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A review of air pollution impact on subjective well-being: Survey versus visual psychophysics

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ABSTRACT

Air pollution is a worldwide environmental and health issue, especially in major developing countries. A recent World Health Organization report shows about 3 million deaths in the world in 2012 are due to ambient air pollution and China and India are the countries with the most severe challenge. Air pollution influences people's thought and experience of their lives directly by visual perceptions. This reduces people's subjective well-being (SWB) to a significant degree. Empirical researchers have made efforts to examine how self-reported well-being varies with air quality typically by survey method - matching SWB data with monitored air pollution data. Their findings show NO_2, particles, lead, SO_2 and O_3 have significant negative impact on SWB. However, it is very hard to match air pollution characteristics from monitor stations with each respondent's state of SWB at the moment a survey is conducted. Also it is very hard to find the detailed trend impact from only air pollution factor on SWB. This review illustrates the features and limitations of previous survey studies on quantifying the effects of air pollution on subjective well-being. This review further displays the progress of psychophysics and its application in landscape and air quality research. We propose using psychophysics application to quantify air pollution impact on SWB.

1. Introduction

Air pollution is a worldwide environmental and health issue, especially in major developing countries. According to World Health Organization (WHO), in the year of 2012, ambient air pollution (AAP) caused 3 million deaths within the world and about 87% of these deaths occur in low- and middle-income countries (WHO, 2016). The most deaths came from the low- and middle-income countries of WHO Western Pacific and South East Asian with 1.1 and 0.79 million respectively. China and India are the countries with the most contribution to the figures and also they are the two countries with the most deaths globally (Liu and Liu, 2011; WHO, 2016). The other low- and middle-income countries and regions share the burden with 0.68 million. The remaining deaths occur in high-income countries of Europe, the Americas, Western Pacific, and Eastern Mediterranean, which are about 0.38 million (WHO, 2016). As China and India are planning for and experiencing rapid urbanization, the air pollution situation will continue to deteriorate.

Smoggy days can impact people's visual perception directly. Subjective well-being (SWB) belongs to a perceptual domain and involves how people think about and experience their lives. In addition, SWB includes different evaluations that individuals' make regarding their lives (Diener, 1984, 2006) that cover the events happening to their bodies and minds and the circumstances in which they live. Rather than conforming to external standards, assessments of SWB are based on an individual's own chosen criteria. Policy-makers are likely to consider SWB in planning and assessing the impact of policy decisions. As a unique example, the Asian nation of Bhutan officially established the Gross National Happiness (GNH) measure by law and replaced the traditional economic policy goal of increased GDP with increased GNH.[1] Subsequently, many western governments have officially introduced or

[1] Further information can be found under the following link: http://ophi.org.uk/policy/national-policy/gross-national-happiness-index/.

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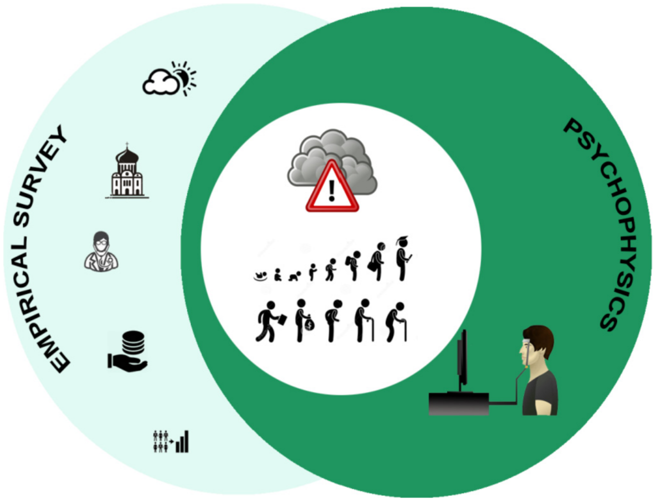

Fig. 1. The structure of this review.

initiated measurements of national happiness or life satisfaction,[2,3] (Schmitt, 2013).

Traditionally, a survey instrument is the tool used to examine air pollution's impact on SWB (one type of people's perception), and it has been widely used by both economists and sociologists. Meanwhile, environmental psychologists have started adopted psychophysical methods to solve environmental issues, including landscape attractiveness and acceptable visual air quality standard. However, psychophysical procedure has never applied to evaluating air pollution impact on SWB. This review work aims to provide a new perspective in measurement of air pollution impact on SWB. Fig. 1 shows the structure of this work. This paper evaluates the performance and limitations of empirical surveys in quantifying air pollution's impact on SWB; reviews certain developments in environmental psychophysics and their application in visual air quality research; proposes to use psychophysical methods to quality air pollution impact on SWB. The remainder of this paper is organized as follows. Section 2 provides a brief introduction of SWB and air pollution. Section 3 illustrates the features and limitations of previous survey studies on quantifying the effects of air pollution on subjective well-being. Section 4 displays the progress of psychophysics and its application in landscape and air quality research. Section 5 summaries the strength and weakness of survey method and proposes an application of visual psychophysical experiments to explain the relation between air pollution and SWB.

2. 2Subjective well-being

For decades, unhappiness has been explored deeply by scientific research, while positive subjective well-being was largely ignored by social scientists prior to the 1970s. In 1973, Psychological Abstracts International began to include happiness as an index term. Since the journal of Social Indicators Research was founded in 1974, many articles have been published that have focused on SWB. Diener (1984) comprehensively reviewed SWB studies, including definitions and measurements.

2.1. Definitions and measurements of SWB

The definitions of well-being can be grouped in three categories. Firstly, researchers represented by Coan (1977) and Tatarkiewicz (1976) have defined well-being by external standard such as virtue or holiness rather than subjective state. They thought that well-being can be obtained by leading a virtuous life. Secondly, social scientists have tried to define well-being by focusing on the factors which leads people believe they are in positive state (Andrews and Withey, 1976; Chekola, 1975; Shin and Johnson, 1978). Thus, happiness is defined as the harmonious state where people's desires and goals are satisfied. The third meaning of happiness emphasizes positive emotional experiences as gaining a superiority of positive affect over negative affect (Bradburn, 1969). SWB emphasizes people's own judgements about themselves and belongs to the second or third well-being definitions categories. The measurement of SWB is often restricted to the measurement of happiness (OECD, 2013). This may be because the notion of SWB is used in research literature as a replace of the term 'happiness'. A definition given by Diener et al. (2006) is commonly identified by research in this field, which is 'Good mental states, including all of the various evaluations, positive and negative, that people make of their lives and the affective reactions of people to their experiences.'

Single-item survey questions frequently constitute measures used by early social scientists. Such measures tend to fall in happiness categories from which scales cannot address all aspects of SWB (Andrews and Withey, 1974; Cantril, 1965; Gurin et al., 1960). Later, multi-item surveys were integrated into scholarly research. During this period, lots of survey scales merged for different purposes of studies and different backgrounds of interviewees. For examples, Lawton (1975) used 17-item scale to measure lonely dissatisfaction, agitation and attitude toward one's aging. Kozma and Stones (1980) used 24 items to measure positive and negative affect and experiences. Researchers have been trying to find general components of SWB, which can be used universally and three general components of SWB were proposed, including life satisfaction judgement, positive affect and negative affect (Andrews and Withey, 1976; Bradburn, 1969; Bryant and Veroff, 1982; Harding, 1982; Zevon and Tellegen, 1982). Bradburn (1969) proposed his global happiness judgement standard Affect Balance Scale by making comparison of people's negative affect with their positive affect. The positive affect may including the proud or pleasant feel and the negative affect may ask about their upset, unhappy or depressed feelings. In a recent study by Kahneman et al. (2004), the SWB for an activity can be measured as the net affect of the average of all positive affects (happy, enjoying themselves) less the average of all negative affects (Frustrated, depressed, worry) and the length of time people spending on it. Nowadays, life satisfaction and affects are both widely studied by researchers.

2.2. Drivers of SWB

Over the last two decades, the importance of SWB has received considerable attention in various fields. The output of SWB measurements is widely implicated in social and health fields (Cohen et al., 2003; Danner et al., 2001; Fujiwara and Campbell, 2011; Ostir et al., 2001; Steptoe et al., 2005). Growing literature in the field of economics has advanced the definition of the factors impacting SWB at the individual level. A predetermined level of happiness unique to each individual's genetics and personality is proposed (Costa et al., 1987; Cummins et al., 2003; Lucas et al., 2003; Lykken and Tellegen, 1996). Easterlin (2003) outlined an improved theory of how life events affect SWB. Life events and personality interact with one another to shape happiness at the

[2] The full article can be downloaded from the web page of the Federal Ministry of Finance: http://www.bundesfinanzministerium.de.

[3] Further information can be found under the following link: https://www.washingtonpost.com/business/economy/if-youre-happy-and-you-know-it-let-the-government-know/2012/03/29/gIQAlSL2jS_story.html?utm_term=.7a170ddc8352.

individual level. Life circumstances such as income (Di Tella et al., 2003), good health (Gerdtham and Johannesson, 2001; Steptoe et al., 2005) and family (Lucas et al., 2003) are characterized by positive relationships with SWB in economic studies. By contrast, other events such as unemployment (Knabe and Ratzel, 2010; Theodossiou, 1998) and inflation (Di Tella et al., 2001) negatively affect SWB.

2.3. Air pollution and SWB

In this context, it is quite important to improve our understanding of the elements that influence SWB, particularly in new lines of research. Air pollution is an environmental and health issue worldwide, particularly in developing countries, that has been implicated as a risk factor in health issues ranging from respiratory diseases, cardiovascular diseases, cancers, and impaired cognitive function (Brook, 2008; Brunekreef and Holgate, 2002; Weir, 2012). Early studies suggest that air pollutants with high concentrations may affect exposed people's emotional state. The effects may range from subclinical alterations of mood to pronounced psychopathological symptoms (Rotten and Frey, 1984; Rotton, 1983; Strahilevitz et al., 1979). Thanks to the psychobiological stress concepts, the relationships between air pollution and well-being is clarified (Bullinger, 1989; Frankenhaeuser, 1980; Lazarus and Cohen, 1978). In line with these concepts, air pollution can be regarded as a stressor (Campbell, 1983) and its influence including emotional, behavioral and physical changes can be mediated by cognitive appraisal (Cohen, 1980; Cohen et al., 1986; Folkman et al., 1979). Thus, air pollution may also damage people health indirectly through influencing people's well-being by its nature of disgust. When exposed people appraising this aversive nature, stress reactions of damaged well-being and physiological dysregulation are induced (Baum et al., 1982; Baum and Singer, 1986). Meertens and Swaen (1997) even proposed that air pollution's psychological effects might have a considerable influence on well-being that exceeds its physical effects. Further refinement of the relationship between SWB and air pollution has been attempted in more recent decades. In the following sections, the challenges encountered and the methods employed in this field of study will be summarized and then a new approach will be explicated that involves the application of psychophysical experiments to assess the effects of air pollution on self-reported well-being.

3. Using surveys to reveal the relationship between air pollution and SWB

However, air pollution characteristics are not normally collected in surveys but instead from monitor stations. Generally, air pollution characteristics can change dramatically based on time, space, weather and climate (Luechinger, 2009; Schmitt, 2013). It is nearly impossible to match air pollution characteristics from monitor stations with each respondent's state of SWB at the moment a survey is conducted. A conventional challenge to empirical studies is to seek high quality air pollution data with fine spatial and temporal disaggregation and to connect this information with a specific respondent. Previous researchers have typically merged the average annual air pollution data at the country or regional level with collected or ready-to-use panel SWB data from surveys to analyse the regression correlations between the two datasets (Schmitt, 2013; Welsch, 2007). Socio-economic and demographic variables are often considered simultaneously in controlling the influence on SWB as opposed to other potential factors. Weather and other climate characteristics are also sometimes covered. Table 1 summaries the findings and contributions of empirical studies according to data spatial and temporal levels. Sections 3.1–3.3 distinguish the reviews of previous studies at different spatial levels.

3.1. Air-quality data collected at the country level

Early researchers examining how self-reported well-being varies with air quality typically used cross-sectional air-quality data collected at the country level. In Welsch's studies, both the SWB and air pollution datasets are based on average country level. One of these studies covers data from 54 countries. The SWB data comes from the World Database of Happiness and air pollution data are taken from the database of the global Environmental Sustainability Index. The variables considered include air pollution (SO_2, NO_2 and particles), freedom, rationality, income and water pollution, and the results show that the impact of air pollution on SWB is difficult to measure (Welsch, 2002, 2007). Another study covers 10 European countries. Again, the SWB data comes from the World Database of Happiness and air pollution data are provided by the Organisation for Economic Co-operation and Development (OECD), based on country-wide networks of measurement stations. Pollutants considered in this study include NO_2, lead and particles. To avoid overcompensating for unobserved heterogeneity, income is the only controlled variable. It has been demonstrated that air pollution plays a significant role in predicting changes in SWB on both cross-country and inter-temporal bases.

In Luechinger (2010), life satisfaction, SO_2 and household income were considered the main variables, and domestic and socioeconomic variables were also controlled. The data cover 13 European countries over the 1979–1994 period. The air pollution data were collected from the OECD at the average year level, and individual-level SWB data came from Eurobarometer. Air pollution was found to have a statistically significant and robust negative impact on SWB. Schmitt (2013) used the individual level for life satisfaction data from the German socio-economic panel (SOEP) survey and the average of country-level air pollution data from 765 monitor stations in Germany to examine the impact of CO, NO_2 and O_3 on life satisfaction. He analysed daily air pollution data in Mecklenburg-West Pomerania in 2005 and found that the density of pollutants varies with the seasons. To improve the sensibility of the survey-based life satisfaction data, average daily country-level air pollution data in Germany were used in his study. Socioeconomic and weather factors were controlled for in the analysis; among the three assessed pollutants, only O_3 has a significantly negative impact on life satisfaction.

3.2. Air-quality data collected at the regional level

Most empirical papers using more spatially disaggregated pollution data at the regional level to illustrate the air pollution impact on SWB have focused on one country. Smyth et al. (2008) evaluated environmental features, including SO_2 emissions, using SWB in 30 cities in urban China. Individual level SWB data were obtained from China Mainland Marketing Research Company (CMMRC). The regional average annual air pollution data from the China Statistical Yearbook were matched to each respondent based on his or her residence. Socio-economic and demographic variables were well-controlled and a clear negative impact of SO_2 emission on SWB was found.

Luechinger (2009) gathered SO_2 concentration data for nearly two decades, covering 553 monitor stations in Germany for the German Federal Environmental Agency. Due to the shortage of air pollution data from some monitor stations in some individual years, interpolation was applied to estimate the missing data. SWB data were provided by the SOEP survey for the matching years. Correlations between the two variables were analysed based on

Table 1
Air pollution and SWB research developments based on survey. ***,**,* denote statistical significance at 1, 3–5 and 10% levels used in empirical studies, respectively. Some pollutants are associated with different significance levels as different models are considered.

Author	Spatial level of air pollution data	Temporal level of air pollution data	Air pollutants	Air pollution data source	Controls of other factors in SWB	Main findings
Welsch (2002)	country level (54 countries)	yearly	SO_2, NO_2, particles	Environmental Sustainability Index	freedom, rationality, income, water pollution	impact is hard to measure
Welsch (2007)	country level (10 countries)	yearly	NO_2, particles, lead	monitor stations	income	negative impact with NO_2^{**}, particles**, lead**
Luechinger (2010)	country level (13 countries)	yearly	SO_2	monitor stations	socio-economic, demographic, climate	negative impact with $SO_2^{*,**}$
Schmitt (2013)	country level (Germany)	daily	CO, NO_2, O_3	monitor stations	socio-economic, weather	negative impact with O_3^{*}
Smyth et al. (2008)	region level (30 regions in China)	yearly	SO_2	monitor stations	socio-economic, demographic	negative impact with SO_2^{***}
Luechinger (2009)	region level (about 445 regions in Germany)	yearly	SO_2	monitor stations and interpolation	socio-economic, particles	negative impact with SO_2^{*}
Ferreira and Moro (2010)	region level (9 regions in Ireland)	yearly	PM_{10}	monitor stations	demographic, socio-economic, climate variables	negative impact with $PM_{10}^{*,**}$
Levinson (2012)	region level	daily	PM_{10}	monitor stations	demographic, weather	negative impact with $PM_{10}^{*,**}$
Ferreira et al. (2013)	region level (248 regions in Europe)	yearly	SO_2	monitor stations	weather, economic	negative impact with SO_2^{*}
Rehdanz and Maddison (2008)	individual level (Germany)	daily	not specified	self-reported affect levels	socio-economic, neighbourhood	negative impact
MacKerron and Mourato (2009)	individual level (London)	monthly	NO_2, PM_{10}	estimated from models, interpolation	socio-economic, demographic	negative impact with NO_2^{**}
Li et al. (2014)	individual level (Jinchuan, Gansu, China)	daily	not specified	self-reported pollutant levels	socio-economic, demographic	negative impact ***
Ambrey et al. (2014)	individual level (Queensland)	monthly	PM_{10}	estimated from models	socio-economic, demographic, weather	negative impact with PM_{10}^{*}
Orru et al. (2016)	individual level (Estonia)	yearly	PM_{10}	estimated from models	socio-economic, demographic	negative impact with PM_{10}^{**}
Zhang et al. (2017)	Individual Level	daily	air pollution index (SO_2, O_2, PM_{10})	monitor stations and estimated from models, interpolation	socio-economic, demographic, weather	negative impact ***

average annual regional data in Germany. Variables such as socio-economic factors and particles were controlled and a significant impact of SO_2 on SWB was found in this study. Ferreira and Moro (2010) valuate PM_{10} with regional data in Ireland. According to respondents' locations, the average annual pollution data from the closest monitoring station were linked with respondents' SWB data. Demographic, socio-economic and climate variables were controlled during the analysis. The concentration of PM_{10} was shown to have an effect on individual-level SWB.

Levinson (2012) obtained the happiness data from the General Social Survey (GSS), which provides the date and location of the survey for each respondent. The EPA's Air Quality System (AQS) provides the daily air quality data collected from thousands of monitor stations and also the locations of these monitors so that most respondents' country or city is identifiable. With the help of the National Climate Data Center, the daily temperature and rainfall information were specified. A significant relationship between happiness and air quality was found in the average at daily and regional levels. He found that higher levels of particulates are negatively correlated with well-being in the US. Demographic and weather variables were well-considered and lower happiness levels were found to be related to worse local air pollution on the interview day.

Ferreira et al. (2013) first conducted cross-sectional analyses with spatially disaggregated data at the region level on SO_2 to explain individual SWB in Europe. Other spatial controls were also considered in their study including temperature, precipitation and regional economic performance. They adopted SWB data provided by the European Social Survey (ESS) collected between 2002 and 2007 and created the dataset on SO_2 concentrations from 248 regions in Europe for the same period. The annual mean SO_2 data were interpolated from the Geographic Information Systems (GIS) in regions in 23 European countries between 2002 and 2007. A robust negative impact of SO_2 concentrations on self-reported life satisfaction was found.

All these studies based on multi regions provide comprehensive interactive information between the significant indicators like relations between air pollutants and economic/climate backgrounds. However, limited air pollutants are investigated in each of the European studies. Little predications of SWB state in developing countries with more serve air pollution can be made.

3.3. Air-quality data collected at individual level

Few papers use spatially disaggregated air pollution data focused on the individual level. Some of them used subjective self-reported air pollution levels instead of objective monitor measures or modelling data. Rehdanz and Maddison (2008) analysed the relationship between self-reported impact of air pollution and SWB data, both of which were obtained from the German socio-economic panel (SOEP) survey. Li et al. (2014) conducted a similar research based on a mining area in Jinchuan, China. Both studies provided a mindful control of socio-demographic, economic variables affecting SWB and showed a negative correlation between SWB and air pollution. However, their air pollution data were individual perspectives from survey but not monitor stations and also pollutants were not specified. Thus, it is difficult to specify the objective impact from air pollution on SWB.

Thanks to air pollution models, the spatial data can be broken down to individual level. MacKerron and Mourato (2009) developed a survey to collect individual SWB data in London. The air pollution data they used were from the Air Dispersion Modelling System provided by Cambridge Environmental Research Consultants Ltd with an average annual level covering an area of 3260 km^2 in 50×50 m grid squares (cells). Pollutants examined included NO_2 and PM_{10}. With this model, the air pollution levels for respondents were estimated according to their postcode. To match the survey time, a linear interpolation was used to estimate the air pollution level during a specific time of year for each respondent. This method was used under the assumption of a smooth and continuous air pollution change in London. Socio-economic and demographic variables were controlled and only NO_2 was found to have a significant impact on SWB. Their results indicate that measured air pollution data are negatively associated with SWB.

In recently years, most studies are based on air pollution models. In Ambrey's work based on Queensland, multi air pollutants were considered. However, only PM_{10} was found to have the strongest negative association with life satisfaction (Ambrey et al., 2014). In Orru et al.'s study in Estonia, individual SWB data were obtained from European social survey (ESS). Air pollution data were gotten from Eulerian air quality dispersion model with 1×1 km grid squares covering the whole country (Orru et al., 2016). A statistical negative influence of PM_{10} is found on SWB. However, all studies only found limited kind of air pollutants negatively related with SWB, which cannot provide an overall prediction of air pollution impacts on SWB. This may be caused by the relatively higher quality of local air conditions. Moreover, the air pollution data is in monthly or yearly levels, which could due to the availability of the source of getting air pollution data. In the very new study by Zhang et al. they successfully valued air quality using moment-to-moment happiness data in a daily and local level and found bad daily air quality affect overall life satisfaction not much but it reduces hedonic happiness and increases the rate of depressive symptoms (Zhang et al., 2017). The API data in their research showed that there is no obvious air quality improvement from 2010. Thus, there is a possibility that long-term air pollution has already caused impact on people's long-term life satisfaction and this perception cannot be easily changed by some days experience of good air condition during a year unless air condition is improved as a long term. This impact is hard to be found by reality of stable poor or good air condition.

SWB involves people's evaluations regarding their mind and body. Of course, the traditional survey measurements address the perceptions of both mind and body aspects. However, the challenges in empirical studies are clear. From a psychological perspective, it is known that the perspective at the time of the interview cannot adequately explain the current SWB state because a respondent's answer to the question of happiness level is strongly dependent on his or her current mood. The air pollution data must be disaggregated at the individual level from both spatial and temporal aspects to explain individual SWB data. Few of the empirical studies achieved this standard, shown in Table 1. Typically, limited air pollutants are examined in difficult locations. However, various air pollutants always appear together, floating in the atmosphere and working together to change people's perception, including affecting SWB. The same levels of air pollutants in different weather and at various sun angles can generate very different sensations. In seldom studies individual's idiosyncrasies were considered from all the perspectives of socio-economic, demographic, climate and weather together although all the considered perspectives can still not explain all the possibilities of individual's idiosyncrasies. In attempting to provide a full picture of the combined effects of air pollutants on SWB, the development of psychophysical applications for landscape attractiveness and visual air quality is reviewed and the possibility of applying psychophysical methods for quantifying the impact of air pollution on SWB is discussed in following sections.

4. The possibility of using psychophysics to assess air pollution impact on SWB

In modern psychophysics research, the term of psychophysics refers to the relationship between external stimuli in the physical domain and mental events in the psychological domain (like people's sensations and perceptions) and the method used to deal with the relation between them (Marks and Gescheider, 2002). Perception is a process of representing and understanding the physical environment by the organization, identification and interpretation of sensory information. All perception involves physical or chemical stimulation of the sense organs (Kail and Cavanaugh, 2015). Psychophysical scaling addresses the quantification of people's sensations and perceptions in psychological domains obtained from external stimuli in the physical domain (Engeldrum, 2000; Marks and Gescheider, 2002). As discussed above, SWB belongs to people's perception domain related to their feelings about life satisfaction. As a type of physical stimuli, changes in air pollution can result in different responses in people's SWB directly through visual experience, and this response can be quantified by psychophysical scaling methods.

It's hard to find any empirical work using psychophysical method to measure the impact of air pollution on SWB. However, lots of empirical studies proofed that visual psychophysical method is a valid and reliable way to estimate the relationship between environmental features and human perceptions. In this section, the developments in this field will be displayed and using photo slides as stimuli to quantify air pollution impact on SWB is proposed.

4.1. The preliminary application of psychophysics in environmental research

Theoretically, visual perception may not entirely represent the entire perception that people process from air pollution, especially for chemical simulations. However, because sight dominates the way we ‘see’ the world and about one-third of our brain is dedicated to processing visual experience (Gilbert and Walsh, 2004), researchers have suggested that visual input plays the primary role in human brain development (Kirk, 2006), and visual air quality is therefore one aspect of the principal information that individuals use to judge air pollution (Barker, 1976; Hyslop, 2009).

Thanks to Craik and Zuhe's (1976) milestone text, convincing arguments have been presented to propose the use of “Perceived Environmental Quality Indices” as an assistant to existing physically based systems for estimating various environmentally relevant aspects. Perceptual judgement procedures have been widely involved in the quantification of environmental features. Scenic quality assessment is an important research area where perceptual approaches are applied in early stage. Compared with other, such as descriptive inventories, questionnaires or opinion surveys, perceptual preference approaches are believed to represent the landscape more intuitively than verbal surveys (Daniel and Boster, 1976). Studies have shown that colour slides or photographs can represent actual landscapes quite well (Boster and Daniel, 1972; Daniel and Boster, 1976; Zube, 1974).

However, professional psychophysical data collection and analysis method are not properly applied at the same time. Among a number of procedures for obtaining observers' judgments, an individual rating approach is quickly used extensively not only because of its efficiency but also because it can provide relative differences between samples. However, to appropriately analyse the data from ratings, researchers must address two potential problems in the perceptual approach. One is the difference in observers' judgment criteria, which depends on the nature of their past experiences. The other is the difference of scale units that observers tend to use, although the same length of scale is provided. In Boster and Daniel's (1972) study, estimations were made of the empirical analysis methods, including the standardization of ratings to adjust an observer's idiosyncratic use of the response scale. This standardization method is efficient for eliminating the arbitrary differences between observers' use of the response scale. Even results from different scales can be directly compared. However, it tends to hide the real discrimination between individual observers' judgments. Based on some classic psychophysical theories and methods (Green and Swetts, 1966; Swetts, 1973; Thurstone, 1927; Torgerson, 1958), an appropriately standardized estimation method, Scenic Beauty Estimates, was proposed (Daniel and Boster, 1976). This method provides an approach to evaluate different landscapes with each landscape containing a number of different scenic photographs/slides.

These studies provide proof that visual psychophysical method can be used to solve perception and environmental problems. Moreover, the psychophysical analysis procedure can also adjust observers' idiosyncratic automatically without collecting observers' social background data. All these works have established a foundation for further visual air quality research (Balling and Falk, 1982; Buhyoff et al., 1983; Peterson, 1967; Peterson and Neumann, 1969; Propst and Buhyoff, 1980). All the developments of psychophysics applied in air quality research are illustrated in Table 2.

4.2. Reliability and validity of slide observation of air quality compared with field studies

Studies by Malm et al. (1980) have shown that observers' visual perceptions of air quality are reliable, which is consistent and reveals substantial sensitivity to measured variables of air quality by optical instruments. Efforts have also been made by previous researchers to determine the relationship between judgments of visual air quality and the field.

In Malm et al. (1981), a total of 40 slides and three-dimensional corresponding scenes were judged. Student's *t*-test and *f*-test were used to compare the means from the field and slide observations. Results indicate no significant difference between the means and also suggest that colour slides/photographs can be acceptable as surrogates for actual scenes for perceptual judgements.

Stewart et al. (1983) published their paper based on a five-year visual air quality study in Denver. A pilot study and a main study were conducted with a large number of observations. The observers made both field and photographic observations. A strong correlation between field and photographic judgments of visual air quality was found, indicating that non-visual cues such as smell or impressions of pollution from earlier have little influence on visual air quality. The paper also suggests that this procedure, with high reliability and validity, can be used to examine the relation between visual air quality and other variables, such as well-being or life quality and pollutant concentrations or sources.

Later, Stewart et al. (1984) improved the methodologies used by the empirical studies on the validity of photographic judgment. In the new study, rather than averages of group ratings, individual observers' judgments were analysed. Moreover, various judgments were collected to compare the relationships between judgments of photographs and the field, and systematic components of the variation in judgments between two observation procedures were examined. The results of this study enhanced previous findings and encouraged the use of photographs to investigate visual air quality issues.

After a broad review of various approaches on visual air quality management, including human perceptual judgment, physical and chemical measurements, Middleton et al. (1985) summarised that photograph judgment has been highly recommended as a feasible, cost-effective substitute for field judgments in evaluating the relationship between other variables and visual air quality. Thus, visual perceptual experiments with photograph judgments are widely used in later research of air quality perceptions (BBC Research and Consulting, 2003; Fajardo et al., 2013; Pryor, 1996).

4.3. Looking for the most satisfactory indicators of visual air quality

Another interesting and relevant study area defines the elements that can influence visual air quality. Researchers attempt to build models to predict human perceptions of air quality according to emissions or relevant perceptual cues like sun angle, clarify, colour and border.

Malm et al. (1980) applied slide and field observation procedures to explore the relations between visual air quality and colour contrast. High correlations were detected between both variables and this relation was found to be independent of the demographic background of observers. In the study by Latimer and Hogo, 1981, the slide observation procedure was adopted to collect perceptual data. Visual range and inherent scenic characteristics were found to be sensitive to visual air quality. Malm et al. (1981) found that sun angle, colour contrast, inherent scenic beauty and the distance to each of the scenic elements are sensitive to observers' perceived visual air quality. However, observers' demographic background affects visual air quality ratings very little.

To develop a physically based index of visual air quality, Mumpower et al. (1981) collected field perceptual data and physical environmental data from various local locations and used factor analysis and multiple regression analysis to investigate the relationships among them. The perceptual data included visual air quality and relevant perceptual cues (distance, clarify, colour and border). The environmental data included aerosol scattering and absorption measures as well as meteorological measures and pollutant data. The results suggest that multiple considerations of perceptual cues can describe visual air quality judgments. However, the collected environmental measurements are not sufficient predictors of perceptual judgments.

Middleton et al. (1983) attempted to build a model to predict human judgments of air quality influenced by emissions. Field research was conducted to obtain perceptual data. Only directly emitted fine particles were included in this model. The model also included the distance between the observer and the target, the sun angle, and the intensities of the background and target. Results indicate that refined concentrations can increase the validity of the model between target clarity and emissions, but sky colour and borders are not easily explained by emissions.

To address the indicators of judgments of visual air quality, in the study of Middleton et al. (1984), physical/chemical environmental data and perceptual data were collected over various time frames, observation locations and atmospheric conditions. The correlation coefficient was used for analysing the single indicator, which can provide the best overall prediction of visual air quality judgments. Light scattering extinction (b_{ext} *or* b_{xp}) by a telephotometer is found to be the most satisfactory and direct indicator of visual air quality. Multiple regressions were applied to compare the prediction performance of different combinations of variables. It is indicated that combinations of physical/chemical measures together seem to provide better predictive ability than the single measurement of b_{xp}. Fine particle 4-h averaged S and 12-h averaged S, sulfate, nitrate and ammonium are all highly correlated with visual air quality judgments. Later, the deciview (*dv*) scale was

Table 2
Developments of perceptual approach in air pollution research.

Authors	Developments	Main findings
Craik and Zuhe (1976)	Psychophysics introduced into landscape research	Propose the use of "Perceived Environmental Quality Indices" as an auxiliary to existing physically based systems for the estimation of various environments.
Boster and Daniel (1972)		Developed the method called Scenic Beauty Estimates based on traditional psychophysical theory.
Balling and Falk (1982)	Perceptual approach used in landscape research	Results provide limited support for the hypothesis that humans have an innate preference for savannah-like settings that arises from their long evolutionary history based on the savannahs of East Africa.
Buhyoff et al. (1983)		Hypotheses regarding cultural influences on landscape preference are extended
Malm et al. (1980)	Reliability and validity evaluation of visual perceptions of air quality	Visual perception of air quality is consistent and substantially sensitive to measured air quality.
Malm et al. (1981)		No significant difference between the means of field and slide observations. Colour slide/photographs can be acceptable as surrogates for actual scenes for perceptual judgments.
Stewart et al. (1983, 1984)		Photographic procedure with high reliability and validity can be used to examine the relation between visual air quality and other variables such as well-being or quality of life and pollutant concentrations or sources.
Middleton et al. (1985)		Judgments of photographs have been highly recommended as a feasible, reduced-cost substitute for field judgments.
Malm et al. (1980)	Modelling of variables influencing visual air quality from different perceptual cues	High correlations are found between visual air quality and colour contrast and this relationship is independent of the demographic background.
Latimer and Hogo, 1981		Visual range and inherent scenic character are found to be sensitive to visual air quality.
Malm et al. (1981)		Sun angle, colour contrast, inherent scenic beauty and the distance to each of the scenic elements are sensitive to observers' perceived visual air quality.
Mumpower et al. (1981)		Perceptual cues (distance, clarify, colour and border) can describe visual air quality but not for environmental data, including aerosol scattering and absorption measures, meteorological measures and pollutant data.
Middleton et al. (1983)		Sky colour and border are difficult to explain by emissions. However, refined concentrations can increase the validity of the model between target clarity and emissions.
Middleton et al. (1984)		Light scattering extinction (b_{ext} *or* b_{xp}) by a telephotometer is found to be the most satisfactory direct indicator of visual air quality.
Ely et al. (1991)	Perceptual approach (actual photographs) used to establish visual air quality standards	The group average violation standard in the Denver area should be at atmospheric extinction level (b_{ext}) of 0.076/km, which is equal to a visual range of approximately 50 km.
Pryor (1996)		In Lower Fraser Valley, criteria of visibility standard (b_{ext}) for Chilliwack and Abbotsford should be 0.096–0.105/km (a visual range of approximately 40 km) and 0.039/km (a visual range of approximately 60 km), respectively.
Malm et al. (1983)	Modelling air pollution images	Simplified atmosphere model and radiative transfer model are used to de visual air quality simulation techniques.
Molenar et al. (1994)		Using atmosphere aerosol and radiative transfer models, advanced simulation model is developed.
BBC Research and Consulting (2003)	Perceptual approach (modelled photographs) used in establishment of visual air quality standards	24 deciviews is an acceptable level of visual range standard in Phoenix area. Gender and age are sensitive.
Fajardo et al. (2013)		19 to 33 deciviews is an acceptable range of visual range standard in Beijing for young people.
Smith (2013)		Different people living in different air quality conditions may vary in their opinions of acceptable levels of visual air quality

created to describe the total light extinction capability of all haze species in the ambient air at a given time at a given location.

From then on, Light scattering extinction (b_{ext} *or* b_{xp})/deciview (*dv*) has been used as a primary index to describe air quality in later research of the evaluation human acceptable air quality (BBC Research and Consulting, 2003; Fajardo et al., 2013; Pryor, 1996).

4.3.1. Perceptual procedure used in the establishment of visual air quality standards

As the reliability and validity of photographs judgment has been proved and widely accepted and also the Light scattering extinction has been taken as a universal indictor to predict human perceptions of air quality, since the 1990s the photographs/slide perceptual procedure has been widely applied to collect observers' judgment data for socio-politically relevant purposes.

To establish a visibility standard in the Denver metropolitan area, a study was conducted in 1989 to measure the acceptable point of visual air quality and its corresponding visual range (Ely et al., 1991). Slides were taken by camera and, at the same time, light extinction was measured by a transmissometer. Slides were selected based on the following criteria: available hourly average transmissometer value; no extremes of over-exposure or under-exposure; no snowstorms; no off-centre extremes; and humidity below 70%. Seventeen groups with a total of 214 observers estimated a total of 160 slides. The report recommends that the group average violation standard should be at an atmospheric extinction level (b_{ext}) of 0.076/km, which is equivalent to a visual range of approximately 50 km.

Pryor (1996) set visibility standards in the Lower Fraser Valley area were set. Again, a camera was used to capture scenic characteristics and open-chamber nephelometers were used to measure atmospheric clarity. Availability of optical clarity data, humidity, cloud cover, and sun angle were considered in selecting experimental slides. About 200 university students evaluated the 26 slides showing the same scenes with differing levels of optical clarity. The results indicate that local rather than regional visibility standards should be set. In the Lower Fraser Valley, the criteria of visibility standard (b_{ext}) for Chilliwack and Abbotsford should be 0.096–0.105/km (a visual range of approximately 40 km) and 0.039/km (a visual range of approximately 60 km), respectively.

Actual photographs of the same view taken at different times were used in both the Denver and Fraser Valley studies. Thus, these photographs varied not only in light extinction but also in lighting and cloud conditions. Computer-imaging techniques made it possible for light extinction to become the sole varying factor in the photographs rather than other factors, such as cloud cover, sun angle, precipitation, vista colour, birds, or jet trails. Using atmosphere aerosol and radiative transfer models, Molenar et al. (1994) developed visual air quality simulation techniques based on the pioneering work of Malm et al. (1983). From then on, modelled images have become the major impetus for investigating visual air quality procedures.

In 2003, BBC Research & Consulting was retained by The Arizona Department of Environmental Quality to conduct the Phoenix Area Visibility Survey to assist in the development of a visibility index for the Phoenix area (BBC Research and Consulting, 2003). Altogether, 385 observers at six separate locations in the Phoenix area evaluated 21 different images with the same scene but with varying visibility levels. The slides with various visibility levels were modelled by WinHaze software and ranged from 15 to 35 deciviews (dv), with “15” and “35” representing the clearest and the least clear visual air quality. The results indicate that 24 deciviews is an acceptable level for the local visual range standard. Gender and age are sensitive to the 50% acceptable level of visual air quality.

In 2013, a similar study was conducted in the Beijing area (Fajardo et al., 2013). Eighty-five young people between 15 and 18 years old participated in this experimental survey. Twenty photographs were simulated by WinHaze software with a range of 15–51 deciviews. The investigated haziness range was designed based on the local air quality state. The 50% acceptable level of visual air quality for young people in Beijing is 19–33 deciviews.

Smith (2013) evaluated previously established visual air quality standards by adopting the previous methods under various specified conditions. He argues that the different acceptable standards recommended by studies may result from the images shown in judgments with different visual range, which indicates that different people living in different air quality conditions may vary in their expectations and that local, rather than regional, visibility standards should be set.

Therefore, photographs judgments based on the perceptual approach should be valid to examine the relationship between SWB and air pollution emissions. This psychophysical procedural has been successfully used to solve other issues between environment and people's perceptions, like landscape beauty evaluation and establishment of visual air quality standard. Thus, traditional psychophysical experiments and analysis methods can be used to collect observers' judgments and quantify the observers' perception on the SWB continuum.

5. Discussion and conclusion

This paper evaluates the advantages and limitations of traditional surveys and psychophysics in quantifying the effects of air pollution's impacts. Survey data fully addresses SWB perception from all senses, and it is a sort of field survey to a certain degree. The shortages of survey data are obvious. Firstly, it takes long time and is hard to match air pollution characteristics from monitor stations with each respondent's state of SWB at the moment a survey is conducted. A conventional challenge to empirical studies is to seek high quality air pollution data with fine spatial and temporal disaggregation and to connect this information with a specific respondent. Most of previous researchers have typically merged the average annual air pollution data at the country or regional level with collected or ready-to-use panel SWB data from surveys to analyse the regression correlations between the two datasets. Secondly, the survey method is under the constraint of local air quality. Neither an averagely comparative good nor poor air condition is enough to explain a full picture of air quality impact on SWB. Thirdly, huge data collection is needed to control the influence on SWB from socio-economic, demographic and weather or climate variables. To control observers' idiosyncrasies, empirical researchers made efforts to take as many as possible variables, which are potential to influence SWB in to consideration. Fourthly, the air pollution data used in empirical studies are in a relatively narrow range with European environmental data so that it is quite hard to predict the SWB states of people who often expose in more serious air pollution environment in developing countries like India and China.

Of course, photographic psychophysical procedures only provide measures in a visual sense and it is not sufficient to describe the SWB state of a person. However, it is a good tool to examine the impact of visual air pollution on SWB and worth to try. Sight dominates the way we ‘see’ the world and visual input has a primary role in brain information processing. Photograph judgment has been highly recommended as a feasible, cost-effective substitute for field judgments. Compared with surveys, it costs less and removes observers' idiosyncrasies easily without collecting socio-economic or demographic data. It even generates high quality results without a large number of observers. For example, just over ten observers were used in Smith (2013). Most importantly, it makes it possible to specify spatial and temporal conditions by examining observers' SWB states when viewing the various photographs and obtaining the environmental data from when the photographs were taken.

Taking psychophysical procedures can improve people's understanding of air pollution effect on SWB. It is essential to build an air concentrations image index with high-resolution images in good format. This should be achievable in countries like China, where air quality shows a wide range from excellent to hazardous and air pollutants data are more reliable. With hourly environmental data, the corresponding details such as various air pollutant concentrations, sun angle, humidity, temperature, wind angle and speed for each photograph can be obtained. Modelling the relationship between hourly environmental data and pixel colours in photographs is the beginning step. With the model and given weather variables, an image-based index with weather conditions control explaining various air pollution levels can be built. Using this image-based index, lots of psychophysical research on air pollution and SWB can be conducted with ease. Studies could be quantifying the impacts of different levels of air pollution on SWB. Studies could evaluate the sensitivity of SWB of different social groups under the impact of air pollution. The air conditions of different cities can also be modelled and shown in images so that air condition impact of different cities can be estimated. With help of colour imaging technology, the psychophysical procedure can also be adopted to solve the other environment and perception issues.

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