of portable air pollution devices in recent years, has it been possible to measure mobility-related air pollution concentrations with higher space-time resolution (Lim et al., 2019; Huang et al., 2022).

Although there is substantial evidence proving the association of measured ambient air pollution with subjectively perceived air pollution levels (e.g., Day, 2007; Reames and Bravo, 2019; Song and Kwan, 2023), individuals with different life circumstances are likely to perceive the same objective level of air pollution differently along with their daily activities and trips. For instance, people with different levels of self-reported health status may have different levels of risk perception toward air pollution, which will potentially influence their subjective wellbeing (Li and Zhou, 2020).

To date, the associations of ambient and perceived air pollution with subjective wellbeing at the daily activity-travel episode level have rarely been examined. Liu et al. (2019) used logistic regression models to analyse the effects of socioeconomic attributes, travel characteristics, health and living conditions, as well as air pollution exposure variables on residents' daily travel satisfaction. Perceived air pollution was found to have a statistically significant and greater effect on travel satisfaction than ambient air pollution. By combining activity-travel diaries that include questions about PAP and SWB for each activity and trip with information on real-time air pollution exposure from portable air pollution sensors in Beijing, Ma et al. (2020) applied multilevel logistic regression models to examine the association of real-time and perceived exposure to air and noise pollution with satisfaction at different activity episodes. They found that perceived air and noise pollution were more important covariates of activity satisfaction than objectively measured pollution and that air pollution had a greater effect than noise pollution on activity satisfaction. However, neither the study by Ma et al. nor that by Li and colleagues considered the intermediation of perceived air pollution, i.e., the indirect effect of real-time $PM_{2.5}$ air pollution exposure on subjective wellbeing via perceived air pollution. A subsequent study by Ma et al. (2021), utilising the same data, employed structural equation models to investigate whether the objectively measured and subjectively perceived exposure to air pollution and noise in different traffic microenvironments are associated with individuals' travel satisfaction and thus life satisfaction. The findings indicate that ambient $PM_{2.5}$ exposure is negatively associated with travel satisfaction indirectly via perceived air pollution. However, the study by Ma et al. (2021) did not consider a wide set of activity and trip characteristics, such as travel distance, duration, start time and companion, which may affect the association between air pollution exposure and subjective wellbeing. That study also did not consider that the effects on people's perception of air pollution and satisfaction with an activity or trip may be time-lagged, so that experiences during the preceding trip or activity episode(s) at t_{-1}, t_{-2}, t_{-n} may affect those at t_0 (Diener, 2012; Dong et al., 2019).

2.3. Conceptual framework

Drawing on Affective Events Theory (AET), this framework will bring in the concept of perceived air pollution and the time-lagged effects of ambient $PM_{2.5}$ exposure on subjective wellbeing as well as consider a wider range of activity-travel characteristics and socio-demographic information. According to AET, individuals' emotional reactions—such as stress, anxiety, or frustration—are strongly influenced by how they perceive the severity and impact of air pollution during an activity or trip. This perception of air pollution, rather than the actual levels of pollution, may play a crucial role in shaping emotional responses. These emotional reactions, in turn, directly affect subjective wellbeing. AET suggests that individuals' cognitive appraisals of air pollution, such as how severe or harmful they believe the pollution is, significantly influence their emotional state during the current exposure (Weiss and Cropanzano, 1996). Thus, perceived air pollution acts as a psychological filter that shapes how individuals experience and emotionally react to their environment.

AET also proposes that the emotional effects of air pollution can persist over time, leading to a time-lagged effect on individuals' subjective wellbeing. The emotional responses triggered by exposure to pollution in one episode can continue to influence how individuals feel and perceive future episodes, even after the initial exposure has ended. This time-lagged effect occurs because individuals may ruminate on past experiences, worrying about potential health risks, which shapes their emotional state and satisfaction in subsequent activities or trips (Ashton-James and Ashkanasy, 2005). In this way, the emotional effect of a preceding pollution episode extends beyond the immediate moment, continuing to be linked to subjective wellbeing in later episodes.

This research will look at the activity episodes and trip episodes separately since the characteristics of activities and trips are different by nature. People's satisfaction with activities may be associated with locations and types of activity, while satisfaction with trips could be more associated with trip purposes and transport modes. However, the activity and trip episodes share the same characteristics of time, duration, and the presence of companions. Thus, we propose the Ambient and Perceived air Pollution, and Subjective wellbeing during Activity-Travel Episodes (APPSATE) model for activity episodes and trip episodes respectively (Fig. 1). In the conceptual model, a circular connection between activity-travel patterns, air pollution and subjective wellbeing is hypothesised. Hypothesis (1) holds that people's ambient air pollution exposure is associated with their daily activity and trip patterns (timing, location, transport mode, trajectory, etc.), whilst ambient air pollution at the current and preceding episode will affect people's perception of air pollution and thus their subjective wellbeing at the episode level (full-line arrow). Hypothesis (2), on the contrary, holds that subjective wellbeing could also be related to people's perception of air pollution and both are associated with their activity-travel patterns; the change of activity-travel patterns will in turn be connected to the change of people's ambient $PM_{2.5}$ exposure (break-line arrow). Back in the loop, this will recondition their perception of air pollution and subjective

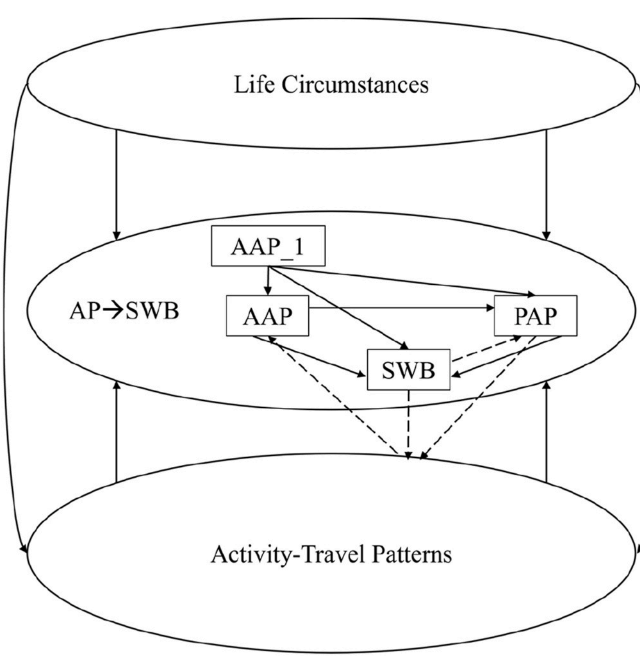

Fig. 1. The APPSATE conceptual framework.

wellbeing. Hypothesis (2) could be an interesting topic to examine, especially regarding the health and wellbeing outcome of behavioural change, which has great value for policy and practical implications. However, this needs to be done using stated preference or tracking surveys rather than activity-travel diaries. This paper will only focus on the hypothesis (1) for the sake of revealing the mechanism of how activity-travel patterns associate with individuals' ambient $PM_{2.5}$ exposure, perceived air pollution and thereupon subjective wellbeing.

3. Materials and methods

3.1. Study area

A suburban community in Beijing, the Meiheyuan residential community, was chosen as the study area. The Meiheyuan residential community is located within Qinghe District near the cross of the north fifth ring road and Jingzang highway (Fig. 2). It has a fairly good development of suburban public infrastructure construction and accessibility to subway and bus stations. The Qinghe District is a residential, employment, and commercial complex with an area of 16 km2 and around 140,000 residents, which is close to a suburban employment sub-centre, Shangdi District. As a mixed residential community, Meiheyuan had a population of 4627 in the year 2017, with a diversity of demographical backgrounds (age, gender, job, income, family structure, etc.) and behavioural patterns.

According to the Beijing Environmental Protection Bureau (2018)B, the monthly average concentration of $PM_{2.5}$ in November 2017, December 2017, and January 2018 of Beijing was 46 μg/m^3, 44 μg/m^3, and 34 μg/m^3, respectively; the annual average concentration was 45.7 μg/m^3. Fig. 3 demonstrates the smoothened daily average concentration and standard deviation for $PM_{2.5}$. There are 302 out of 365 days (25 days per month on average) in the period November 2017–October 2018 on which the average daily concentration for $PM_{2.5}$ exceeded 15 μg/m^3, which is the updated WHO 24 h standard (World Health Organization, 2021a). The number of days that $PM_{2.5}$ exceeded the standard was 24 for November 2017, and 26 each for December 2017 and January 2018. From this information, we can reasonably infer that many study participants will have experienced high levels of air pollution on the days they recorded their activities, trips and exposure to air pollution.

3.2. Data and methods

3.2.1. Survey and air pollution exposure data

117 residents of the Meiheyuan community have generated complete data on activity-travel participation, air pollution and life circumstances. Activity-travel information was collected for two continuous

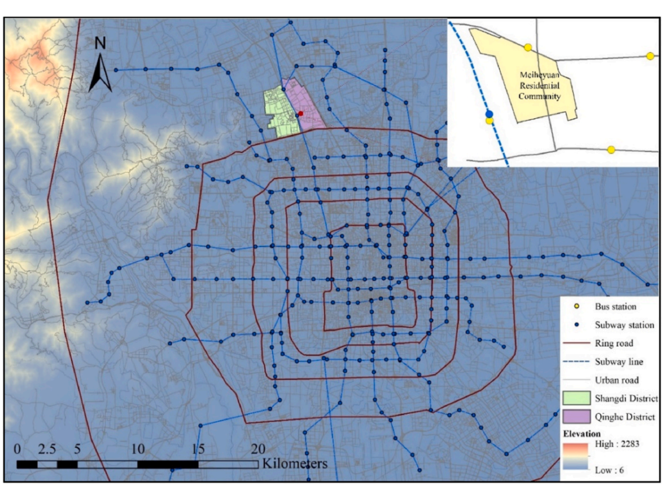

Fig. 2. Study area.

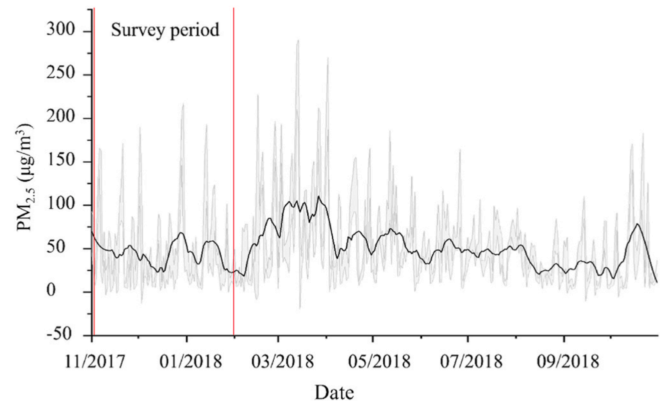

Fig. 3. Smoothened lines with band (24 h standard deviation) for daily $PM_{2.5}$ in Beijing from Nov 2017 to Oct 2018.
Note: the black line represents the daily average $PM_{2.5}$ concentration and the grey lines represent the 24 h standard deviation of $PM_{2.5}$ concentration.
Data source: the Beijing Environmental Protection Bureau.

days, including one weekday and one weekend day i.e., Friday and Saturday or Sunday and Monday. Data was not collected on Tuesdays, Wednesdays, and Thursdays. Participants were also asked to carry a portable air pollution sensor (AirBeam from HabitatMap, placed in the side fishnet pocket of a bag) during their daily activities and trips on the two survey days. $PM_{2.5}$ was selected as the proxy indicator for air pollution, as PM consists of a complex mixture of sulfate, nitrates, ammonia, sodium chloride, black carbon, mineral dust and water and affects more people than any other pollutant, and $PM_{2.5}$ can penetrate the lungs and enter the blood circulation system, contributing to the risk of developing multiple severe diseases (World Health Organization, 2021b). Field testing for the portable air pollution sensors was conducted using the colocation calibration technique. The AirBeam sensors were collocated with the stationary monitoring stations of different urban and geographical environments for two days, and the linear regression of the derived two sets of data showed a strong correlation ($R^2 = 0.86$) (Ma et al., 2020). $PM_{2.5}$ concentration data were recorded at 1-s intervals over a 24-h period throughout the survey. The raw data were averaged to produce per-minute values, excluding instances where data were missing for more than 1 min. Average $PM_{2.5}$ concentrations were then assigned to each activity or trip episode based on their timestamps, ensuring that the exposure reflects the full time span of the activity or trip. Missing data were estimated using linear interpolation.

At the end of each survey day, participants were required to complete a paper-based recalled activity-travel diary, covering information on each episode of travel and activity and their socio-economic status. Together with the information on the episodes of trips and activities, satisfaction information was collected using a 5-point Likert scale for each episode (1: very dissatisfied; 5: very satisfied), and similarly, the perceived air pollution was recorded (1: very light pollution; 5: very severe pollution). In short, this study employs three types of data: real-time ambient air pollution; activity-travel diary data on perceived air pollution, activity and travel episodes information, and subjective wellbeing; and questionnaire data on life circumstances, including sociodemographic characteristics. In order to explore the within-and-between individual effects, we excluded individuals for whom the data are only available for only one day (weekday or weekend day), with a valid number of 112 participants involved in this study.

Compared to all residents of the Meiheyuan residential community and Qinghe District, participants in the study are older, more highly educated, and more often held local *hukou* status. There is also a slight overrepresentation of women: 51.3 % of the participants are women against 53.1 % among all Meiheyuan residents and 51.8 % in the Qinghe District. Participants aged under 30, 30–49 and those above 49 separately account for 18.8 %, 56.4 % and 24.8 %, whilst more than 40 % of the population in the community and district is aged under 30. 64.1 % of participants have a college diploma or above, but the respective shares for the community and district are only 49.4 % and 40.9 %. Those who hold a Beijing hukou make up 81.2 % of the study respondents. However, the shares for the community and district conversely are only 38.1 % and 33.0 %. Additionally, 71.9 % of respondents were married. In terms of household income, the largest group (26.8 %) earned between 6000 and 9999 RMB per month, followed by those earning below 3000 RMB (24.1 %). Higher-income groups (15,000 RMB and above) made up 20.5 %, while 17.0 % and 11.6 % fell into the 3000–5999 RMB and 10,000–14,999 RMB ranges, respectively.

3.2.2. Statistical analysis and modelling

We utilise multi-level structural equation modelling (ML-SEM) to test the APPSATE framework (Fig. 1) using the empirical data introduced above. The advantage of SEM is that it allows for more complex statistical interactions among sets of variables than conventional regression analysis (Bollen, 1989). SEM can separate the effects into direct, indirect and total effects. A direct effect occurs if one variable has an effect on one other variable without the involvement of one or more other variables. With an indirect effect, one variable is associated with another variable via one or more additional variables. The total effect is the sum of the direct and indirect effects from one variable to another. Multi-level structural equation modelling extends the capability to analyse hierarchical data by simultaneously estimating relationships within and between levels, effectively addressing the nested nature of data (Hox et al., 2017). This approach enhances interpretability by decomposing variance into within- and between-level components, enabling the examination of cross-level interactions and complex relationships (Preacher et al., 2010). Individuals' life circumstance variables are treated as between-level variables, while the subjective wellbeing, ambient and perceived air pollution and activity/trip characteristics are treated as within-level variables. We employed the robust maximum likelihood (MLR) estimation method in MPlus 8.3, which accounts for the non-independence of observations and provides robust standard errors. This estimation method ensures that the findings are reliable, robust and accurate (Cudeck et al., 2001). It is hypothesised that the episodes of activities and trips are isolated except for the analysis of AAP_1 (ambient air pollution of the preceding episode), as we only look at the associations at the activity-travel episodes.

Table 1 summarises the variables drawn from the survey and included in the analysis.

We acknowledge that participants' subjective wellbeing at the episode level is influenced by a 3-level hierarchical structure, where the episode-level factors are nested within weekday/weekend factors, and weekday/weekend factors within individual-level factors. However, for estimation purposes, we adopt a 2-level structure, where episode-level factors are nested within individual-level factors, due to the limited sample size. Specifically, at Level 1, the within-individual level, we propose that subjective wellbeing at the episode level is associated with measured ambient exposure to $PM_{2.5}$ (during both the current and the preceding episode), perceived air pollution, characteristics of the activity or travel episodes, and individuals' life circumstances. Additionally, we assume that individuals' perception of air pollution at the episode level is associated with ambient air pollution and characteristics of the activity or travel episodes, with ambient air pollution exposure at the episode level also related to characteristics of the activity or travel episodes. This within-level structure can be represented as the following function:

$$SWB_{ij} = \beta_{0j} + \beta_1 AAP_{ij} + \beta_2 AAP_{i-1,j} + \beta_3 PAP_{ij} + \beta_4 TAC_{ij} + \varepsilon_{ij} \quad (1)$$

$$PAP_{ij} = \gamma_{0j} + \gamma_1 AAP_{ij} + \gamma_2 AAP_{i-1,j} + \gamma_3 TAC_{ij} + v_{ij} \quad (2)$$

$$AAP_{ij} = \varnothing_{0j} + \varnothing_1 AAP_{i-1,j} + \varnothing_2 TAC_{ij} + w_{ij} \quad (3)$$

Table 1
List of variables in the analysis.

Variables	Activity	Travel
	Mean/ Share	Mean/ Share
SWB		
Very dissatisfied	0.3 %	0 %
Dissatisfied	2.3 %	6.4 %
Neutral	19.5 %	32.3 %
Satisfied	43.6 %	42.4 %
Very satisfied	34.4 %	18.9 %
PAP		
Excellent	41.7 %	18.4 %
Good	28.5 %	27.7 %
Lightly polluted	22.7 %	35.8 %
Moderately polluted	6.4 %	16.4 %
Heavily polluted	0.8 %	1.9 %
AAP	47.4 μg/m^3	39.6 μg/m^3
AAP_1 (AAP of the preceding episode)	47.7 μg/m^3	39.9 μg/m^3
Activity-travel episode characteristics		
Duration	129min	23min
Start time	13:42	14:16
Companions (Ref: no companions)	46.8 %	34.3 %
Location (Ref: in-home)	30.4 %	
Distance (log)	–	3623 m
Activity type: Leisure activity (Ref: Maintenance and subsistence activity)	21.2 %	
Trip mode (Ref: Walk, bike and motorbike)		
Public transport use		14.7 %
Vehicle and van use		22.3 %
Life circumstances		
Gender (Ref: female)	Male: 49.1 % Female: 50.9 %	
Age (Ref: 30 and below)	30 and below: 81.7 % Above 30: 18.3 %	
Hukou (Ref: non-local *hukou* ownership)	82.1 %	82.6 %
Edu (Ref: high school or under)	56.1 %	54.3 %
Marital status (Ref: single)	Married: 71.9 % Single: 28.1 %	
Household income (Monthly: RMB)		
Below 3000	24.1 %	
3000 - 5999	17.0 %	
6000 - 9999	26.8 %	
10,000 - 14,999	11.6 %	
15,000 and above	20.5 %	
Household size	3.3	

Where SWB_{ij} denotes subjective wellbeing at episode i for individual j, AAP_{ij} and $AAP_{i-1,j}$ represent the ambient air pollution exposure at episode i and the last episode prior to episode i for individual j, PAP_{ij} is the perceived air pollution at episode i for individual j, TAC_{ij} is the set of activity or travel episode characteristics for individual j. β_{0j}, γ_{0j}, $\varnothing_{0j}$ are individual-specific intercepts for SWB_{ij}, PAP_{ij} and AAP_{ij}, respectively. β_1-β_4, γ_1-γ_3 and $\varnothing_1$-$\varnothing_2$ are fixed slopes of the predictors, and ε_{ij}, v_{ij} and w_{ij} are the random error terms.

At Level 2, the between-individual level, life circumstances variables, including gender, age, marital status and household income, are assumed to be associated with episode-level subjective wellbeing, ambient and perceived air pollution and activity or travel characteristics. The random intercept for SWB_{ij}, PAP_{ij} and AAP_{ij} are modeled as a function of LC_j.

$$\beta_{0j} = \beta_{00} + \beta_{01} LC_j + \varepsilon_{0j} \quad (4)$$

$$\gamma_{0j} = \gamma_{00} + \gamma_{01} LC_j + v_{0j} \quad (5)$$

$$\varnothing_{0j} = \varnothing_{00} + \varnothing_{01} LC_j + w_{0j} \quad (6)$$

Where β_{00}, γ_{00}, $\varnothing_{00}$ are fixed effects representing the average intercept across individuals for SWB_{ij}, PAP_{ij} and AAP_{ij}; β_{01}, γ_{01}, $\varnothing_{01}$ are fixed effects of LC_j on the intercept for SWB_{ij}, PAP_{ij} and AAP_{ij}; ε_{0j}, v_{0j}, w_{0j} are the random effect capturing individual-level variability for SWB_{ij}, PAP_{ij} and AAP_{ij}, respectively.

Based on the theoretical framework, the structure of causal pathways was developed separately for activity and trip episodes (Fig. 4). We adopted a step-by-step method for developing the structure of causal paths. First, the direct effects of AAP and PAP on SWB were specified, followed by direct paths from AAP_1 to PAP and SWB in order to analyse the lagged effect of AAP. Second, a set of interacting characteristics of the activity or travel episodes under consideration was tested, including the involvement of the indoor/outdoor environment in the activity model and trip purposes and companionship in the trip model, to identify the final models with decent goodness of fit. Specifically, in the activity model (Fig. 4a), activity type[1] and start time are expected to have direct effects on both companionship and activity location, companionship to have a direct effect on location, and all these variables have direct effects on AAP, PAP and SWB. In the trip model (Fig. 4b), start time is anticipated to have direct effects on trip mode and trip distance, where trip mode has a direct effect on distance, and all these variables have direct effects on AAP, PAP and SWB. In both models, the life circumstances were treated as exogenous variables relating to AAP, PAP, SWB and the characteristics of the activity or travel episode.

4. Results and discussion

4.1. Descriptive statistics

The dataset used for model estimation included 1688 activity episodes and 573 trip episodes. As Fig. 5 shows, people tend to be exposed to more severe ambient air pollution (AAP) in terms of $PM_{2.5}$ concentrations when conducting activities than taking trips, with 10 per cent points more over 40 μg/m^3. Despite similar levels of $PM_{2.5}$ exposure during the preceding episode (AAP_1) for both activities and trips, people tend to perceive higher levels of air pollution during trips than during activities. This misperception is likely due to the difficulty in detecting $PM_{2.5}$ with human senses, which can lead to an underestimation of its presence, particularly during everyday activities. $PM_{2.5}$, as a key component of ambient air pollution, is one of the most difficult to detect or perceive due to its fine particle size. In comparison, the shares of moderate and heavy pollution are much lower for PAP than for AAP and AAP_1, suggesting that overall people tend to underestimate the severity of air pollution, particularly for trips.

Chi-squared tests were conducted to examine if PAP and the categorized AAP and AAP_1 levels [1,5] are associated with satisfaction with the activity or trip episodes (Table 2). The Cramér's V statistic [0,1] indicates how strongly two ordinal categorical variables are associated with each other, where Cramér's V $<$ 0.25 suggests a weak relationship, 0.25$<$Cramér's V $<$ 0.75 a moderate relationship, and Cramér's V $>$ 0.75 a strong association (Pintz, 2007). In our data, there are moderate associations between PAP and SWB, where the association for trips is stronger than for activity episodes. However, the associations of SWB with AAP and AAP_1 are weak. There is consistency between AAP of the current and preceding episode, as the Cramér's V values are of moderate strength, with that for activity episodes slightly higher than for trips.

4.2. ML-SEM results

Tables 3 and 4 summarise the final versions of the structural equation models for activity episodes and trip episodes, respectively. The results demonstrate that the specified models for both activities and trips fit the data very well, with RMSEA = 0.049, CFI = 0.967, Chi-Square Value/Degrees of Freedom = 4.91, SRMR (within-level) = 0.036 and SRMR (between-level) = 0.036 for the activity model, and RMSEA = 0.021, CFI = 0.988, Chi-Square Value/Degrees of Freedom = 1.24, SRMR (within-level) = 0.058 and SRMR (between-level) = 0.055 for the trip model.

Below, the main results for the ML-SEM analysis separately on activity episodes and trip episodes are summarised. The text first considers the effects of AAP of current and preceding episodes on SWB of the current episode and then discusses the association of ATC with SWB at the within level. Last, the associations of LC with SWB, PAP, APP and ATC at the between level are elaborated.

4.2.1. Activity episodes

AAP on SWB: As shown in Table 3 and Fig. 6, exposure to ambient $PM_{2.5}$ during the activity episode is not directly related to episode-level subjective wellbeing. However, a perception of higher levels of ambient air pollution is accompanied by a lower level of satisfaction with the activity episode. This establishes a statistically significant (at $p < 0.10$) indirect path from ambient exposure to $PM_{2.5}$ to subjective wellbeing via perceived air pollution, meaning that people experience lower subjective wellbeing during an activity episode with higher levels of ambient $PM_{2.5}$ exposure, as they perceive higher levels of air pollution. This finding aligns with AET, which suggests that the perceived experience of environmental conditions (in this case, air pollution) acts as an "affective event," shaping the emotional response (i.e., lower satisfaction) to the activity. The indirect effect of AAP on SWB via PAP demonstrates that people's perceptions of air quality are strongly associated with their emotional state during activity episodes, even when the objective level of ambient PM2.5 exposure does not directly correlate with subjective wellbeing.

ATC on SWB: Among the activity characteristics, location, start time, subsistence activity and leisure activity have statistically significant total effects (at $p < 0.10$) on subjective wellbeing at the activity episode. Out-of-home activities and subsistence activities are associated with lower levels of subjective wellbeing, while later starting time and leisure activities are linked to higher levels of subjective wellbeing.

Participants feel more satisfied with in-home activities not only directly but also indirectly, as their lower perception of air pollution during these activities further enhances their satisfaction. The total effect of leisure activities on subjective wellbeing is also attributed to both direct effect and indirect effects via location and location-PAP. AET suggests that these activities create emotional responses, either positive or negative, based on the perceived environmental conditions (such as air pollution) that accompany them (Holman et al., 2018). In this case, in-home activities not only directly enhance satisfaction but also indirectly link to satisfaction by perceiving lower levels of ambient air pollution. This is consistent with the AET perspective that the emotional experience of the environment shapes one's perception of the activity itself. While individuals generally experience higher subjective wellbeing during leisure activities, this effect is weakened if the activity occurs out-of-home, where they perceive higher levels of air pollution. The total effect of leisure activities on subjective wellbeing is positive as the direct effect outweighs the indirect effects.

The effects of subsistence activities and start time on subjective wellbeing are primarily driven by the indirect paths via location and location-PAP. Participants report lower satisfaction with subsistence activities if these activities take place outside the home, and particularly

[1] The categorisation of activity types into maintenance, subsistence, and leisure types follows established typologies in time-use and travel behaviour research (Pas, 1984; Ettema and Timmermans, 1997). Maintenance activities include essential tasks for personal and household upkeep, such as sleeping, meals, personal care, household chores (e.g., cleaning, cooking, grocery shopping), caregiving responsibilities, and attending to essential errands like doctor visits or banking. Subsistence activities encompass obligatory tasks related to income generation, education, and business, such as working, studying, or conducting business trips. Leisure activities are discretionary and focus on relaxation, entertainment, and social interaction, including shopping, recreational reading or watching movies, physical exercise, walking, sightseeing, online entertainment, and socialising through visits, parties, or online contact.

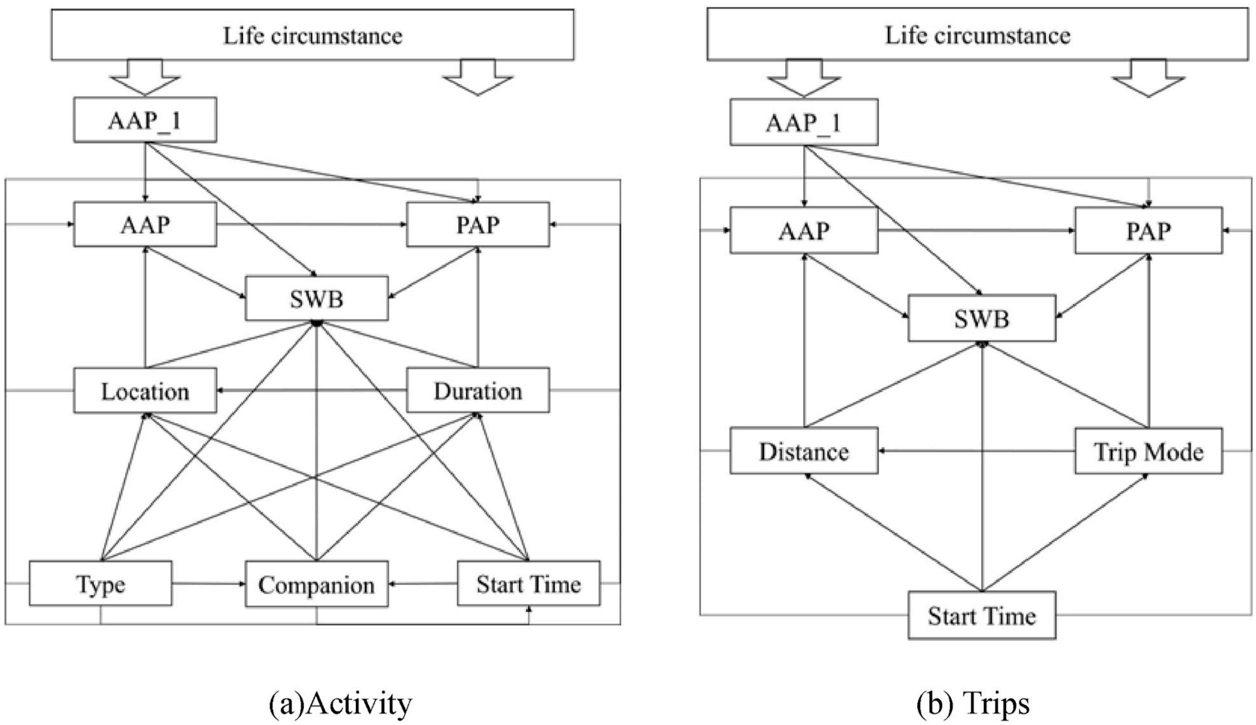

Fig. 4. Path diagrams of structural equation model for activity and trip episodes.

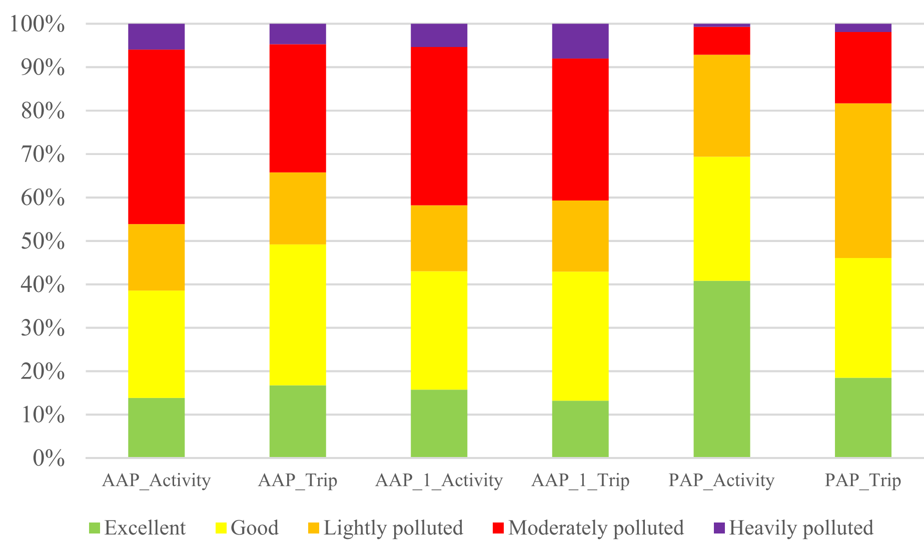

Fig. 5. Levels of AAP, AAP_1 and PAP of activity and trip episodes.
Note: Excellent, good, lightly polluted, moderately polluted, and heavily polluted separately represent AAP ($PM_{2.5}$) at the following levels, based on World Health Organization (2006): below 10 μg/m^3, 10–25 μg/m^3, 25–40 μg/m^3, 40–125 μg/m^3 and above 125 μg/m^3. For PAP participants rated their exposure to air pollution using an ordinal scale from excellent to heavily polluted.

if they perceive higher levels of ambient air pollution during these out-of-home activities. Likewise, a later start time for activities results in higher satisfaction with activities if individuals are at home and perceive lower levels of air pollution during the activities they conduct at home. Worth mentioning, there is also an indirect path of duration on subjective wellbeing via location and location-PAP. The longer duration of in-home activities is associated with higher satisfaction, partly because participants perceive lower levels of air pollution at home. However, the indirect path and direct path cancel out each other, resulting in the total effect being statistically insignificant at $p < 0.10$.

ATC on AAP and PAP: Location and duration have statistically significant (at $p < 0.10$) total effects on ambient $PM_{2.5}$ exposure, with the effect of location being attributed to direct effect and the effect of duration being attributed to both direct and indirect effects. In-home activities are directly associated with higher levels of ambient $PM_{2.5}$ exposure. Duration of activities is directly and negatively associated with ambient $PM_{2.5}$ exposure, though the indirect positive effect of duration on ambient $PM_{2.5}$ exposure via location slightly weakened the direct effect of duration on ambient $PM_{2.5}$ exposure. There are also indirect effects of subsistence activities and leisure activities on ambient $PM_{2.5}$ exposure primarily via location. When conducting subsistence and leisure activities outside the home, participants are less exposed to $PM_{2.5}$ than during in-home activities. While the positive direct effect of leisure activities on ambient air pollution indicates a higher concentration of

Table 2
Bivariate associations among air pollution exposure and SWB variables.

		Activity episodes			Trip episodes		
		PAP	AAP	AAP_1	PAP	AAP	AAP_1
SWB	Chi-square	817.6	30.3	22.2	343.9	17.1	19.1
	p-level	0.000	0.017	0.137	0.000	0.146	0.086
	Cramér's V	0.349	0.067	0.057	0.447	0.100	0.105
PAP	Chi-square		34.2	22.8		46.2	21.8
	p-level		0.005	0.119		0.000	0.100
	Cramér's V		0.071	0.058		0.142	0.097
AAP	Chi-square			1808.9			533.1
	p-level			0.000			0.000
	Cramér's V			0.519			0.482

Table 3
ML-SEM results for activity episodes.

		SWB	PAP	AAP	Location	Duration	Companion	Start Time	Subsistence	Leisure
Level 1: Variables within individuals										
PAP	D	−0.403***								
AAP	D	−0.007	0.070*							
	I	−0.028*								
	T	−0.035	0.070*							
AAP_1	D	0.033	−0.007	0.609***						
	I	−0.022	0.050*							
	T	0.011	0.043	0.609***						
Start Time	D	0.015	−0.023	−0.027	−0.142***	0.229***	0.130***			
	I	0.044***	−0.053***	0.005	−0.006	0.009**				
	T	0.058*	−0.076**	−0.022	−0.148***	0.238***	0.130***			
Duration	D	−0.015	−0.026	−0.034**	−0.094***					
	I	0.030**	−0.028***	0.007**						
	T	0.014	−0.054**	−0.027*	−0.094***					
Location	D	−0.081*	0.273***	−0.074***						
	I	−0.108***	−0.005							
	T	−0.188***	0.268***	−0.074***						
Subsistence	D	−0.056	0.007	0.040	0.449***	0.268***	0.135***	−0.160***		
	I	−0.091***	0.120***	−0.036***	0.015	−0.028***	−0.021***			
	T	−0.146***	0.127***	0.004	0.463***	0.240***	0.114***	−0.160***		
Leisure	D	0.099***	−0.022	0.039**	0.202***	0.048*	−0.063**	0.085***		
	I	−0.026*	0.048***	−0.019***	−0.025***	0.016***	0.011**			
	T	0.073**	0.026	0.020	0.177***	0.063**	−0.051*	0.085***		
Companion	D	0.036	−0.035	0.019	0.129***	0.072***				
	I	−0.010	0.032**	−0.011**	−0.007**					
	T	0.026	−0.003	0.007	0.122***	0.072***				
Level 2: Variables between individuals										
Gender	D	0.040	0.144	0.064			−0.183*		0.154	0.158
Age	D	−0.224**	0.318***						−0.253*	0.340**
Marital Status	D	−0.017	−0.139				0.219**			−0.233
Household Income	D	0.162*	−0.121	−0.308***					0.251**	
Intercepts		6.811	2.214	3.145	1.170	0.311	0.660	3.031	1.330	1.905
Residual Variances		0.902	0.878	0.898	0.710	0.879	0.920	0.967	0.821	0.898

Note: ***, significantly different from zero at p < 0.01; **, significantly different from zero at p < 0.05; *, significantly different from zero at p < 0.10; D, direct effect; I, indirect effect; T, total effect.

ambient $PM_{2.5}$ during leisure activities, the indirect effects with opposite signs offset this direct effect, leading to a total effect that is too small to be significant at $p < 0.10$. Moreover, those who conduct out-of-home activities with a companion tend to be exposed to lower levels of ambient $PM_{2.5}$ exposure.

Location, subsistence activity, start time and duration have statistically significant (at $p < 0.05$) total effects on perceived air pollution, with the effect of location primarily attributed to direct effects, while the effects of the others mainly result from indirect paths. In-home activities, later start times and longer durations are associated with lower levels of perceived air pollution, whereas subsistence activities are related to higher levels of perceived air pollution. Individuals generally perceive cleaner air quality for in-home activities. Individuals tend to associate later start times and longer durations with in-home activities, which are linked to lower perceived levels of air pollution. In contrast, subsistence activities, which people are less likely to conduct in-home, are typically associated with higher levels of perceived air pollution. There are also indirect positive effects of leisure activities and companionship on perceived air pollution, mainly via location. Individuals who engage in leisure activities are significantly more likely to participate in out-of-home activities, which are further linked to higher levels of perceived air pollution. Additionally, those who conduct in-home activities with a companion tend to perceive higher levels of air pollution.

LC on SWB, AAP, PAP and ATC: At the between-individual level, subjective wellbeing is significantly associated with age and income. Individuals over the age of 30 generally report lower satisfaction with their activities, while those with higher incomes report greater satisfaction. Age also plays a key role in perceptions of air pollution, with older individuals perceiving higher levels of pollution, whereas higher-

Table 4
ML-SEM results for trip episodes.

		SWB	PAP	AAP	Distance	Public Transport	Vehicle	Start Time
Level 1: Variables within individuals								
PAP	D	−0.398***						
AAP	D	0.029	0.025					
	I	−0.010						
	T	0.019	0.025					
AAP_1	D	−0.128**	0.079	0.699***				
	I	−0.018	0.018					
	T	−0.146	0.097	0.699***				
Distance	D			−0.092*				
	I	−0.002	−0.002					
	T	−0.002	−0.002	−0.092*				
Public transport use	D	−0.074*			0.544***			
	I	−0.001	−0.001	−0.050*				
	T	−0.075**	−0.001	−0.050*	0.544***			
Vehicle use	D			−0.079**	0.469***			
	I	−0.002	−0.003	−0.043*				
	T	−0.002	−0.003	−0.122***	0.469***			
Start Time	D	−0.032			−0.067*	−0.019	−0.005	
	I	0.002	0.000	0.008	−0.013			
	T	−0.030	0.000	0.008	−0.080	−0.019	−0.005	
Level 2: Variables between individuals								
Gender		0.143*						
Age		−0.248**	0.358***	−0.105				
Marital Status		0.188*	−0.395***			−0.381***		−0.392*
Income					0.541***		0.343***	
Intercepts		6.206	2.871	1.298	−1.036	1.305	0.182	14.372
Residual Variances		0.921	0.858	0.989	0.707	0.855	0.882	0.846

Notes: ***, significantly different from zero at $p < 0.01$; **, significantly different from zero at $p < 0.05$; *, significantly different from zero at $p < 0.10$; D, direct effect; I, indirect effect; T, total effect.

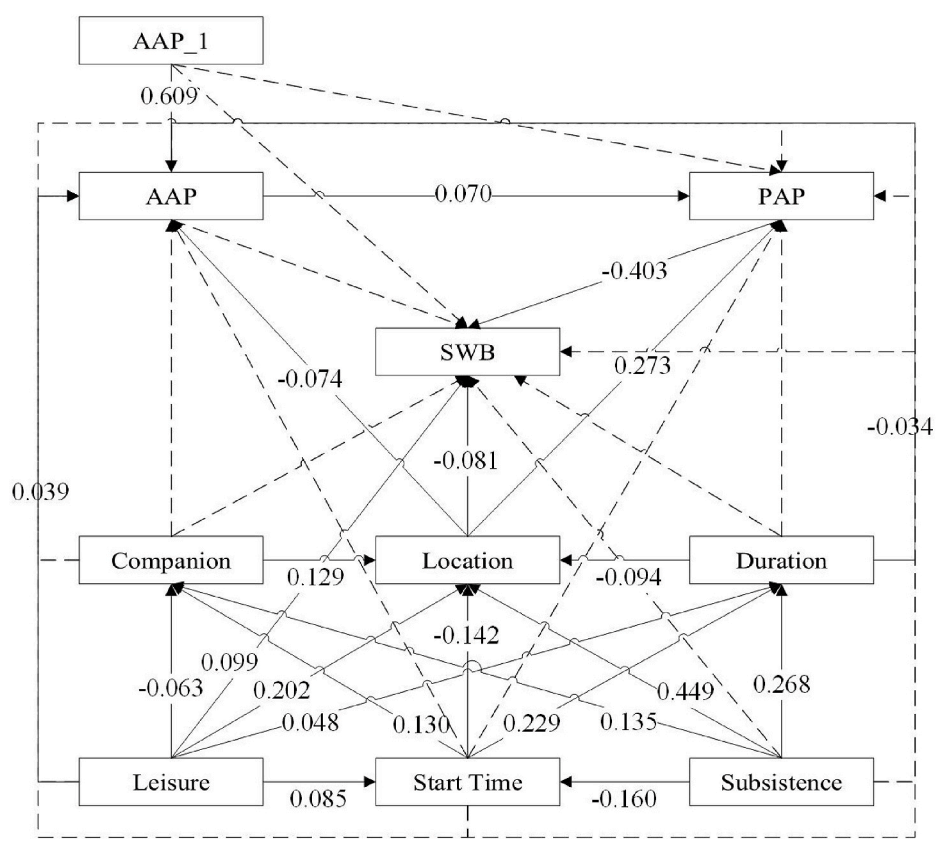

Fig. 6. Path diagram for activity model.
Note: solid line, direct effects with statistical significance; dotted line, direct effects with no statistical significance.

income groups tend to experience lower exposure to ambient $PM_{2.5}$. When it comes to activity characteristics, females and married individuals are more likely to engage in activities accompanied by others. However, neither gender nor marital status has a statistically significant effect on subjective wellbeing, ambient $PM_{2.5}$ exposure or perceived air pollution. From the perspective of Affective Events Theory (AET), these findings highlight how emotional responses to the environment are shaped by both objective conditions, such as ambient air pollution, and subjective perceptions, such as perceived air pollution. Moreover, the results support AET's premise that emotional reactions are influenced by environmental factors and socio-economic circumstances, emphasising the complex interplay of these elements in shaping individual wellbeing (Weiss and Cropanzano, 1996).

4.2.2. Trip episodes

AAP on SWB: Table 4 and Fig. 7 demonstrate that satisfaction with the trip is not directly associated with the ambient $PM_{2.5}$ exposure encountered during the current trip itself (AAP). Rather, it is statistically significantly associated with the ambient air pollution experienced at the preceding episode (AAP_1). This suggests that prior exposure to ambient $PM_{2.5}$, even before the current trip, plays a more crucial role in shaping trip satisfaction. The time-lagged effects of ambient air pollution from a previous activity experience directly contribute to a negative response of how satisfied individuals feel during the current trip. The stronger effect of prior compared to concurrent exposure to $PM_{2.5}$ can be explained using AET. According to this theory, emotional responses to past events in the environment can extend beyond the immediate context, shaping subsequent attitudes and subjective wellbeing, even when the current event does not directly involve the same environmental stressor (Weiss, 2009). In this scenario, ambient $PM_{2.5}$ exposure acts as an "affective event", triggering negative emotions such as discomfort or frustration. These emotions are not confined to the initial exposure but can carry effects into later episodes, affecting individuals' emotional states during subsequent trips.

ATC on SWB: Among all the trip characteristic variables, only public transport use is significantly associated with trip satisfaction, with both direct and total effects at a significant level ($p < 0.10$). Participants are generally less satisfied with trips by public transport. This finding is in line with the majority of previous studies (e.g., Heinen and Bohte, 2014; De Vos et al., 2020).

ATC on AAP and PAP: Distance and transport mode choice are both significantly associated with exposure to ambient $PM_{2.5}$, with total effects observed at a statistically significant level ($p < 0.10$). Longer trips are directly linked to reduced exposure to ambient $PM_{2.5}$, likely because the Meiheyuan residential community is located in a highly polluted area of Beijing, particularly during the winter survey period (Ma et al., 2021). Participants travelling longer distances tend to move away from residential areas with higher pollution levels, thereby reducing their ambient $PM_{2.5}$ exposure (Ma et al., 2020).

Public transport use is indirectly associated with lower ambient $PM_{2.5}$ exposure through its relationship with distance. Compared with walking, cycling, or motorcycling, public transport is more commonly used for longer trips, which take participants further from the polluted residential area, which is further associated with lower levels of ambient $PM_{2.5}$ exposure.

For vehicle and van use, the total effect with significance ($p < 0.01$) on ambient $PM_{2.5}$ exposure is attributed to both a direct effect and an indirect effect via distance. Car drivers and passengers are generally exposed to lower levels of ambient $PM_{2.5}$ exposure compared with open-air modes such as walking, cycling or motorcycling. This direct effect is further strengthened by the indirect path via distance, as they took trips with longer distances that likely make them move away from the highly

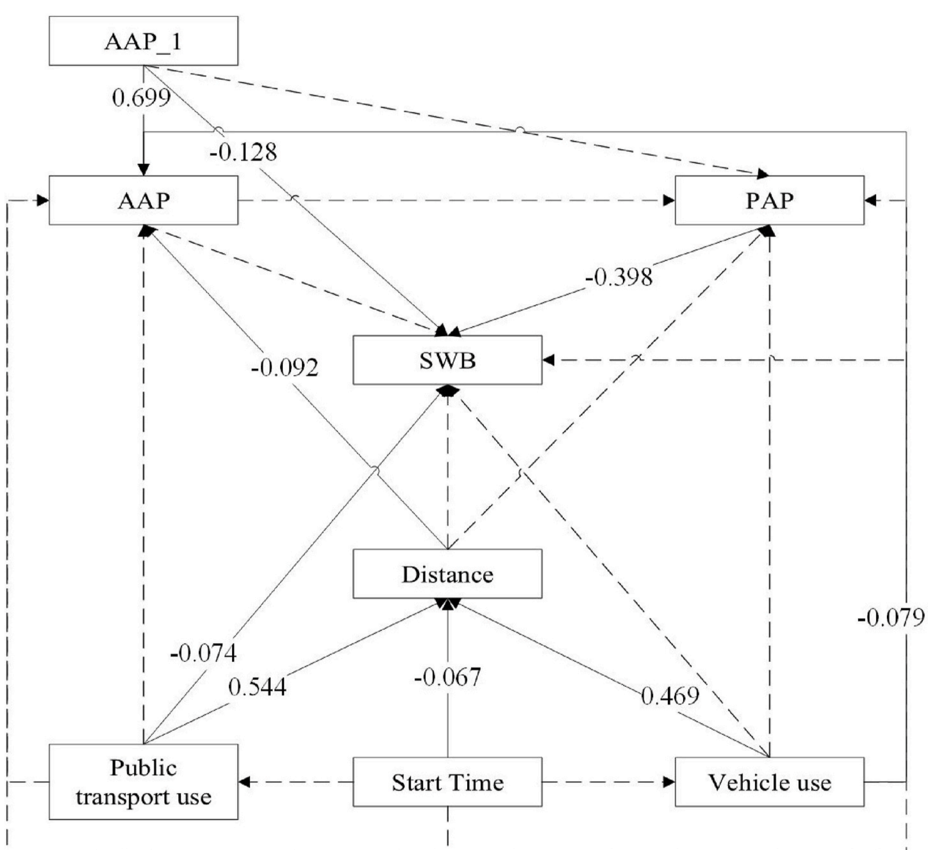

Fig. 7. Path diagram for trip model
Note: solid line, direct effects with statistical significance; dotted line, direct effects with no statistical significance.

polluted residential area.

LC on SWB, AAP, PAP and ATC: Among all the life circumstance variables, gender, age and marital status have a statistically significant effect ($p < 0.10$) on subjective wellbeing. Males are generally more satisfied with their daily trips. Those aged over 30 years report lower satisfaction with trips and tend to perceive higher levels of air pollution. Married individuals exhibit greater satisfaction with their trips, perceive lower ambient air pollution, and tend to use public transport less frequently. Additionally, they are more likely to start their trips earlier. Furthermore, individuals from higher-income groups have greater propensity to use private vehicles and tend to undertake longer trips.

The effects of life circumstances on subjective wellbeing, ambient $PM_{2.5}$ exposure and perceived air pollution are generally more pronounced in the trip model than in the activity model, primarily due to the inherent differences in the nature of trips versus activities. Trips, by nature, are more variable and influenced by a wider range of external factors, such as transportation mode, trip duration and external environmental conditions. These factors are often beyond individual control and are more closely linked to socioeconomic characteristics like age, gender, marital status, and income (Mokhtarian, 2019). In contrast, activities, such as work, sleep and personal care, are generally more routine and stable, with less variation between individuals in terms of environmental exposure. Life circumstances such as age or income may have a less substantial effect on subjective wellbeing derived from these activities since they are less dependent on external factors and more related to personal preferences or lifestyle (Kahneman, 2003; Diener et al., 2009). Activities tend to be less influenced by external environmental conditions, making the effects of life circumstances on subjective wellbeing weaker in this context.

5. Conclusions

This study has examined the associations among various indicators of ambient $PM_{2.5}$ exposure, subjective wellbeing, characteristics of activity-travel episodes, and life circumstances using an advanced dataset of activity-travel diary information, GPS trajectories, and real-time air pollution exposure information from 112 participants in the Meiheyuan residential community in suburban Beijing. A total of 1688 activities and 573 trips recorded between November 2017 to January 2018 were included in the analysis. We employed ML-SEM to investigate the complex relationships among AAP, AAP_1, PAP and SWB separately for activity and travel episodes.

To conclude, our main findings are as follows. First, the perception of air pollution plays a more pronounced role than ambient $PM_{2.5}$ exposure in shaping individuals' subjective wellbeing during both activity and trip episodes, consistent with previous studies (e.g., Liu et al., 2019; Ma et al., 2020, 2021; Rao et al., 2022), with the effect being slightly stronger at trips than during activities. The discrepancy between ambient air pollution ($PM_{2.5}$) and perceived air pollution in association with subjective wellbeing highlights the critical role of individuals' subjective assessments and interpretations of air pollution over the objective measurements. One contributing factor to this disparity is that $PM_{2.5}$ is invisible to the naked eye, making it difficult for individuals to directly detect. Instead, individuals' subjective wellbeing states are more directly associated with their awareness, concerns and beliefs about air pollution. Sensationalised media coverage of severe pollution events ever since 2012, when $PM_{2.5}$ concentration in Beijing reached a highly hazardous level, has heightened public awareness and anxiety about air pollution (Kay et al., 2015). Information, personal experiences and dramatic visuals about air pollution and its adverse health effects are often circulated rapidly on social media, reinforcing perceptions of pollution severity even when objective air pollution levels are low (Chen et al., 2017). This phenomenon emphasises the need to tackle not only the tangible challenges of objective air pollution but also the social and psychological factors influencing public perceptions. Educational campaigns designed to raise awareness about air pollution, its origins and its effects can help align public perceptions with reality (Riley et al., 2021).

Second, for activities, ambient $PM_{2.5}$ exposure at the current episode is associated with people's subjective wellbeing indirectly via their perceptions of air pollution, whereas, for trips, it is the ambient $PM_{2.5}$ exposure of the preceding episode that is directly related to satisfaction. It highlights the mediating role of perceived air pollution in the relationship between ambient $PM_{2.5}$ exposure and subjective wellbeing during activities, rather than trips. This may be due to that activities tend to involve longer exposure periods, increasing the likelihood that individuals could notice and be affected by the air pollution. In contrast, trips may involve shorter exposure durations, reducing the chance that individuals will perceive and react to air quality in the same way. Moreover, trips may also involve a different type of cognitive or emotional engagement, with individuals focusing more on the destination or other aspects of the journey rather than their immediate surroundings (Diener et al., 2017), leading to a diminished effect of ambient $PM_{2.5}$ exposure on their subjective wellbeing.

These two main findings can be supported by the Affective Events Theory (AET), which posits that how individuals appraise or interpret events significantly influences their emotional responses (Weiss and Cropanzano, 1996). While ambient air pollution is linked to subjective wellbeing, subjective perceptions of air pollution may play an even larger role. Cognitive appraisals—the way people perceive and interpret the severity or impact of air pollution—can trigger emotional responses such as stress, anxiety, or frustration, which are directly tied to subjective wellbeing (Ashton-James and Ashkanasy, 2005). Perceived air pollution serves as a psychological filter that shapes individuals' experiences and emotional responses to their environment, encompassing their subjective interpretations and feelings about pollution.

Third, there is a significant time-lagged effect of ambient $PM_{2.5}$ exposure at the current activity episode on subjective wellbeing at the subsequent trip episode. One plausible explanation lies in the transition between indoor and outdoor environments. When individuals step outside after a stationary activity episode, they may become more acutely aware of differences in air quality, particularly if the indoor environment was perceived as stuffy or confining. This contrast—between the relatively stagnant air inside and, on many occasions, the fresher air outside—can trigger cognitive and emotional responses, such as reflecting on prior discomfort or concerns about exposure to pollutants.

According to AET, individuals tend to ruminate on significant events, particularly those that involve a noticeable change in their environment. This rumination can cause negative emotions to persist beyond immediate experience, continuing to shape future emotional experiences and subjective wellbeing over time (Weiss and Cropanzano, 1996; Weiss and Beal, 2005). The physiological responses associated with improved breathing comfort or the psychological awareness of potential health risks may become particularly salient when transitioning from indoors to outdoors. Although $PM_{2.5}$ is not directly perceptible to human senses, other more noticeable air quality cues (e.g., smells, visibility, or other physical sensations) may also amplify awareness of prior exposure. In addition, longer and more stationary exposure during activities allows the physiological or psychological impacts to manifest and persist (Diener et al., 2017; White et al., 2019). People also tend to process and internalise their exposure, either positive or negative environmental stimuli, more effectively during stationary activities than while navigating trips (Weiss and Merlo, 2020; Ellsworth, 2024).

In contrast, the time-lagged effect does not occur for SWB during the current activity episode at a stationary location. This may be because that the environmental conditions during many activity episodes remain relatively stable, as most activities (68.8 %) are preceded by another activity within the same stationary location. This lack of significant environmental change reduces the likelihood of triggering reflective or ruminative processes related to air quality. Moreover, stationary activities typically involve prolonged exposure to relatively stable environmental conditions with fewer distractions. This steadiness in exposure may result in a less pronounced emotional or cognitive response to air quality compared to the dynamic environmental shifts experienced during trips. The absence of a perceptible environmental change further limits the activation of psychological mechanisms, as those described by AET.

Fourth, activity-travel characteristics play a critical role in the association between air pollution and subjective wellbeing for activities, while only public transport is associated with subjective wellbeing for trips. Study participants perceived higher levels of air pollution for out-of-home activities, and this contributes to a higher level of satisfaction with in-home activities, even though ambient air pollution is actually higher for in-home activities. This may be because home provides people with more sense of security, control and comfort (Després, 1991; Blunt and Dowling, 2022), which may make them less sensitive to air pollution. Later start times and longer durations are linked to lower levels of perceived air pollution, while subsistence activities are associated with higher levels of perceived air pollution. These observed effects are largely shaped by the mediator roles related to the location of activities and individuals' perception of the air pollution in those locations. People's subjective experiences of air pollution may differ depending on where they are located and how they interpret the pollution in those spaces, ultimately shaping their overall wellbeing and satisfaction with different types of activities.

Fifth, life circumstances, such as gender, age, marital status and household income play significant roles in shaping activity/trip engagement, perceived air pollution, and subjective wellbeing. Females are generally less satisfied with trips. Gender is not significantly associated with ambient or perceived air pollution at both activity and trip episodes. Age is a key determinant, with individuals over 30 reporting lower satisfaction and higher levels of perceived air pollution for both activity and trip episodes. Higher-income groups experience greater satisfaction and lower ambient pollution for activities. However, household income does not have statistically significant effects on subjective wellbeing, ambient air pollution and perceived air pollution for trips. The findings on the relationship between these factors highlight the complexity of how individuals' life circumstances shape their exposure to and perceptions of air pollution, as well as their subjective wellbeing during activity and trip episodes.

The current study is constrained by the small sample size and its specific geographical and social context. With technical improvements in portable air pollution devices (e.g., greater accuracy) and costs per device coming down, future research can utilise a larger sample size and verify whether the observed relationships can also be identified in different countries and cities. The threshold of time-lagged effects of AAP and PAP on SWB across episodes and varying lengths of time could be further examined by considering earlier episodes and times (t_{-2}, t_{-3}, … t_{-n}) beyond the immediately preceding one. Further research is also needed to better understand how AAP, PAP and SWB accumulate and interact over time, ultimately shaping an individual's current SWB.

In addition, recall bias in self-reported assessments of perceived air pollution and subjective wellbeing is a potential concern, which may lead to inaccuracies due to memory limitations or subjective reinterpretation of experiences (Schwarz, 2007). While our study mitigates this bias through a short recall period (i.e., daily reporting) and an activity-travel diary format that prompts participants to systematically reconstruct their day, participants may still face challenges in accurately recalling their experiences at different times of the day. This could result in over- or under-estimation based on their most salient or recent moments, rather than reflecting an average of the entire episode (Kahneman et al., 1993; Horwitz et al., 2024). The extent to which this recall bias manifests in transport studies remains an open question and warrants further exploration (Abenoza et al., 2019; Guo et al., 2022). Moreover, other aspects of subjectively experienced wellbeing beyond satisfaction warrant attention. These include not only affective dimensions of subjective wellbeing, as negative emotions often occur when air pollution increases (Li et al., 2019), but also aspects of eudaimonic wellbeing such as if and how activities and trips contribute to people's sense of autonomy, self-worth, purpose in life or role in society (Nordbakke and Schwanen, 2014; Anderson and Fowers, 2020). Despite its limitations, the current paper provides detailed insights into how air pollution is associated with subjective wellbeing at the level of daily activity-travel episodes and deepens understanding of how environmental exposure during activities and trips in particular places and at specific times is associated with people's experience of wellbeing.

CRediT authorship contribution statement

Wenbo Guo: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis. **Tim Schwanen:** Writing – review & editing, Supervision. **Christian Brand:** Writing – review & editing, Supervision, Funding acquisition. **Yanwei Chai:** Writing – review & editing, Funding acquisition, Data curation.

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Declarations of interest

None.

Abbreviation

(AP) Air pollution
(AAP) ($PM_{2.5}$) Ambient air pollution
(AAP_1) ($PM_{2.5}$) Ambient air pollution of the preceding episode
(ATC) Activity-travel characteristics
(PAP) Perceived air pollution
(SWB) Subjective wellbeing
(WHO) World Health Organization

Data availability

The authors do not have permission to share data.

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