A R T Y K U Ł Y

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Can Smog Make Us Unhappy? Effects of Perceived and Objective Air Quality on Subjective Well-being[1]

Abstract: The study aims to explore the interrelation of perceived air pollution and objective air pollution in the context of various subjective wellbeing (SWB) measures. An original survey data is used, and matched with exogenous levels of $PM_{2.5}$ pollution in one of Warsaw's city districts, to capture the short-term exposure and immediate SWB assessments. The log-linear analysis and the Two-Stage Conditional Maximum Likelihood estimations have found both the perceived and objective air pollution to have a negative effect on reported life satisfaction. Using the instrumental variable approach, the hypothesis of endogeneity of perceived pollution to SWB is rejected.

Keywords: air pollution, subjective wellbeing, happiness economics, perceived pollution

Czy smog nas unieszczęśliwia? Wpływ postrzeganej i obiektywnej jakości powietrza na subiektywny dobrostan

Streszczenie: Celem badania jest eksploracja związku między postrzeganym a obiektywnym zanieczyszczeniem powietrza w kontekście różnych miar dobrostanu. Dane z ankiety przeprowadzonej w jednej z dzielnic Warszawy zostały zestawione z wynikami pomiarów $PM_{2.5}$ w celu uchwycenia krótkoterminowej ekspozycji na zanieczyszczenie oraz bieżącej oceny dobrostanu. Wyniki analizy log-linearnej oraz modelu dwustopniowej estymacji metodą największej wiarygodności wskazują na negatywny związek zarówno postrzeganego, jak i obiektywnego zanieczyszczenia, z deklarowanym poziomem satysfakcji z życia. Wykorzystując metodę zmiennej instrumentalnej, odrzucono hipotezę o endogenności postrzeganego zanieczyszczenia względem subiektywnego dobrostanu.

Słowa kluczowe: zanieczyszczenie powietrza, subiektywny dobrostan, ekonomia szczęścia, postrzegane zanieczyszczenie

1. Introduction

Ambient air pollution (AP) is a major global health hazard, leading to an estimated 8.8 million deaths annually (Lelieveld et al. 2019). Direct health effects of both the short and long-term exposure encompass respiratory diseases, cardiovascular diseases and impaired cognitive functioning (World Bank 2016; Orru et al. 2018). While health effects are of utmost concern, AP has also less tangible and

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less studied consequences for exposed populations, including reduced subjective wellbeing (Ambrey et al. 2014).

AP is a localised phenomenon, particularly acute in urban areas, with over 80% of the world urban population being affected by AP levels exceeding the WHO limits (WHO 2018). Polish cities stand out as the most polluted in Europe (WHO 2018), an effect accentuated by approximately 44,500 premature deaths per year attributed solely to fine particulate matter ($PM_{2.5}$) (EEA 2018). The awareness of the drivers and consequences of AP is growing both locally and globally, but the problem remains unresolved (UNGC 2018). Understanding the broader implications of AP for human wellbeing is thus a vital research task.

This task overlaps with the overarching global challenge of shaping a sustainable mode of socio-environmental relations (O'Neill et al. 2018). The sustainable path requires learning to "value what matters" to stop the destruction of the life-supporting systems. The vibrant field of subjective wellbeing (SWB) studies allows to reframe the inevitable limits to resource consumption as a move from quantitative expansion to qualitative improvement (MacKerron and Mourato 2009; Stiglitz et al. 2018). By demonstrating the benefits derived by humans from higher levels of environmental quality in their surroundings, SWB provides a solid foundation for inclusion of environmental sphere in the development considerations.

The remaining part of the article is structured as follows: Section 2 reviews the literature on SWB and its relation to AP and formulates research questions, Section 3 introduces the study area and data sources, Section 4 describes methods used to answer the research questions, the results are presented in Section 5, and Section 6 concludes.

2. Literature review

SWB is defined as individuals' overall evaluations of their lives and emotional experiences, but it is also an umbrella term that encompasses such concepts as life satisfaction or happiness, applied in numerous socio-economic investigations (Diener et al. 2016)[2]. It builds on a notion of experienced utility, addressing the limitations of the rational choice model, e.g. cognitive bias and asymmetry of information (Kahneman and Krueger 2006). A growing body of research supports the heuristic value of SWB measures, demonstrating its reliability (Frey et al. 2010), and usefulness for policymaking (Odermatt and Stutzer 2017). The SWB research looks beyond traditional economic determinants of wellbeing, highlighting the role of more qualitative personal and social features, e.g. health, civil status, trust, social cohesion, housing quality, unemployment (see Graham 2005 for a review). Increasingly, the SWB research pays attention to the spatial aspect, demonstrating the significance of environmental conditions for human

[2] Throughout the article, we use the term SWB to refer to the broad concept of subjective wellbeing, while happiness (or Happy) and life satisfaction (or LS) refer to particular approaches to measuring SWB.

wellbeing, accounting for climate change (Sekulova and van den Bergh 2013), noise pollution (Van Praag and Baarsma 2005), access to greenspaces (Yuan et al. 2018), and AP (see Li et al. 2018 for a review).

The AP-SWB relationship has recently emerged as the key research focus of the environmentally-oriented SWB studies, and several general trends can be now discerned. Firstly, studies using the national- and regional-level data (Brereton et al. 2008; Welsch and Kühling 2009; Luechinger 2010) are being replaced by more spatially disaggregated analyses that account for a heterogenous and localised distribution of AP (MacKerron and Mourato 2009; Orru et al. 2016; Zhang et al. 2017; Du et al. 2018; Laffan 2018). This entails matching AP exposure at the individual level, relying either on modelled grid estimates of mean AP levels (MacKerron and Mourato 2009; Orru et al. 2016), or on linking respondents' location to the nearest monitor station (Levinson 2012; Zhang et al. 2017; Barrington-Leigh and Behzadnejad 2017). Secondly, the dominant approach of using the long-term exposure has been shown to induce endogeneity (Barrington-Leigh and Behzadnejad 2017) and habituation bias (Levinson 2012). Thus, a new approach has emerged, providing tentative evidence for the immediate negative effect of short-term variations in AP on individual-level SWB (Zhang et al. 2017; Du et al. 2018). The main geographical focus of AP-SWB studies has switched from the Western Europe and North America towards China. Central and Eastern Europe remains significantly understudied despite its excessive levels of pollution; the only sub-national study in this region has been conducted in Estonia, where AP is rather low (Orru et al. 2016).

Despite the relatively well-established negative impact of AP on SWB, there are still some significant gaps. Firstly, the AP-SWB relationship depends on the type of SWB measure employed, with a majority of studies referring to life satisfaction only (Dolan and Laffan 2016). This relationship may, however significantly vary with regard to particular SWB approaches (Laffan 2018). For instance, Gu et al. (2015) found that short-term AP exposure leads to an actual increase in eudaimonic SWB. They draw on the Meaning Maintenance Model to hypothesise that if exposure to toxic haze is a violation of one's worldview-based expectation (e.g. living in a healthy environment), then it might induce individuals to reaffirm the meaning of their life, in order to compensate for the potential loss. Secondly, the mechanism underlying the AP-SWB relationship is unclear (Laffan 2018). Drawing on MacKerron and Mourato (2009) and Orru et al. (2018), 2 possible pathways can be distinguished: (1) through health, even without being conscious about the cause-and-effect relationship between health and environmental quality, or (2) through awareness of pollution and its consequences, which may reduce individuals' SWB directly and independently of the health effects. It is therefore crucial to disentangle the perceived AP-objective AP relationship and its impact on SWB. Only a handful of studies approached this topic directly, and the results are mixed. MacKerron and Mourato (2009) found that individuals' perceptions of AP are positively correlated with objective AP; to avoid collinearity, they constructed separate models confirming that both these variables are significant predictors of wellbeing, but simultaneously failed to account for their interrelation. Liao et al. (2015) applied the instrumental variable approach and found that objective AP has only an indirect effect on SWB, mediated by perceived AP. Employing a similar methodology, Goetzke and Rave (2015) showed that perceived AP is endogenous to SWB, i.e. that unhappy people are more likely to report high pollution. Using path analysis, Orru et al. (2018) found the perceived exposure to be independent from the measured AP level.

The purpose of this article is to contribute to these scant and ambiguous research findings by further exploring the interrelation of perceived AP and objective AP in the context of various SWB measures. To the best of the author's knowledge, this is also the first attempt to investigate this topic using short-term AP data, reflecting the growing interest in studying the AP-SWB pathways related to acute health effects and immediate psychological consequences. Thus, the research questions are the following:

– What is the influence of perceived AP and short-term variations in objective AP on various SWB measures?
– Does the perceived AP mediate the effect of objective AP on SWB?
– Is perceived AP endogenous to the SWB function?

To answer these questions, an original CATI survey was conducted in Warsaw, Poland, and a set of advanced statistical methods has been applied on the collected data.

3. Data

3.1. Study area

The study area is limited to Targówek, one of the city districts of Warsaw, with a population of 124,000 and an area of 24 km^2. The district is socially and spatially diverse, encompassing old tenements, big housing estates constructed in the communist era, newly built apartments, as well as suburban residential areas dominated by detached and semi-detached houses; 30% of the area is covered by parks and urban forests.

3.2. Survey data

The CATI survey follows a repeated cross-sectional study design, matched with an exogenously changing independent variable – objective AP. The purpose is to assess the relationship between perceived AP and SWB at varying pollution levels, and using such design allows to account for the unobservable and time-invariant spatial characteristics correlated with pollution (Barrington-Leigh et al. 2017; Alkon and Wang 2018). In total, 3 rounds were completed over 9 days in April 2019, in fixed 6-hours periods characterised by significantly varied AP levels (see: Table 1). During each round, exactly the same questionnaire was applied at the (new) representative sample of 125 respondents, giving a total sample size of 375 respondents. The SWB items were asked at the beginning, followed by other personal variables and items related to air pollution, in order to avoid the confounding effects of other questions on reported SWB. For the same reason, the initial explanation of the study purpose did not refer to environmental quality. Five SWB items, representing 3 distinct theoretical approaches, were included[3]:

– Eudaimonic SWB: *Meaning*, *Purpose*, measured with a 5-point Daily Meaning Scale (Steger et al. 2008)
– Experiential SWB: *Happy_5*, *Anxious*, measured with two 5-point items, adapted from the UK Office for National Statistics (Oguz et al. 2013)
– Evaluative SWB: *LS*, measured with the well-established Life Satisfaction item on a 0-10 scale (see e.g. ESS 2016)

The perceived AP (*AQ_today*) is derived from the question "How would you rate the level of AP in your neighbourhood today?", assessed on a 5-point Likert scale. A set of personal characteristics was included in the survey to provide explanatory variables for the SWB function, drawing on the results of earlier localised AP-SWB studies (MacKerron and Mourato 2009; Levinson 2012, Orru et al. 2016; Zhang et al. 2017; Du et al. 2018). All survey variables included in the further analysis are presented in Table 2.

Table 1. Repeated cross-sectional CATI and exogenous $PM_{2.5}$ levels

	PM2.5 24h concentration			
Round	[μg/m³]	[% of the 3-month average]	[% of WHO 24h guidelines]	*PM_ord*
08-April	55.5	263%	222%	3 (high)
10-April	13.7	65%	55%	1 (low)
16-April	22.5	107%	90%	2 (medium)

Source: own calculations based on data from the Polish Inspectorate of Environmental Protection

3.3. Objective AP data

AP data is retrieved from the urban background monitoring station located in Targówek, a part of the public monitoring network managed by the Polish Inspectorate of Environmental Protection. All the respondents are located within a 5 km radius from the station, which guarantees a relatively good fit between the measured 5 km AP and the actual exposure (conventionally, a 40 km radius is used, see: Zhang et al. 2017). From a set of pollutants measured at the station, the $PM_{2.5}$ was selected for 2 reasons: (1) it is the major health burden in Warsaw, responsible for over 80% of all mortality cases related to AP; (2) over 90% of the population weighted exposure to $PM_{2.5}$ is derived from the relatively uniformly distributed sources, i.e. residential combustion and external inflow (Holnicki et al. 2017). The latter feature is used to justify the assumption of identical exposure of all respondents of a given survey round. The objective AP was calculated as a mean concentration of $PM_{2.5}$ recorded in Targówek over 24 hours prior to the completion of a given survey round, and transformed to a 3-point ordinal variable

[3] For a theory behind these three approaches to SWB, see e.g. OECD 2013, Stiglitz et al. 2018.

PM_ord (Table 1). Thus, the focus of the study is on the immediate effects of AP levels, and not the long-term exposure.

Table 2. Statistical summary of the variables

Variables	Scale / proportion	Mean (SD)
SWB		
Meaning: How meaningful do you feel your life is today?	1-5 (5= very meaningful)	4.28 (0.9)
Purpose: How much do you feel your life has purpose today?	1-5 (5=very purposeful)	4.33 (0.9)
Happy_5: Overall, how happy do you feel today?	1-5 (5= very happy)	4.06 (0.9)
– *Happy:* [item recoded with a truncated scale]*	1-3 (3=very happy)	2.30 (0.5)
Anxious: Overall, how anxious do you feel today?	1-5 (5=very anxious)	2.09 (1.2)
LS: All things considered, how satisfied are you with your life as a whole?	0-10 (10= very satisfied)	7.45 (1.8)
– *LS_tr*: [item recoded with a truncated scale]*	1-3 (3= very satisfied)	2.03 (0.7)
Predictors		
AQ_today: How would you rate the level of air pollution in your neighbourhood today?	1-5 (5= very polluted)	2.71 (1.0)
– *AQ_tod:* [item recoded with a truncated scale]*	1-3 (3=high)	1.81 (0.7)
PM_ord: [$PM_{2.5}$ values recoded into ordinal variable]	1-3 (3= high)	2.00 (0.8)
Controls		
Age	1-4	
– 20–34	21.3%	
– 35-49	30.7%	
– 50-64	20.8%	
– >65	27.2%	
AQ_problem: How would you rate the overall air quality in your neighbourhood?	1-3 (3= it's a problem)	2.19 (0.8)
Child: Household with children below 18 years old	1= yes, 0= otherwise	0.332
Female	1= yes, 0= otherwise	0.535
Health: How is your health in general?	1-4 (4= very good)	2.70 (0.8)
High_ed: Completed higher education	1= yes, 0= otherwise	0.406
Income: How do you feel about your household's income nowadays?	1-5 (5= living comfortably on present income)	3.44 (1.2)
Married: Married or in an informal relationship	1= yes, 0= otherwise	0.706
Outdoor: How much time did you spend outdoors over the last 24 hours?	0-24	4.45 (3.2)

* See Table 4 for details.

Source: own calculations based on the CATI survey.

4. Methods

A 3-stage methodological approach is applied, based on quantitative techniques. First, the exploratory correlational analysis is performed to identify the relations between various SWB measures and their hypothesised predictors. Secondly, a log-linear analysis is applied to explore the interrelations between perceived AP, objective AP, and selected SWB measures. Finally, a 2-stage estimation is conducted, to take account of the potentially confounding effect of control variables and to test for exogeneity of the perceived AP. All statistical procedures were performed with the R software, using the following packages: *MASS*, *Performance Analytics, ordinal*, *olsrr*.

The log-linear analysis is a statistical technique used to examine relationships between >2 ordinal variables (Liu and Agresti 2005). No distinction is made between response and explanatory components, allowing for a comprehensive exploration of the interrelations among potentially endogenous variables. Log-linear models describe how the expected cell counts in a contingency table vary in response to variables included. To solve the estimation, a least complex model is sought that would account for the largest part of variance in observed frequencies of *Happy/LS_tr*, *AQ_tod* and *PM_ord*. The log-linear analysis examines if there is an interaction effect between variables, e.g. if the interaction between perceived and objective AP leads to a significant variation of the investigated relationship. With 3 variables, there are 9 possible log-linear models to fit the data, starting from a simple 3-factor additive model and moving towards the saturated model (Rodriguez 2007). However, only 4 of them are considered here, given their relevance for this study (Equations 1-4):

(1) Complete independence $\log(\mu_{ijk}) = \lambda + \lambda_i^W + \lambda_j^P + \lambda_k^O$

(2) Joint independence $\log(\mu_{ijk}) = \lambda + \lambda_i^W + \lambda_j^P + \lambda_k^O + \lambda_{jk}^{PO}$

(3) Conditional independence $\log(\mu_{ijk}) = \lambda + \lambda_i^W + \lambda_j^P + \lambda_k^O + \lambda_{ij}^{WP} + \lambda_{jk}^{PO}$

(4) Homogenous association $\log(\mu_{ijk}) = \lambda + \lambda_i^W + \lambda_j^P + \lambda_k^O + \lambda_{ij}^{WP} + \lambda_{jk}^{PO} + \lambda_{ik}^{WO}$

where:
W = SWB (Happy /LS_tr), P = perceived AP (AQ_tod), O = objective AP (PM_ord)
μ_{ijk} denotes the mean probability that an observation falls in the cell (i, j, k) of the contingency table

To satisfy the assumption of a normal distribution of observed frequencies required for the log-linear analysis, a set of data transformations is performed. The variables included in the estimation are recoded with abridged 3-point scales (see Table 4) to merge the cells of the contingency table with a limited number of observations.

Finally, a 2-stage estimation is employed to comprehensively investigate the relationship of perceived and objective AP as predictors of SWB. To this end, the 2SCML (Two-Stage Conditional Maximum Likelihood) estimation method is applied, developed by Rivers and Vuong (1988). In the first stage it runs an Ordinary Least Squares (OLS) regression for the endogenous component, using instrumental variables as predictors. The residuals are then used along the potentially endogenous variable in the second-stage ordered model. The 2SCML approach allows to obtain consistent and efficient estimates of the coefficients as well as to conduct a simple and robust exogeneity test for selected variables. It was proved to outperform alternative approaches such as instrumental variable probit and 2-stage least squares (Alvarez and Glasgow 1999); it is preferred for small data samples (Arendt 2004), and was successfully applied to investigate the endogeneity of perceived AP in the life satisfaction function by Goetzke and Rave (2015). Two steps of the 2SCLM are specified as follows:

(5) Step 1: $y_{1i} = X_1\alpha_1 + Z_1\beta_1 + v_1$

(6) Step 2: $y^*_{2i} = X_2\beta_2 + y_{1i}\gamma + u_1$

$$\text{with:}\quad y^*_{2i} = \begin{cases} 0 \; if \; y_{2i} \le 0 \\ 1 \; if \; 0 < y_{2i} \le \mu_1 \\ 2 \; if \; \mu_1 < y_{2i} \le \mu_2 \\ 3 \; if \; \mu_2 < y_{2i} \end{cases}$$

where y_{1i} is the hypothesised endogenous effect, i.e. the *AQ_today* for respondent i, y^*_{2i} is the ordered *LS_tr*/*Happy* score for an i-th respondent; y_{2i} is the i-th respondent's level of latent SWB function; μ_j depicts SWB threshold values for $1 \le j \le 3$; Z_i represents a vector for objective AP; X_i represents a vector of other explanatory variables; α, β, γ are regression coefficients, while v_1 and u_1 are unobserved error terms.

Following Wooldridge (2002) and Goetzke and Rave (2015), several assumptions are made. First, it is assumed that error terms v_1 and u_1 are identically distributed, with a mean of zero. Second, further normalisation is performed to allow identification of the parameters in equation (6), assuming var(v) ≡ 1 and setting $u_1 \equiv v_1\lambda + \eta_1$ where $\lambda = \text{cov}(v, u)\ \text{var}(u)$. The equation (6) might be rewritten as:

(7) $y^*_{2i} = X_2\beta_2 + y_{1i}\gamma + v_i\lambda + \eta_1$

The starting point for the 2SCML estimation method is the estimation of the unobserved u_1 by running the OLS regression (Equation 5) of the hypothesised endogenous variable y_{1i}, using the observed variables X_1 and Z_i. The OLS residuals are then inserted as a predictor variable in the logit model of y^*_{2i}, along observed variables X_2 and hypothesised endogenous variable y_{1i}. The obtained estimators of the scaled coefficients are sufficient to verify the significance and the sign of the original coefficients. The 2SCML has a built-in test for exogeneity – if the estimate for residuals is non-significant as a predictor in the final model, the hypothesis of endogeneity can be rejected.

Table 3. Instrumental variables for 2SCML – correlation matrix

	AQ_today	*LS_tr*	*Happy*	*PM_ord*
LS_tr	-0.18***			
Happy	-0.15***	0.49***		
PM_ord	0.02	-0.06	0.08	
AQ_problem	0.24***	-0.10*	-0.07	-0.02

Note: * p<0.1; ** p<0.05; *** p<0.01.

Source: own calculation.

Two instrumental variables are used in order to facilitate the 2SCML-based test of *AQ_today* endogeneity. First, an indicator of pollution awareness is selected, capturing the respondents' opinion on the general intensity of the AP problem in their neighbourhood (*AQ_Problem*). Then, the objective AP measure *PM_ord* is selected. Its correlation coefficient with *AQ_today* is insignificant, but the log-linear analysis provides evidence to assume that these 2 variables are related (see: Section 5.3). Importantly, the 2 instruments are not correlated with each other, suggesting their complementarity, and their correlation with the SWB is negligible. It is significant at the 10% level only in one instance (*AQ_Problem : LS_tr*), and in the case of *Happy* none of the instruments is significantly correlated.

5. Results

5.1. Survey results

The Social Diagnosis 2015 results are used as a point of reference for the SWB measures collected in the survey. The average result for Warsaw of the short-term evaluative SWB indicator employed in the Social Diagnosis equals 2.93 on a 1-4 scale. After the recalculation of the scale, to match life satisfaction indicator used in the CATI survey, it equals 8.08, providing a fair comparability with the recorded *LS* mean value of 7.45. There is no direct comparison for perceived AP levels for Warsaw. MacKerron and Mourato (2009) found that 59% of Londoners consider the AP levels in their neighbourhood a problem – a similar concern is expressed by 72.5% of CATI respondents (*AQ_problem*), reflecting a relative severity of AP in Warsaw. Other studies on perceived AP use country-wide samples, and therefore the level of concern expressed by CATI respondents in Targówek is similar to the one recorded in highly urbanised Taiwan (Liao et al. 2015), and much higher than the levels found for Germany (Goetzke and Rave 2015). Regarding the objective AP levels recorded during the survey, their variability is significantly higher than in other studies on the perceived-objective AP – a combined effect of Warsaw's acute AP and using short-term rather than long-term exposure.

5.2. Correlational analysis

The results of the exploratory Spearman correlation analysis between objective AP, perceived AP and a full set of SWB measures are presented in Figure 1. The obtained coefficients suggest that *PM_ord* is not related to any of the variables included in the matrix, while *AQ_today* is significantly and negatively correlated with *LS* and *Happy_5,* and positively correlated with *Anxious* at a 10% significance level. The immediate eudaimonic SWB measures are not significantly correlated with short-term perceived AP – contrary to what Gu et al. (2015) have found for a more general 10-item scale, where the respondents assessed their concern with AP. Given the reported results, 2 variables, *Happy* and *LS*, are selected to explore the AP-SWB relationship in more depth.

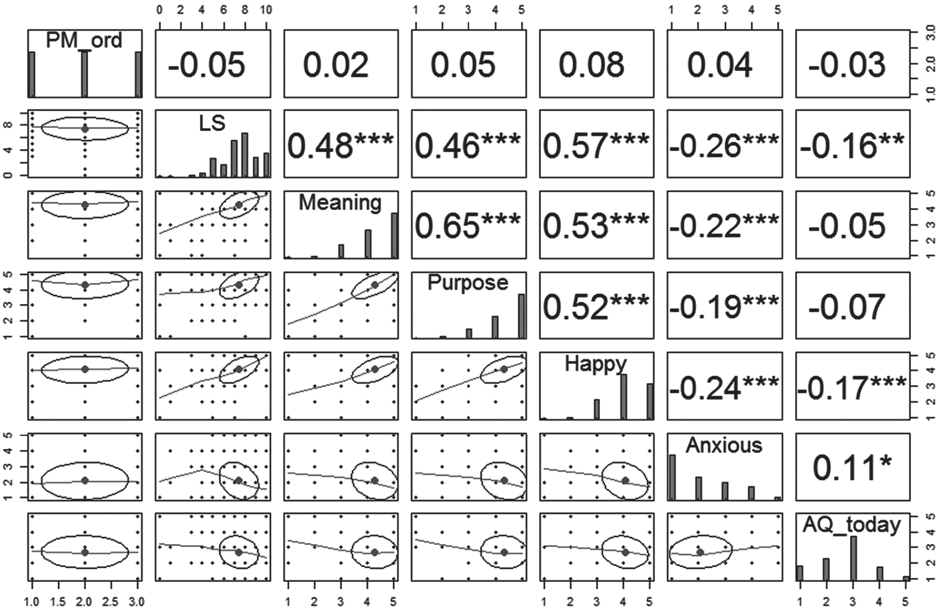

Figure 1. The AP-SWB correlation matrix

Note: *p<0.1; **p<0.05; ***p<0.0.

Source: own calculation.

5.3. Log-linear analysis

SWB measures are typically skewed toward the right (see the histograms above), which compromises the assumption of a normal distribution of the observed frequencies, necessary for the log-linear analysis. To make the log-linear estimation feasible, the existing variables were transformed using an abridged 3-point Likert scale (see Table 4). The correlation results reported in Figure 1 above are robust for these transformations.

Table 4. Data transformations – truncated scale

Variable transformed	Full scale	Truncated scale
LS → LS_tr	0-10, where 10 is fully satisfied	based on SD deviation from mean, 1→1÷6, 2→7÷8, 3→9÷10
Happy_5 → Happy	1-5, where 5 is very happy	1→1÷2, 2→3÷4, 3→5
AQ_today → AQ_tod	1-5, where 5 is very polluted	1→1÷2, 2→3, 3→4÷5

Source: own elaboration.

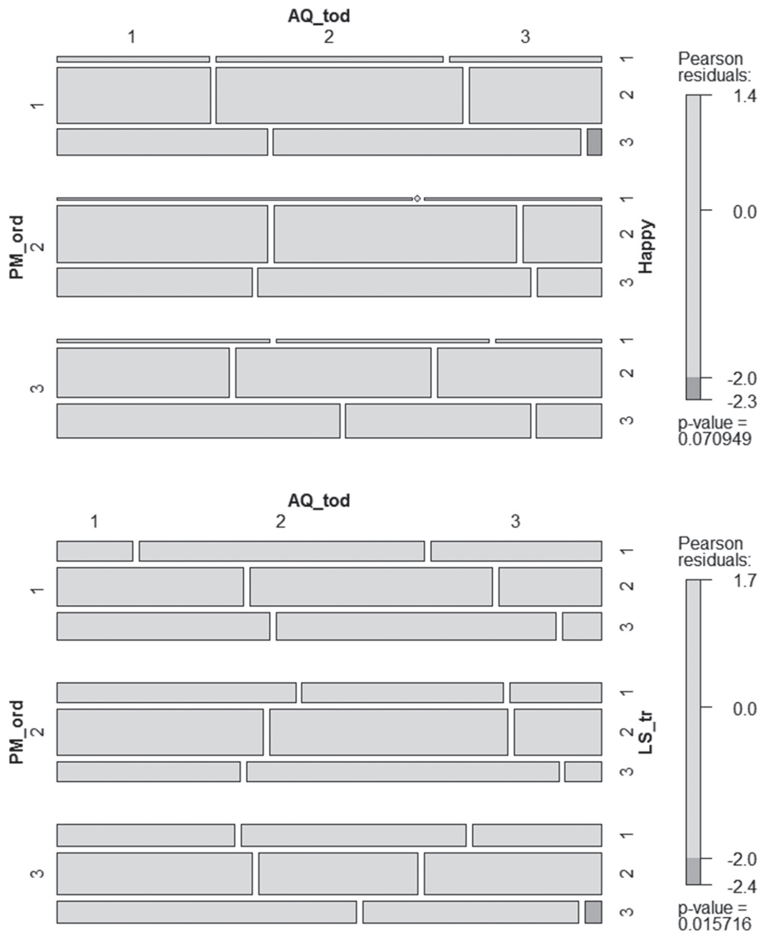

Figure 2. Mosaic plot for the SWB-perceived AP-objective AP

Source: own calculation.

Abridged data is used to construct the contingency tables for *Happy/LS_tr*, *AQ_tod*, and *PM_ord* – represented by mosaic plots in Figure 2. A mosaic plot is an area-proportional visualisation of a table of expected frequencies, where the size of each tile is proportional to the corresponding cell entry. Two statistically significant deviations from the expected proportions are found, pointing to an interesting difference between *LS_tr* and *Happy*. During the low AP episode, among the respondents who declared a high level of happiness (=3), a relatively small share perceived the current air quality as polluted (=3). For *LS_tr*, a similar pattern occurred during the high AP episode. It thus suggests that – if endogeneity of perceived AP exists – high life satisfaction is associated with increased likelihood of making an overly optimistic judgements about the current AP levels, while happiness is correlated with downplaying the issue of pollution when its harmfulness is limited.

Next, the Equations (1)-(4) elaborated in Section 4.1 are estimated. The (1) complete independence assumes no pairwise relations between any of the included variables. The P-value of the likelihood ratio is significant at 5% for both LS and Happy, which means that this hypothesis can be rejected. The (2) joint independence assumes that perceived AP and objective AP values are associated, but are not related to the SWB measure. The resulting likelihood ratios are below the 5% threshold, which means that this hypothesis is also rejected. The (3) conditional independence model has a significantly higher goodness of fit, with p-values of the likelihood ratio equalling 0.261 for *Happy* and 0.344 for *LS_tr*. It assumes 2 pairwise relations, between SWB and perceived AP, and between perceived AP and objective AP. At the same time, objective AP has no direct effect on SWB. A more complex (4) homogeneous association model yields similar likelihood ratios as the conditional independence estimation (0.268: *Happy*, 0.293: *LS_tr*). However, the likelihood ratio statistic proves that the more complex model does not offer any significant improvement over the conditional independence assumption.

Contrary to the correlational analysis, the results of the log-linear estimation suggest that the objective and perceived AP are significantly related, but only the latter is associated with SWB – these outcomes are consistent with those reported by Liao et al. (2015), based on an instrumental variable study.

5.4. Two-Stage Conditional Maximum Likelihood (2SCLM) estimation

Finally, a 2SCLM model is applied to obtain robust estimates of SWB predictors, and their hypothesised endogeneity. In total, 7 estimations are performed, and their results are presented in Table 5. The first 4 models (1)-(4) are basic ordered logit estimations explaining *LS_tr* / *Happy* levels, and assuming no endogeneity. Models (1)-(2) account for the perceived AP, assuming it is an exogenous variable, while (3) and (4) replace it with the instruments described in Section 4.2. The OLS model (5) was estimated as a first step in the 2SCML procedure, to obtain the residuals that are later imputed in the estimations (6)-(7) to test the exogeneity of perceived AP.

Models (1)-(2) indicate that SWB is driven upwards by higher self-reported health status, by being married (only *LS_tr*), earning higher income and spending more time outdoors (only *Happy*) – comprising a fairly intuitive set of findings, in line with the previous SWB research. Perceived AP is negatively related

Table 5. Estimation results

	Dependent variable:						
	LS_tr	*Happy*	*LS_tr*	*Happy*	*AQ_today*	*LS_tr*	*Happy*
Method:	ordered logit	ordered logit	ordered logit	ordered logit	OLS	ordered logit	ordered logit
Model:	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Female	0.073 (0.212)	0.175 (0.233)	0.072 (0.212)	0.159 (0.234)	0.015 (0.108)	0.084 (0.212)	0.177 (0.234)
Health	0.723*** (0.162)	0.627*** (0.174)	0.780*** (0.162)	0.647*** (0.175)	-0.180** (0.078)	0.661*** (0.182)	0.616*** (0.198)
Children	0.118 (0.265)	0.227 (0.294)	0.165 (0.267)	0.257 (0.296)	-0.194 (0.137)	0.082 (0.270)	0.221 (0.298)
Married	0.463* (0.243)	0.172 (0.266)	0.402* (0.243)	0.175 (0.268)	0.142 (0.124)	0.504** (0.249)	0.178 (0.272)
Income	0.267*** (0.095)	0.354*** (0.106)	0.260*** (0.096)	0.357*** (0.106)	-0.030 (0.047)	0.252*** (0.097)	0.351*** (0.108)
High_ed	0.305 (0.211)	-0.125 (0.234)	0.333 (0.211)	-0.089 (0.234)	-0.124 (0.109)	0.275 (0.215)	-0.130 (0.238)
Age	0.009 (0.120)	0.008 (0.132)	0.0005 (0.122)	-0.008 (0.133)	0.037 (0.061)	0.012 (0.120)	0.009 (0.132)
Outdoor	0.040 (0.032)	0.081** (0.036)	0.042 (0.032)	0.083** (0.036)	-0.028* (0.017)	0.030 (0.035)	0.079** (0.039)
AQ_today	-0.190* (0.101)	-0.178 (0.111)				-0.479 (0.406)	-0.226 (0.447)
AQ_problem			-0.151 (0.125)	-0.051 (0.137)	0.295*** (0.064)		
(PM_ord).L			-0.297* (0.176)	0.243 (0.193)	0.007 (0.090)		
(PM_ord).Q			0.035 (0.174)	-0.078 (0.191)	0.118 (0.089)		
θ_AQ_today						0.3072 (0.419)	0.051 (0.4583)
Observations	374	374	374	374	374	374	374
H_0: AQ_today exogenous						H_0 not rejected	H_0 not rejected
Adjusted R2					0.098		
Pseudo R2	0.082	0.085	0.083	0.084		0.082	0.085

Note: *p<0.1; **p<0.05; ***p<0.01; Terms *(PM_ord).L* and *(PM_ord).Q* represents linear (L) and quadratic (Q) polynomial approximations for *PM_ord* ordinal variable.

Source: own calculations.

to both SWB measures, although only in the case of LS the 10% significance threshold is achieved. Lack of significance of gender and education is considered a standard outcome in SWB estimations (Veenhoven 1997). Models (3)-(4) yield very similar results for the personal characteristics reported above, simultaneously indicating a negative and significant effect of a linear approximation of the objective AP on life satisfaction. The pollution awareness indicator *AQ_problem* does not surpass the 10% significance level. Model (5) explains the perceived AP, highlighting the negative influence of the health status and positive of the pollution awareness indicator. The significance of health, time spent outdoors, and the negligible role played by age and income, are all in line with the results obtained by MacKerron and Mourato (2009), with a considerable difference regarding only the objective AP level, which in our case is not related to *AQ_today*. To verify the strength of the instruments applied in the estimation, their joint significance is tested with an F-statistic. The resulting value of 10.76 is slightly above the conventional threshold value of 10, suggesting that the instruments used should not be considered weak (Staiger and Stock 1997). Finally, models (6)-(7) are used to assess whether the perceived AP is exogenous. Lack of significance for the inserted *θ_AQ_today* term indicates that the exogeneity hypothesis cannot be rejected.

Using the Pseudo-R^2, the goodness of fit of the ordered logit models is evaluated, providing uniform results of 8-9%. The obtained values correspond to other AP-SWB studies, e.g. Brereton et al. (2008) reported Pseudo-R^2 of 9-16% for estimations using up to 67 regressors, while MacKerron and Mourato's (2009) of 9% for a model with 27 regressors and a comparable sample size. Given the caveats reported by MacKerron and Mourato (2009), the multicollinearity is assessed for Equation (5), using the variance inflation factor. The maximum obtained value is 1.75, confirming the stability of the proposed estimation.

6. Conclusion and discussion of results

Two methods were used to explore the perceived/objective AP-SWB nexus to clarify which mechanisms drive the hypothesised relationship between pollution and wellbeing. The log-linear analysis allowed for testing and comparing various combinations of these 3 variables. The results imply that the best fit is offered by the conditional independence model, where SWB is related to perceived AP, and perceived AP to objective AP, but no direct relation exists between the latter and SWB.

The regression analysis included a broader set of explanatory variables, to further investigate this issue. According to performed estimations, there is no evidence to assume any significant relationship between objective and perceived AP, a finding consistent with results reported by Orru et al. (2018) for Estonia. However, similarly to log-linear analysis, perceived AP was found to negatively affect LS. A significant negative correlation was also detected between objective AP and LS, confirming the results of some earlier studies (Orru et al. 2016; Zhang et al. 2017; Du et al. 2018). Finally, the outcomes of the instrumental variable estimations suggest that perceived AP is not endogenous to SWB, contradicting the earlier findings of Goetzke and Rave (2015). In other words, there is no evidence to assume that the personal assessment of current air quality is driven by the SWB of an individual. Reaching a conclusion on the issue of potential endogeneity of perceived environmental characteristics in the SWB function is of utmost importance for the emerging life satisfaction approach to valuation (Luechinger 2009) – an innovative method to derive prices for non-marketed goods. It is thus recommended that further investigations be undertaken in this field, using larger data sets and exploring different pollutants and new geographic spaces.

The important contribution of this study lies in extending the discussion on the perceived/objective AP-SWB nexus to short-term exposure and immediate effects on SWB. The relationship between short-term perceived and objective AP is found to be much more vague than that in long-term studies, where respondents' perceptions of air quality in their area are matched with monthly or annual average AP concentrations. Despite the lack of a clear link between perceived and objective AP, there is (a weak) evidence for a negative effect of measured $PM_{2.5}$ concentrations on reported life satisfaction. Such observation lends support to the hypothesis that high levels of transient AP may influence our wellbeing irrespectively of us being conscious of the actual exposure, e.g. by inducing reactions of the chemical warning system, such as sweating, coughing, etc. (Orru et al. 2018).

A key limitation of this study is a small number of repetitions of the CATI survey, which may undermine the validity of matching SWB with exogenous AP levels due to unobserved, time-variant confounding factors. However, the consecutive rounds of the survey were conducted over a very short time-span (thus reducing the influence of long-term trends, e.g. seasonal changes), and captured stark differences in the $PM_{2.5}$ levels. Moreover, unlike other repeated cross-sectional studies (e.g. Alkon and Wang 2018), the sample design was representative, allowing for a higher generalisability of the obtained results.

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