Are citizens willing to accept changes in public lighting for biodiversity conservation?

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Abstract

Light pollution has significantly increased in recent years, in concert with urban sprawl. Light pollution consequences for nocturnal wildlife, human health, and energy consumption are numerous but are poorly tackled in urban policies. The regulation and mitigation of light pollution is possible, but requires an important shift in the lighting paradigm, including in public lighting often managed by local authorities. One of the main sources of reticence of local authorities to regulate light pollution is the potential rejection by citizens of lighting changes. In this article, we investigate citizens' willingness to accept the transition to more sustainable lighting regimes. We use a discrete choice experiment in a large French metropolis to measure the relative weight of different characteristics of public lighting - light intensity, light extinction, light colour - in respondents' decisions. We show that respondents are globally open to public lighting shifts, but their preferences in terms of the changes are highly heterogeneous. By incorporating socioeconomic variables of respondents into our econometric models, we characterise the main profiles of preferences regarding lighting changes. This provides practical information to urban and environmental planners allowing them to match the municipalities where the need for light pollution control is a priority with those where measures seem socially acceptable by citizens.

Keywords: Light pollution, social acceptability, Discrete choice experiment (DCE), Latent class model, sustainable lighting, dark ecological corridor.

Highlights

- Municipalities can change public lighting to mitigate light pollution
- We identify citizens' preferences for sustainable public lighting shifts
- Respondents support changes, but not according to the same modalities
- Socioeconomic characteristics influence respondents' preferences regarding lighting changes
- Municipalities where socially acceptable changes in public lighting exist can be targeted

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1. Introduction

About 290,000 km^2 of natural and semi-natural habitats are forecast to be converted to urban land uses worldwide by 2030 (McDonald et al., 2020). One direct consequence of this massive urbanization is the important increase in public and private artificial lighting. In 2016, 83% of the world's population and 99% of Europeans and Americans lived under a light-polluted [1] sky (Falchi et al., 2016). Natural areas are not spared by light pollution, either. In Europe and North America, more than 17% of protected areas have already experienced high levels of light pollution (Gaston et al., 2015). According to the National Agency for the Protection of the Night Sky and Environment, a French association fighting against light pollution, the number of streetlights increased by 89% between 1992 and 2012 in France. The consequences of light pollution, still poorly known by the public and decision-makers (Lyytimäki and Rinne, 2013), are numerous and relate to many areas such as biodiversity, health, astronomic observations and energy consumption.

First, light pollution has many negative impacts on biodiversity (see Hölker et al. (2021) for a recent and comprehensive description of the pressing research questions on this topic). For thousands of years, flora and fauna have adapted to the day/night alternations resulting from the earth's rotation. This alternation is crucial to the biological rhythm and behaviour of species. For species that are active during daylight, night is a period of rest. On the contrary, nocturnal species have developed various adaptations that allow them to be active at night - the bioluminescence of various insects such as fireflies is one example (Sordello et al., 2021). An increasing number of papers show that exposure to artificial lights has many adverse effects on flora and fauna behaviours (foraging, reproduction, orientation, etc). For example, it disturbs the growth or metamorphosis of certain species such as amphibians (Dananay and Benard, 2018) or molluscs (Gao et al., 2017). For other species, such as insects, artificial lighting is an ecological trap because of the power of attraction of lights, which makes them die of exhaustion (Sordello et al., 2021). In addition, it damages or even destroys habitats for species that are averse to light (like certain bats), thereby intensifying the fragmentation of their habitats, as shown by Laforge et al. (2019) in urban areas. The colour of light also influences biodiversity. Although little is known about the sensitivity of various species to different wavelengths (Sordello et al., 2021), research has demonstrated that red, green and blue lights have negative impacts on many species (Sordello, 2017). The overall effects of lighting on biodiversity vary across ecosystems and landscapes and research on this point must be pursued (Barré et al., 2022; Hölker et al., 2021). In any case, even if less regulated than other types of pollution, over-lighting is an important driver of biodiversity loss.

In addition to pressures on biodiversity, artificial lighting has impacts on human societies (Challéat et al., 2021; Challéat and Lapostolle, 2018). First, it can have harmful effects on human health (i) when outdoor lighting illuminates the interior of houses (light trespass), disturbing the sleep of city dwellers (Argys et al., 2020); and (ii) when it emits blue light, which often makes up LED light, disturbing the production of melatonin and therefore the quality of sleep (Davis et al., 2001; Navara and Nelson, 2007), or damaging the retina of the eye (ANSES, 2019). These effects, in addition to other urban nuisances (e.g., urban heat islands, air pollution, noise pollution), have significant effects on the observed rates of obesity, heart disease and cancer (Rajput et al., 2021; Han and Lee, 2021). In addition to health effects, light pollution harms astronomical observations by reducing the visibility of galaxies, nebulae or other astronomical objects (Gallaway et al., 2010).

1. Light pollution refers to excessive or obtrusive artificial light caused by bad lighting design, and includes such things as glare, sky glow, and light trespass (Gallaway et al., 2010)

Finally, lighting wastes energy. In France, the energy consumed by public lighting currently represents 41% of local authorities' electricity consumption. According to the ADEME [2], more than half of the public lighting equipment is obsolete and overconsuming. In the United States, 30% of the electricity produced for outdoor lighting is wasted as light pollution. It represents a cost of almost 7 billion dollars a year (Gallaway et al., 2010). Accordingly, the potential for reducing electricity consumption - and thus CO_2 - emissions is considerable (Gallaway et al., 2010) and crucial for meeting commitments for the signatories of the Paris Agreement. One solution could be new lighting systems, such as LED lighting, showing strong energy-saving benefits. This led a large number of French municipalities to adopt this type of lighting (Sordello et al., 2021). But this blue-coloured lighting, as described above, is particularly disruptive to species and health, leading to a trade-off between energy savings and ecosystem or human health.

The regulation and mitigation of light pollution requires adapted public policies and most likely a shift from the supply-side policy currently applied - *lighting where and when you can* - to a demand-side policy adapted to the population and biodiversity needs. However, the harmful consequences of light pollution are still little-known, and the presence of streetlights is often considered as a form of progress (Lyytimäki and Rinne, 2013). Bright lights contribute to the inhabitant's feeling of safety and to the dynamics of night life and leisure (Challéat and Lapostolle, 2018; Vrij and Winkel, 1991; Boyce et al., 2000; Hanyu, 2000; Painter, 1994; Koga et al., 2003; Blöbaum and Hunecke, 2005; Loewen et al., 1993; Okuda et al., 2007). In France, the light regime shift is a decision made at the municipal level. However, the fear of a strong opposition by citizens (for safety reasons for instance) often leads mayors to avoid making any change (ANPCEN). Moreover, changing the lighting regime can be expensive for municipalities that are subject to budget constraint (e.g. installation of new equipment, information campaign, administrative costs, etc.). Thus, to provide a better design for such policy, decision-makers need to be informed of many parameters, including (i) the factors causing light pollution ; (ii) the priority locations for limiting light pollution in order to conserve or restore a dark corridor for biodiversity [3] ; (iii) the costs and benefits of changing public lighting ; and (iv) residents' willingness to accept a change in lighting regimes. However, to our knowledge, studies that aim to inform public policies on these issues - and in particular on the populations' preferences - are still rare and residents should be sought through questionnaires and other means to understand their needs and uses in this regard (Challéat and Lapostolle, 2018).

Lyytimäki and Rinne (2013) conducted a survey in Finland on the perception of light pollution. Most of their respondents think that light pollution has spread over too wide an area, and a majority (55.7%) think that artificial lighting reduces the quality of life in their neighbourhood. Crossing these results with the respondents' socioeconomic profiles, they find that the denser the area surrounding the respondents, the less they see light pollution as a problem. These results inform on the disutility of light pollution, but do not address the social acceptability and preferences of users regarding adaptation of street lighting.

Some recent studies partially address this question with qualitative surveys. In their article, Silver and Hickey (2020) develop a survey on the advantages and drawbacks of light pollution mitigation for residents. They conclude that a majority supports lighting control, particularly for commercial lighting, and are aware of the impacts of light pollution on health and nature. Lyytimäki and Rinne (2013) find similar results, adding that older respondents (more than 50 years old) are more likely to accept turning off streetlights than

2. ADEME is the French agency for the environment and energy control `https://www.ademe.fr/collectivites-secteur-public/patrimoine-communes-comment-passer-a-laction/eclairage-public-gisement-deconomies-denergie`

3. In France, the notion of Dark corridor (*Trame Noire*) aims at considering and dealing with the fragmentation and loss of natural habitat due to artificial light taking into account human activities (Franchomme et al., 2019).

younger people (31 to 50 years old and less than 30 years old). In France, two qualitative studies in Lille and Paris obtain similar results (Franchomme et al., 2019; Cornet and Touzain, 2021)) : a majority of local residents are in favour of modifying public lighting to reduce disturbances to biodiversity.

In this small literature, very few contributions propose a quantitative analysis to measure the costs and benefits of light mitigation for populations. Mitchell et al. (2017) use a contingent valuation and show that half of the surveyed individuals would be willing to pay for having access to a dark sky (without light pollution). They also show that individuals most exposed to light pollution are the most likely to have a positive willingness to pay (people living in rural areas are less willing to pay than people living in urban or periurban areas). Willis et al. (2005) also use a contingent valuation to measure willingness to pay for improved street lighting in the U.K. and also find that these are higher in urban areas. They use a factor analysis showing that safety concerns represent a significant factor. Simpson and Hanna (2010) use a contingent valuation on a small sample of American students (Rochester city) and find positive willingnesses to pay to improve the visibility of stars at night. Discrete choice experiments (DCEs) are another quantitative nonmarket valuation method that elicits preferences based on repeated fictional choices. Compared to contingent valuation, they include various attributes of a problem in the same study and thus allow to exhibit the tradeoffs at stake. To our knowledge, no DCEs have been published on the issue of light pollution, whereas understanding the tradeoffs between, among others, biodiversity, energy savings and security issues are key to document decision-making. Our work intends to fill this gap.

We use a DCE to address the following questions : are urban citizens willing to accept changes in public lighting and, more importantly, according to which modalities ? More precisely, are they willing to pay, or do they need to receive compensation to accept changes in lighting regimes ? Further, we aim to characterise preferences for the different parameters which make up streetlights (e.g., light intensity, light extinction, light colour), according to citizens' socioeconomic profiles. The DCE permits estimating how changes in the different attributes of public lighting influences the acceptability of individuals. It also allows estimating individuals' willingness to pay (WTP) for or willingness to accept (WTA) the different lighting alternatives. By relating the choices made with the socioeconomic characteristics of residents, this method helps to understand if and when people are willing to accept a change in street lighting. As a result, it can lead to spatially targeted recommendations for changes in lighting that are both useful for biodiversity and acceptable to the population.

We focus on an emblematic case study located in the Montpellier metropolitan area in the south of France. Its proximity with the *Cévennes* national park, registered at the UNESCO as a Biosphere Reserve [4] and retaining the prestigious International Dark Sky Reserve label, makes this area particularly relevant to examine this issue. Moreoever, the effect of light pollution is shown to be affected by the landscape composition and local characteristics, such as the proximity to protected areas (Guetté et al., 2018) or to urban areas (Barré et al., 2022; Laforge et al., 2019; Lapostolle and Challéat, 2021).

We obtained a significant sample of 1,703 respondents. We used several econometric models and retained a latent class model, which enables us to distinguish between two groups of citizens with rather different preferences on public lighting. Both are in favour of improving the lighting regime in principle, but not according to the same modalities. Class 1 respondents (the "anti-change") are broadly against the changes in the modalities presented in the choice sets, while class 2 respondents (the "pro-change") accept them. This is the case for light intensity reduction and for light extinction from 11 p.m. to 6 a.m. We also find that

4. https ://en.unesco.org/biosphere/eu-na/cevennes

respondents who live in periurban areas are more likely to belong to the pro-change (class 2) compared to respondents who live in urban areas.

The remainder of the article is as follow. In Section 2, we detail the design of the choice experiment and the survey that we conducted. Section 3 gives the results of the survey. Finally, we discuss these results in Section 4 and conclude in Section 5.

2. Materials and Methods

2.1. Case study : Montpellier metropolitan area (MMA)

Our study focuses on the Montpellier metropolitan area (MMA). Montpellier is a city located in the department of Hérault, in the south of France. Its population is growing rapidly with more than 290,000 inhabitants in the city itself and 481,000 residents in its metropolitan area, which comprises 31 municipalities.

The MMA land use and land cover is divided in three main parts : natural and seminatural areas (37%), agricultural areas (32%) and urban areas (31%). The level of light pollution is high with a very low sky brightness in the centre of the city of Montpellier (Figure 1) [5]. The MMA is located south of the *Cévennes* national park, which received the International Dark Sky Reserve label in August 2018. This label rewards areas with a starry sky of high quality and where surrounding municipalities and companies are committed to its long-term protection. Given their geographical proximity, the *Cévennes* national park and its Dark Sky Reserve are threatened by light pollution from the MMA.

The MMA manages 75,000 streetlights, most of which were installed without taking into account light pollution and its harmful impacts. Public lighting represents a considerable budget of the MMA with 13.5 million euros per year, including 7 million euros for current expenditures and 6.5 million euros for the modernisation of installations. In order to limit light pollution [6], the MMA is currently developing a "Lighting Plan" (*Plan Lumière*). This plan, in partnership with INRAE [7], has two main objectives. First, it aims at mapping the sources of light pollution and the *Dark corridor* to identify the areas of biodiversity to be preserved. Second, it seeks to identify the needs of the inhabitants in terms of public lighting, which is where our study steps in. To our knowledge, this plan has not yet fully taken into account the specificity of the MMA area and in particular its proximity with the International Dark Sky Reserve of the *Cévennes* national park. These area-based characteristics and the landscape dimension of the issue are however essential as they affect the social perception of light and darkness (Shaw, 2015, 2018), for example regarding the aesthetic and sensitive dimension associated with a starry sky. As suggested by Challéat and Lapostolle (2018), lighting policies should take into account local nocturnal characteristics and consider the needs and uses of individual residents rather than only experts' technocratic opinion. Our work, by incorporating the population's opinion through questionnaires - and trying to explain the individual and local variations of preferences through socioeconomic variables - is a first step towards this objective.

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5. The unit of these measurements is the magnitude per second of arc^2(mag/arcsec^2), which corresponds to the brightness of stars perceived from the ground.

6. Light pollution is an issue whose impacts are increasingly being considered and which is more and more regulated. Article L371-1 of the French Environment Code now stipulates that the Green and Blue Corridor policy must take into account the "management of artificial lights". The French ministerial decree of 27 December 2018 also implements further regulations of light pollution, for example by prohibiting excessively high colour temperatures, or by regulating the orientation of streetlamps.

7. The French national research institute on agronomy and the environment.

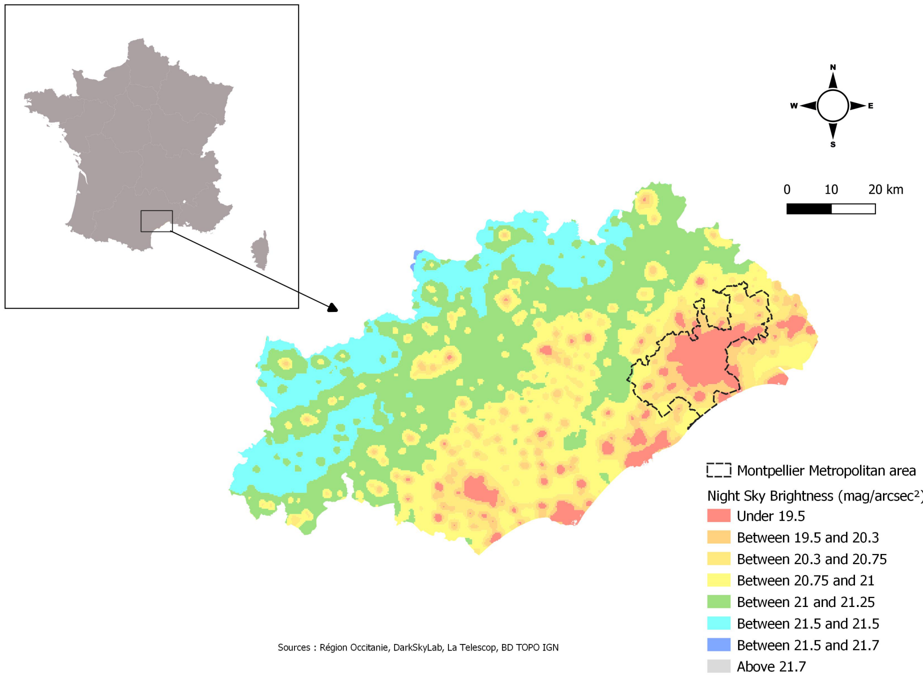

FIGURE 1 – Light pollution map of The Herault

Source : La TeleScop

2.2. The discrete choice experiment

We rely on a discrete choice experiment (DCE) to elicit preferences regarding public lighting. The DCE approach is a stated preference method based on microeconomic theory of consumer choice and nonmarket valuation. Respondents are asked to choose between several options of a good or service, which is defined by its attributes (i.e., the fundamental characteristics that make up the good or service). In our case, the good under study is the lighting profile of a street, and the respondents are the inhabitants of the MMA. A detailed description of the method is provided in Louviere et al. (2000). This method is particularly useful for this study as it permits measuring the relative weight of public lighting's different characteristics in the respondents' opinion.

2.2.1. Choice of the attributes and their levels

First, we need to choose the main attributes that define the street lighting profile and their levels. The number of attributes must not be too high in order to limit the number of alternatives and the cognitive burden for the respondent (Hanley et al., 2002). Moreover, the chosen attributes should have an impact on both the acceptability of the inhabitants and on light pollution. Finally, the attributes must be independent of each other (Mariel et al., 2021). The selection of the attributes was made through (i) the literature on light pollution and social acceptability of the dark corridor policy, (ii) consultation with different professionals in the field of public lighting, and (iii) two focus groups with members of the MMA and with members of the Green and Blue corridor resource centre. Table 1 depicts the five professionals who were interviewed (the first interview was with two people) as well as the two focus groups. During the interviews, the design of the choice was presented to the professionals, who gave their opinion on the attributes and the other questions of the survey. They gave us information on the parameters that influence light pollution, on realistic lighting

Interview number	Description	Date
I1 (Two peoples)	Head of outdoor lighting in Douai & Executive director of AFE (French Lighting Association)	04/06/2021
FG1	Members of the 'Green and blue corridor' resource centre	07/06/2021
I2	Research Analyst (ecologist) at the Urban and Rural Environment Department of the Institut Paris Région. In charge of the *trame noire* project.	11/06/2021
I3	Senior lecturer at the University of Lille	18/06/2021
FG2	Members of the MMA, in charge of (i) public lighting and (ii) biodiversity conservation	24/06/2021
I4	Head of Biodiversity and Land Research at Cerema Méditerranée	30/06/2021

Table 1 – List of conducted interviews and focus groups

regimes and technical constraints, and on the regulations in force. We also had the opportunity to explore the general population's perception of urban lighting through several meetings and discussions with associations representing inhabitants.

Finally, we chose the following attributes and levels. First, the *light intensity*, expressed in the percent of reduction of light intensity. The amount of light emitted has indeed a very strong impact on biodiversity (Matzke, 1936; Gaston et al., 2013; Eccard et al., 2018; Azam et al., 2018; Xue et al., 2020). Moreover, several articles show that a reduction in light intensity negatively impacts the feeling of safety (Vrij and Winkel, 1991; Boyce et al., 2000; Hanyu, 2000; Painter, 1994; Koga et al., 2003; Blöbaum and Hunecke, 2005). We chose two levels for this attribute : no reduction in light intensity and a 75% reduction in light intensity. We represent this attribute with a picture in the choice sets for two reasons. First, it shows to the respondent the initial level of light emitted (in the picture "no reduction in light intensity", see Figure 2). Second, we believe that a picture helps the respondent imagine what a place would look like with reduced lighting, which may limit a potential hypothetical bias. However, the environment's characteristics represented in the picture might affect the acceptability of the light level. Therefore, we choose a picture where there is just a house that can apply to a narrow or a wide street, in an urban or rural area.

Second, we chose the attribute *Light extinction* : Pauwels et al. (2021) point out that light extinction during certain hours is the most effective way to reduce the effects of light pollution. It is also a key parameter for the feeling of safety (Loewen et al., 1993; Okuda et al., 2007), and therefore for social acceptability. The hours during which streetlights are switched off are crucial for nocturnal species. Many species have a peak of activity at dusk or dawn rather than in the middle of the night. This is the case for bats (Azam et al., 2018; Day et al., 2015). Ideally, light extinction should be carried out as early as possible (Sordello et al., 2021). We chose three levels : no light extinction, light extinction between 1 a.m. and 5 a.m., and light extinction between 11 p.m. and 6 a.m. As the survey took place during the summer, we did not include a "10 p.m. to 6 a.m." level as the sun has sometimes not set at 10 p.m. and, therefore, the streetlights are not on.

The third chosen attribute was the *colour of the light* emitted, which can also have an impact on certain species. Sordello et al. (2021) recommend reducing harmful wavelengths such as the colour blue, and to favour orange-coloured lights which are less harmful to nocturnal biodiversity and to humans. Some articles show that the colour emitted by outdoor lighting has an impact on the feeling of safety, although the results differ [8]. The colour of light depends on its temperature : the higher the temperature, the bluer the colour. In France, regulations prohibit the installation of lamps with a temperature above 3000 K. Therefore, we chose two

8. Some studies show that lamps with a white or bluish colour increase the feeling of safety compared to lamps with an orange colour (Morante, 2008; Akashi et al., 2008; Knight, 2010). Portnov et al. (2020) show the opposite.

levels for this attribute : orange colour (which corresponds to a temperature of about 1500 K) and neutral white colour (3000 K). We represent these levels by means of a picture, because we believe that it makes it easier for the respondents to imagine the rendering of lighting.

Last, we chose the variation of the *residence tax* as the monetary attribute. We believe that a variation of the residence tax is credible enough in our case. This tax is transferred to the municipality, which is responsible for outdoor lighting. Moreover, the residence tax is paid by every citizens, unlike other local taxes such as the property tax, the television licence fee, or the waste disposal tax. However, the residence tax was removed in France in 2020 for 80% of the households and will not affect any households by 2023. Consequently, we call this attribute "Change of the residence tax or other equivalent tax". The levels of this attribute are -30 €, -10 €, 0 €, 10 € and 30 €. We chose to include both positive and negative values for the monetary attribute for two main reasons. First, the reaction of residents to the modification of "lighting profiles" can be ambivalent. Some residents may see advantages (e.g., reduction of light pollution, reduction of energy consumption), and, thus, may be willing to pay for a change in streetlighting. On the contrary, others may be reluctant, especially as it could weaken their feeling of safety, and they may need to receive compensation to accept a change. Second, the financial consequences of the change of streetlighting is ambiguous for the municipality. On the one hand, it can save energy and consequently money, if electricity prices stay stable. On the other hand, it is costly (e.g., equipment and installation costs, information campaigns, regulatory costs). The attributes and their levels are summarised in Table 2 and Figure 2 shows an example of a choice set, on which respondents must choose their preferred situation.

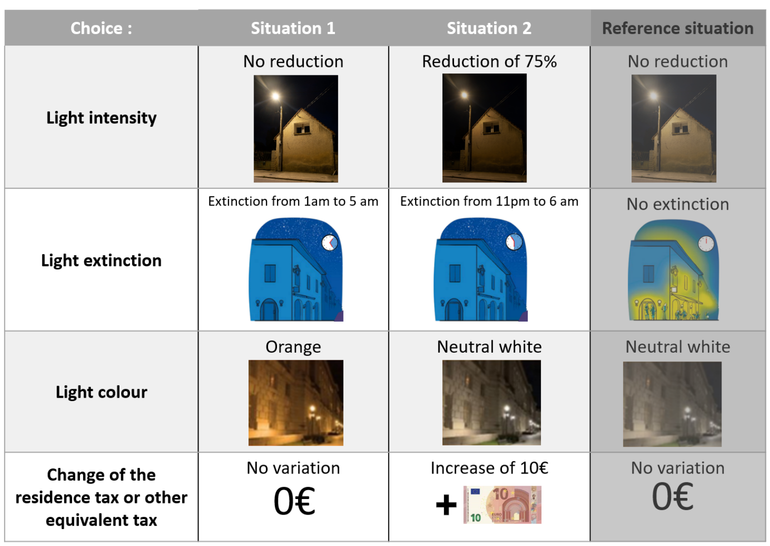

Figure 2 – Example of a choice set

We initially considered two other attributes which were finally not included : the direction and the height of the lights. The former plays a crucial role in the reduction of light pollution. If the streetlamp is badly oriented, light can be emitted towards the sky, thus creating a halo of light. Knowing the social acceptability

9. For the sake of clarity in interpreting the results, we reverse the coding from that of INSEE (the variable "Communal density" thus increases with density). Besides, in the MMA, there are no municipalities classified as 4 by the INSEE and only 8 respondents live in a municipality classified as 3, so we decided to group them with municipalities classified as 2 ("intermediate density"). Regarding France, few respondents live in a municipality classified as 4 by the INSEE, so for our simulation throughout France (section 4.1.2), we grouped them with municipalities classified as 3 ("sparsely populated").

Variable name	Description	Level	Coding
Attributes			
Intensity reduction	Reduction of light intensity, in percentage (%)	75% 0%	75 0
Light extinction	Time of light extinction	Extinction2 : Extinction from 1a.m. to 5a.m. Extinction3 : Extinction from 11p.m. to 6a.m. No extinction	1 if Extinction2, 0 if Extinction3 1 if Extinction3, 0 if Extinction2 *(Reference -1)*
Colour	Colour of the light	Orange Neutral white	1 if Orange *(Reference -1)*
Tax	Variation in resident tax or other equivalent tax	-30 € -10 € 0 € 10 € 30 €	-30 -10 0 10 30
Socioeconomic variables			
Gender	Gender	Woman Man Other	1 2 3
Age	Age	19-30 years old 31-50 years old 51-65 years old More than 66 years old	1 2 3 4
Children	Whether or not the respondent has children	No children Has children	0 1
Communal density [9]	Communal density grid created by the INSEE, which assigns to each municipality a number between 1 and 4 (1 : "densely populated", 4 : "very sparsely populated")	Densely populated Intermediate density Sparsely populated Very sparsely populated	1 (2 in section 4.1.2) 0 (1 in section 4.1.2) (0 in section 4.1.2) -
Extinction profile	Whether or not the municipality already switches off streetlights	No light extinction Light extinction	0 1
Income	Individual's net income (in thousands)	Less than 1400 € 1400 € to 2000 € 2000 € to 3000 € More than 3000 €	0.7 1.7 2.5 3.5
Other variable			
ASC	Reference situation	Fictive situation 1 or 2 Status quo	0 1

Table 2 – Description of attributes, levels and socioeconomic variables

of the direction of lights would have been interesting. However, in France, the ministerial decree of December the 27th 2018 already states that the proportion of light emitted by streetlamps above the horizontal must be strictly less than 1%. The levels of this attribute should have complied with the decree, which would have made the difference between levels insignificant. The height of lamps also plays an important role in limiting light trespass and the impact of light pollution (Pauwels et al., 2021). According to Heinrich (2018), the height is often too high compared to what is needed. Higher lighting increases the likelihood of illuminating an area that does not need to be illuminated, for example at the edges of roads or streets (Rivier, 2020). However, this attribute cannot be subject to many changes as it is regulated to 4 to 6 meters for pedestrian ways in France. Moreover, following the focus groups, we consider that people do not differentiate between these heights, and that this attribute would not have impacted their choices much.

One of the aims of this study is to guide public decision which explains why our attributes were determined in collaboration with decision makers, in order to be realistic and feasible. We are aware that lighting's social acceptability is not only a technical matter and includes aesthetic and sensorial perception of individuals. Although the chosen attributes are of a technical nature, some of them (colour, light intensity..) have direct aesthetic/sensorial consequences that respondents may take into account when making their choices. Moreover, as a complement to the choice experiment, aesthetic and sensorial considerations were explored in follow-up questions on the role of stargazing, the perception of light with dense vegetation or the feeling of safety (see the questionnaire in the Supplementary materials for more details).

In the choice sets, we included a *status quo* alternative which corresponds to a reference situation with no lighting changes : no reduction in light intensity, no light extinction, neutral white light and no variation in the resident tax (Figure 2, last column). We did not choose an individual *status quo* ("I prefer to keep my current situation"), with which the individual would refer to her own situation, because we believe that many people do not know precisely the lighting parameters of their street, especially the colour and intensity of the light. We believe that people who live in municipalities that have already changed their lighting regime (for example with light extinctions) can still easily take the no-change situation as a reference.

The discrete choice experiment is presented as a role-playing. First, respondents are asked which transport they use to travel at night, between walking and cycling/scootering, as acceptability may differ depending on the type of transport. For example, a pedestrian might fear an attack, while a cyclist might fear a fall because of a lack of visibility. Respondents are told to imagine themselves walking (or biking/other) at night in a residential area, in the current period (summer) [10].

2.2.2. Experimental design

The purpose of the experimental design is to define the alternatives and the choice sets that are presented to respondents. Since we have 4 attributes, each with 2 to 5 levels, the full factorial design is equal to 60 combinations, which is a too heavy cognitive burden for respondents. Therefore, we choose the most relevant combinations in order to obtain as much information as possible on respondents' preferences while limiting the number of choice sets. We first used the SAS software to determine the optimal number of choice sets that can be shown to respondents. We found a number of 6 or 9 choice sets. This is in line with what is advised in the Ngene user manual, which states that the number of choice sets should be greater than $\frac{K}{J-1}$ with K being the number of attributes (4 here) and J being the number of non-*status quo* alternatives (2

10. The season can play an important role in respondents' choices because, in France, the times of sunset and sunrise vary radically. The type of neighbourhood is also important : a survey conducted by the Paris Region Institute shows that the acceptability of a change in the lighting regime varies greatly according to where one lives (Cornet and Touzain, 2021). People living in city centres that are bustling at night seem more reluctant to switch off lights than those living in residential areas.

here), i.e., 4 in our case. Following pretests indicating that the cognitive load was acceptable, we chose to display 9 choice sets without blocking. We used the Ngene software to obtain a statistically optimal subset of combinations based on a Bayesian D-optimal efficient design (see experimental design techniques in Louviere et al., 2000; Street et al., 2005). The exact code used for the experimental design as well as the 9 choice sets are available upon request.

2.3. Presentation of the survey and data collection

The DCE was circulated as an online survey from July 16th to September 10th 2021. The survey was public and open to the entire French population, but we favoured circulation to the MMA. We used several channels to optimise our chances of obtaining a significant and representative sample, including social networks, associations and town halls.

The survey lasts around 15 minutes and contains several parts [11]. First, the respondents are informed of the consequences of light pollution on several areas (biodiversity, health, energy), and about the possible means to change outdoor lighting to limit light pollution. We chose to provide this information because we assume that a municipality wishing to modify its public lighting would launch an information campaign on the consequences of light pollution. Furthermore, respondents are not forced to read the text. The software that we used for the survey, LimeSurvey, provides the time spent by each respondent on each section of the survey. Therefore, we used the time spent on the information section as a proxy of the respondents' level of information on light pollution, in order to estimate the impact of this information on the social acceptability of lighting regimes. Second, respondents are presented with questions about their socioeconomic characteristics (e.g., gender, age, income, children, socioprofessional category). Then, the 9 choice sets are presented. They are displayed in a random order to avoid that a possible decrease in concentration always affects the same choice sets (the last ones). After the choice experiment, respondents are presented with questions to identify protest responses. Finally, in the last part, they are asked about their use of the public space at night (e.g., frequency of outings, night work), their aesthetic perception of light and their sensitivity to environmental issues. These questions help to understand the respondent's preferences, but they are not compulsory, so they come at the end to avoid losing answers if the respondents find the questionnaire too long.

3. Results

3.1. Sample characteristics

We collected 1,703 complete answers out of 2,991 answers in total. Among the complete answers, 1,134 were from the MMA (66.6%). We included 35 answers of respondents who did not entirely complete the survey but who stopped after the choice experiment. We excluded some inappropriate answers : protest answers [12] and low-quality answers. We used three criteria which, when simultaneously verified, identify protest answers or rejection of the survey : (i) respondents who systematically choose the *status quo* ; (ii) those who answered "No" to the question "Regardless of the context, are you in favour of a change in the lighting regime ?" ; and (iii) those who spent less than 140 seconds on the choice experiment. The last criterion is based on the assumption that less than 140 seconds confirms a disinterest in the survey as it is too short to answer

11. The survey is available in the supplementary material.
12. According to Strazzera et al. (2003), excluding protest answers may induce some selection bias as the discarded respondents may have WTPs that are very different from the average. These authors propose statistical methodologies to include these protest answers in the estimates in contingent valuation. However, to our knowledge these do not apply to DCEs and the state of the art in the DCE literature recommends to exclude protest answers (Louviere et al., 2000; Mariel et al., 2021).

conscientiously the DCE (Börger, 2016). To avoid low-quality answers, we also excluded respondents who spent less than 60 seconds on the choices whatever their other answers, as this very short time cannot be compatible with the cognitive burden of the questionnaire. Finally, we excluded people younger than 18 years old. Following these criteria, we excluded 21 responses from the final sample ; respondents from the MMA are reduced to $1,134+35-21 = 1,148$ respondents. Figure 3 depicts the number of respondents per municipality of the MMA. It is proportional to the population of the municipalities, with minor exceptions. See Table 6 and section 4.1.1 for an extensive discussion on the sample's representativeness and associated robustness checks.

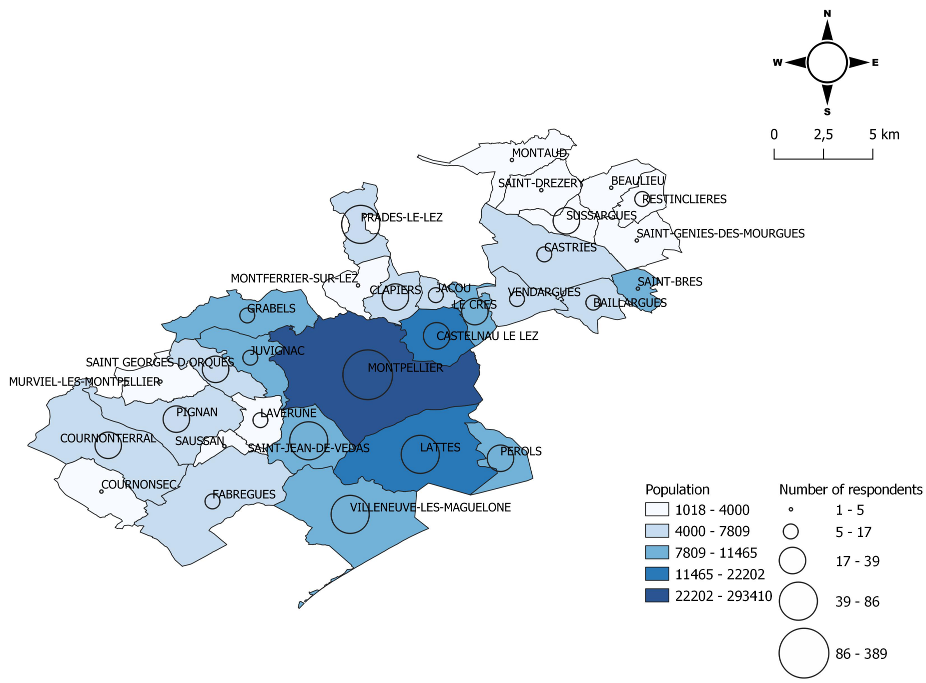

Figure 3 – Number of respondents per municipality in the MMA

3.2. Econometric analysis

3.2.1. Choice of the model

We used a latent class model to analyse our data. The principles and details of the econometric specifications are presented in section 3.2.2. The latent class model was preferred to the random parameter logit (RPL) [13], also known as mixed logit, because we observed strong heterogeneity in preferences and potential distinct classes of respondents for some attributes. While the RPL allows us to obtain the mean and distribution of the parameters accounting for preference heterogeneity, the latent class model is better at explaining heterogeneity due to classes of respondents. From a policy support perspective, it is particularly interesting to characterise these differences in preferences and identify these classes.

We used effects coding instead of dummy coding for the categorical variables (light extinction and colour) [14] : light extinction from 1 a.m. to 5 a.m. and from 11 p.m. to 6 p.m. are coded as -1 if the level of

13. The results of the RPL model are available from the authors upon request.

14. With dummy coding, the effect of the levels characterising the *status quo* is captured by the constant term. The use of *effects coding*, therefore, makes it possible to interpret the utility of the *status quo* as such, and not to confound the coefficients

the alternative is "no light extinction", and the orange colour is coded as -1 if the level of the alternative is "neutral white" (Table 2).

We used the STATA command *lclogit*, created by Pacifico and Yoo (2013), to compute the latent class model. First, we found the number of classes of our model using the AIC and BIC criteria as well as the predictive quality of the model, which led us to opt for a two-class model (see Table 3) [15]. The estimation with two latent classes is presented in Table 4.

	Number of classes			
	2 classes	3 classes	4 classes	5 classes
Log-Likelihood	-7774.8	-7412.1	-7256.2	-7160.7
AIC	15575.5	14864.2	14566.5	14389.5
BIC	15641.1	14965.1	14702.7	14561.0
Predictive quality (%)	99.1	92.8	89.9	88.2

TABLE 3 – Information criteria and model selection

3.2.2. Econometric specification

Similarly to the RPL model, the latent class model has two main advantages compared to the Conditional Logit : (i) it allows for heterogeneity - in other words, it assumes that parameters (i.e. β's) can vary from one individual to another - which is useful to take into account individual specificities and (ii) it frees from the IIA (Dahlberg and Eklöf, 2003; Brownstone and Train, 1999). However, contrary to the RPL model, the latent class model frees from making assumption on the distribution of preferences among the population. Instead, it allows for unobserved preference heterogeneity with membership in latent classes of preferences. It relies on the assumption that the population is divided in Q subgroups (or classes). Individuals in a given class are assumed to have homogeneous preferences, but these preferences differ from individuals belonging to other classes (Pacifico and Yoo, 2013). The probability that individual n chooses alternative i in the choice situation t given that he belongs to class q is :

$$P(y_{nt} = i|class = q) = P_{nt|q}(i) = \frac{exp(X'_{nit}\beta_q)}{\sum_{j=1}^{J} exp(X'_{njt})\beta_q}$$

For a given class q, individual n's contribution to the likelihood would be :

$$P_{n|q} = \prod_{t=1}^{T}\prod_{j=1}^{J}(P_{nt|q})^{y_{njt}}$$

where y_{nit} is a binary variable equal to 1 if agent n chooses alternative j in scenario t, and equal to 0 otherwise.

when the levels of the attributes of the alternatives intersect with the levels of the ASC variable (Bech and Gyrd-Hansen, 2005; Mariel et al., 2021).

15. Although the model with two classes has the largest AIC and BIC, its predictive quality is much higher than that of the others.

Class assignment is unknown. Greene and Hensher (2003) note H_{nq} the prior probability that individual n belongs to class q :

$$H_{nq} = \frac{exp(z_n'\theta_q)}{\sum_{q=1}^{Q} exp(z_n'\theta_q)}, q = 1, ...Q, \theta_Q = 0$$

where z_n is a set of observable agent-specific characteristics which impact class membership, like socioeconomic characteristics, and θ_q are class membership model parameters. The likelihood for individual n is :

$$P_n = \sum_{q=1}^{Q} H_{nq} P_{n|q}$$

The log-likelihood for the sample is :

$$ln(L) = \sum_{n=1}^{N} ln(\sum_{q=1}^{Q} H_{nq} P_{n|q})$$

Individual-specific estimate

After estimating θ_q, we can obtain, for each individual, the probability that he/she belongs to class q given her answers to the choice sets. The posterior membership probability is estimated as follows :

$$\hat{H_{q|n}} = \frac{\hat{P_{n|q}} \hat{H_{nq}}}{\sum_{q=1}^{Q} \hat{P_{n|q}} \hat{H_{nq}}}$$

Influence of auxiliary variables on class membership

The latent class model identifies homogeneous groups in terms of individuals' preferences for the different attributes that make up a good. It can be assumed that certain socioeconomic variables influence the membership of individuals in these groups. To find out this influence, we regress the posterior probability $\hat{H_{q|i}}$ on A auxiliary variables :

$$log(\frac{\hat{H_{q|n}}}{1 - \hat{H_{q|n}}}) = \beta_1 X_1 + ... + \beta_A X_A$$

Willingness to pay

The willingness to pay (resp. to accept) for a unit change in an attribute is the marginal rate of substitution between this attribute and the monetary attribute (Chèze et al., 2020). It estimates the amount of money that an individual is ready ot pay (resp. to accept) in compensation of (resp. in exchange for) a change in an unit of an attribute, so that her utility stays unchanged. The WTP (resp. to accept) is estimated as follows :

$$WTP_k = -\frac{\beta_{X_k}}{\beta_{tax}}$$

where β_{X_k} is the estimated coefficient for the considered attribute X_k and β_{X_tax} is the estimated coefficient for the monetary attribute. As we use effect coding, the estimation of WTP for categorical variables (colour and light extinction) is slightly different :

$$WTP_k = -\frac{2\beta_{X_k}}{\beta_{tax}}$$

3.2.3. Class membership analysis

We tested the class membership with several variables : gender, age, whether the respondent has children, communal density, extinction profile of the municipality, income and main mean of transport. We identified two distinct groups of respondents. As shown in Table 4, class 2 includes many more respondents than class 1 (80% compared to 20%). The probability of belonging to class 1 compared to class 2 increases when the individual lives in a very dense municipality rather than a municipality of intermediate density (i.e., individuals living in periurban areas are more likely to belong to class 2 than those living in urban areas). Another significant membership coefficient is the one associated with *Biking* : people who cycle rather than walk at night are more likely to belong to class 2 than class 1. The other membership variables are not significant. To summarise, the typical profile of class 1 respondent is a person that lives in dense municipality like urban area and that walk rather than cycle at night. On the contrary, people in class 2 are more likely to be periurban inhabitants that cycle more than class 1.

3.2.4. Class preference analysis

In both classes, respondents' utility decreases when the resident tax increases, which is unsurprising and consistent with the mixed logit results. Apart from this monetary attribute, class 1 and class 2's respondents have quite different preferences. The coefficients associated with *Intensity reduction* are both significant, but of opposite signs. Respondents belonging to class 2 prefer a reduction of light intensity, while class 1's utility decreases when reducing light intensity. The coefficients for *Extinction2* and *Extinction3* are significantly positive for class 2 : they value light extinction both from 1 a.m. to 5 a.m. and from 11 p.m. to 6 a.m., with a preference for the former indicated by its larger coefficient. On the contrary, respondents belonging to class 1 are opposed to light extinction from 1 a.m. to 5 a.m. and even more strongly opposed from 11 p.m. to 6 a.m. Respondents in class 2 have a weakly significant preference for an orange-coloured light, whereas this attribute is insignificant for class 1.

Overall, these results allow us to identify two different preference profiles. Respondents in class 2 (hereinafter, "the pro-change" in public lighting) are in favour of all the presented changes : reduction of light intensity, modification of the colour of the light to orange, and light extinction from 1 a.m. to 5 a.m. as well as from 11 p.m. to 6 a.m. On the contrary, respondents in class 1 (hereinafter, "the anti-change" in public lighting) are indifferent to a change in light colour and opposed to the three other presented changes.

These results show that the pro-change (class 2) seem more sensitive to light pollution and/or less prone to safety problems ; they are thus more willing to change street lighting (which is confirmed by their strongly significant negative ASC coefficient). This is consistent with the fact that people living in periurban areas (more likely to belong to class 2) are less prone to safety and crime problems as they often travel by car/bike and go less outside at night. Moreover, people travelling by bike are more likely to belong to pro-change (class 2) than people walking. They might have a higher feeling of safety when travelling at night, because they are less prone to attacks than people travelling by foot [16].

In both cases, the *ASC* coefficient is negative and significant, indicating that respondents in both classes are reluctant to stay in the reference situation and are willing to change street lighting. This shows that class 1's respondents (the anti-change) are also ready to change lighting ; they might be sensitive to the issues raised by light pollution or energy consumption, but they are also sensitive to safety problems. They are willing to change but only under certain conditions and not in the way that we propose. The *ASC* coefficient

16. However, this variable may also capture the fact that people using a bicycle are more sensitive to environmental issues and are therefore more willing to make efforts to combat light pollution.

	Dependent variable :	
	Choice	
	Class 1	Class 2
	Coefficient	Coefficient
	(S.E.)	(S.E.)
Attributes		
Intensity reduction	-0.006***	0.008***
	(0.001)	(0.000)
Extinction2	-0.146*	0.282***
	(0.076)	(0.034)
Extinction3	-1.312***	0.163***
	(0.097)	(0.035)
Colour	0.045	0.076*
	(0.060)	(0.042)
Tax	-0.034***	-0.052***
	(0.003)	(0.006)
ASC	-0.361**	-2.321***
	(0.147)	(0.172)
Membership		
Gender2	-0.036	Ref.
	(0.168)	
Gender3	1.261	Ref.
	(1.430)	
Age	0.174	Ref.
	(0.109)	
Communal density	0.386**	Ref.
	(0.188)	
Extinction profile	0.057	Ref.
	(0.271)	
Children	0.083	Ref.
	(0.170)	
Time introduction	-0.000	Ref.
	(0.000)	
Income	0.053	Ref.
	(0.100)	
Biking	-1.048***	Ref.
	(0.255)	
Constant	-2.192***	Ref.
	(0.433)	
N (obs.)	30672	
N (ind.)	1136	
Log Likelihood	-7694	
AIC	15432	
CAIC	15565	
BIC	15615	
Preditive quality	99%	
Class membership (%)	19.7	80.3
Note :	*p<0.1 ; **p<0.05 ; ***p<0.01	

Table 4 – Latent class model results

is much larger for the pro-change (class 2), almost 6 times higher than the anti-change (class 1), which means that respondents in this class are much more willing to change street lighting.

3.2.5. Descriptive statistics on class membership

We estimated the posterior membership probability, i.e., the probability of an individual belonging to a class knowing her answers to the choice experiment (see Appendix A, more graphs are available in the supplementary material). This allows us to make descriptive statistics on certain answers to the survey, to better understand respondents' preferences. As these questions are optional, we did not add them to the regressions to avoid losing too much data.

We observe that the anti-change (class 1) are more likely to use public space and streets at night (78.5% travel at night in class 1 compared to 70.6% in class 2). They also work more often at night (46.3% in class 1 compared to 34.5% in class 2). This obviously explains their reluctance to turn off street lighting compared to the pro-change (class 2).

Both classes are also different with regards to their sensitivity to environmental issues. 66.3% of the pro-change (class 2) say that they care very much about environmental issues, while this share represents 38.3% for the anti-change (class 1). These results are consistent with the greater willingness of respondents in class 2 to reduce light pollution.

Light trespass also seems to be a factor explaining differences in preferences : 69.7% of the pro-change (class 2) report to be bothered by light trespass in their home, compared to only 39.0% for the anti-change (class 1).

Finally, our results show the importance of the feeling of safety in the social acceptability of public lighting changes. People belonging to the anti-change (class 1) have a lower feeling of safety than the pro-change as 66.3% agree that they live in an area where there are safety risks due to inadequate lighting, against 24.6% in class 2.

3.2.6. WTP estimates

Using the formulas given in section 3.2.2 and the coefficients found in Table 4, we estimated an average WTP by attribute and by class, only for significant coefficients (see Table 5).

The pro-change (class 2) are ready to pay an additional 0.15 € of annual resident tax for each extra percentage of reduction in light intensity. This WTP is negative for respondents of class 1 (anti-change) : they need to receive 0.16 € for each extra percentage of reduction in light intensity. As a result, the pro-change (class 2) are, on average, willing to pay 11.25 € per year to reduce light intensity by 75% and the anti-change need to receive, on average, 12 € per year for the same 75% reduction. The large WTPs for light extinction show that this attribute is a dominant criterion for our respondents' decisions. The pro-change (class 2) are ready to pay almost 11 € annually to turn off streetlights from 1 a.m. to 5 a.m. and 6.3 € to switch them off from 11 p.m. to 6 a.m. On the contrary, the anti-change (class 1) need to receive 76.73 € annually to accept light extinction from 11 p.m. to 6 a.m., but only 8.58 € to accept it from 1a.m. to 5 a.m. Individuals in class 2 (the pro-change) are ready to pay 2.92 € to change the colour of the light from white to orange. Finally, the pro-change need to receive, on average, 90 € per year to agree to stay in the reference situation (no change in public lighting) while the anti-change need to receive 21 €.

	Average WTP estimates (€)	
	Class 1	Class 2
Intensity reduction	-0.167	0.157
Extinction2	-8.58	10.91
Extinction3	-76.95	6.30
Colour	*Not significant*	2.92
ASC	-21.16	-89.78

Table 5 – Average WTP estimates for the latent class model

4. Discussion

4.1. Robustness checks

We conducted various robustness tests of our results. In this section, we present the most important ones : the sample selection bias and the comparison with France. The other tests that have been conducted are related to the influence of the physical characteristics of the street (narrow street / large street), and to partial answers. They are available in the supplementary material.

4.1.1. Sample selection bias

As shown in Table 6, the sample over-represents some categories of the MMA population. Globally, the survey reached more women, managers and professions requiring higher educational levels. The latter are found to be one of the most sensitive categories of the population to environmental issues (Dron, 2011). Thus, they are more likely to be willing to answer a survey on this issue and self-select themselves. As for women, this survey was circulated internally at the MMA, whose employees are mostly women. On the contrary, some categories of the population were much more difficult to reach. This is the case with blue-collar workers and individuals older than 66 years old. An obvious disadvantage of online surveys is the potential exclusion of people with limited computer skills or limited access to the internet. According to the French National Institute of Statistics and Economic Studies (INSEE), in France in 2019, 77% of the population had access to the internet, which varies with the age of the population : over 90% of the 15-29 years old, while only 52% of people aged 60 years old and over. It is thus more difficult to reach the 66+ age group with an online survey. In general, it is highly likely that the people who opened and answered the survey are more sensitive to the environment than the rest of the population. To check the extent of this bias, we compared the answers to the question "In general, are you concerned about environmental protection ?" in our survey with the results of a study carried out by the CGDD [17] on the opinion of French citizens on the environment in which respondents are asked to rate their level of sensitivity to the environment on a scale of 1-7. The average for 2019 is 5.16/7. To compare this figure with our results, we coded the answers to our question "In general, are you concerned about environmental protection ?" as follows : "Not at all" = 1, "Not too much" = 2, "Yes, but not more than other topics" = 3, "Yes, a lot" = 4. We found an average of 3.57/4, which corresponds to an average of 6.25 out of 7. This confirms the fact that our sample has a slightly higher sensitivity to the environment than the general population. Therefore, we must be careful when interpreting the results and take this bias into account.

In order to obtain a representative sample of the MMA's population, we used the raking ratio method to adjust the sample, with the package "Icarus" in R (Rebecq, 2016). More precisely, we used the penalised

17. The Commissariat Général au Développement Durable is a department of the French Ministry of Ecological Transition.

Variable	Share in the sample (MMA respondents)	Share in the population of MMA (2018)	Share in the sample after recalibration (raking ratio)
Gender			
Female	64.0%	53%	53.1%
Male	35.8%	47%	46.9%
Other	0.2%	-	-
Age			
19 30 y.o.	10.1%	27.9%	27.7%
31 50 y.o.	56.8%	32.3%	32.9%
51 65 y.o.	27.8%	19.9%	20.5%
More than 66 y.o.	5.2%	19.9%	19.0%
Socio-professional category			
Farmer	0.1%	0.1%	0.3%
Craftsmen, traders, entrepreneurs	3.2%	3.7%	4.4%
Managers and higher-educational professions	37.0%	12.6%	14.0%
Intermediate professions	13.2%	15.9%	16.7%
Employees	34.6%	15.1%	16.4%
Workers	0.7%	7.8%	5.0%
Pensioners	7.9%	20.9%	21.4%
Others without professional activity	3.3%	24.1%	21.8%

Table 6 – Sociodemographic comparison of the samples before and after calibration

calibration method to facilitate the convergence of the procedure. We adjusted the sample according to three variables : gender, age and socio-professional category [18]. The new characteristics of the sample (after assigning the new weights) are presented in Table 6, last column. Weighting regressions is not an obvious issue. To find out whether weighting was a good idea, we relied on the article by Davezies and D'Haultfoeuille (2009). Based on this article, we chose to check the robustness of our regressions by weighting them. The results of the weighted latent class model are presented in Table 7.

When we compare the results of the weighted and unweighted latent class models, we see that some results are slightly different. Although preferences in class 2 (pro-change) are very similar, they change slightly in class 1 (anti-change). Respondents in this class seem to no longer care about light intensity reduction, as shown by the insignificant coefficient. The coefficient associated with the ASC, which was weakly significant, becomes insignificant, showing that individuals in class 1 are undecided on whether they globally want to change the lighting regime or not. These results do not modify the conclusions obtained in the unweighted regression and only strengthen the idea that respondents in class 1 (anti-change) are more hesitant about changing public lighting than the others.

Regarding variables that influence membership, the communal density becomes insignificant while age becomes significantly negative, indicating that older respondents are more likely to belong to class 1 (the anti-change). This is consistent with the fact that older people may be more sensitive to safety and visibility concerns associated to light reduction.

18. We remove the gender category "Other" from the sample because this gender category is not available in French national statistics.

	Dependent variable :	
	Choice	
	Class 1	Class 2
	Coefficient	Coefficient
	(S.E.)	(S.E.)
Attributes		
Intensity	-0.001	0.007***
	(0.002)	(0.001)
Extinction2	-0.235	0.260***
	(0.146)	(0.069)
Extinction3	-1.116***	0.170**
	(0.182)	(0.079)
Colour	0.134	0.099
	(0.110)	(0.093)
Tax	-0.030***	-0.052***
	(0.006)	(0.013)
ASC	0.172	-2.352***
	(0.276)	(0.338)
Membership		
Gender	Ref.	-0.186
		(0.231)
Age	Ref.	-0.314**
		(0.130)
Communal density	Ref.	0.303
		(0.270)
Extinction profile	Ref.	0.303
		(0.394)
Children	Ref.	0.073
		(0.262)
Time introduction	Ref.	0.000
		(0.000)
Income	Ref.	-0.000
		(0.000)
Bike	Ref.	1.285***
		(0.350)
Constant	Ref.	2.834***
		(0.577)
N (obs.)	30,618	
N (ind.)	1134	
Log Likelihood	-3188415	
AIC	6376872	
CAIC	6377047	
BIC	6376998	
Predictive quality	99.2%	
Class membership (%)	19.8	80.2
Note :	*p<0.1 ; **p<0.05 ; ***p<0.01	

TABLE 7 – Weighted latent class model

4.1.2. Comparison with France

We have so far focused on the answers of MMA residents. This region has its own particular characteristics, and it would be interesting to study whether the results are similar throughout France. Thus, we computed our model using the answers of respondents who do not live in the MMA [19]. The characteristics of this sample and the comparison with the characteristics of the French population are presented in Appendix B.1. Similar to the MMA sample, the national sample over-represents some categories of the French population, particularly the 19- to 30- and 31- to 50 years old categories, as well as managers. On the contrary, categories of people who are more than 66 years old and workers are under-represented.

The results of the regression on the national sample are presented in Appendix B.2. We did not include the *Extinction profile* (profile of the municipality) variable in these regressions because we do not have this information for all the municipalities in France. Even if we observe the same polarization in two classes, we observe slight differences between both regressions regarding the anti-change (class 1)'s preferences. They are still strongly opposed to light extinction from 11 p.m. to 6 a.m., but become in favour of light intensity reduction and of light extinction from 1 a.m. to 5 a.m. The variables that influence membership are also different. The variable *Gender2* becomes significant, with a positive sign, which means that men are more likely to belong to class 2 (the pro-change), and therefore to be in favour of light extinction from 11 p.m. to 6 a.m. Women may feel more sensitive to security issues compared to men. The variable *Age* also becomes significantly positive, meaning that older people are more likely to be in favour of light extinction from 11 p.m. to 6 a.m. than younger people. This is consistent with the results found by Lyytimäki and Rinne (2013), but not with those in the MMA weighted sample, nor with Mitchell et al. (2017), who find that people over 65 years old are less likely to be willing to pay for a dark sky, which means that they are less likely to want less light [20]. Two main effects explain these opposite results. On the one hand, older people are less likely to use public space at these hours and to need lighting - which is consistent with the results that we find in the French sample. On the other hand, they may feel more vulnerable *vis-à-vis* a potential attack or visibility and thus have a higher sense of insecurity when walking down a street, which may be exacerbated by light extinction. In this model, with the French sample, the former effect prevails over the latter, while the opposite is observed for the model with the MMA sample.

4.2. Understanding the reluctance of the population

It is crucial to understand why citizens may be reluctant to change public lighting. In our survey, we included an open question on the disadvantages of such changes. We analysed the answers to this question by classifying them into categories according to the main arguments of the answer. Although imprecise, this analysis gives a first idea of the main reasons for the potential reluctance of respondents to change lighting regimes and allows to explore the sensorial perception of respondents. Out of the 1,146 respondents in our sample, 349 answered this optional question. Sixty-one of them stated that they did not see any drawback to making changes in street lighting. The vast majority of the respondents mentioned problems of safety (186) or a decrease in the feeling of safety (70). Fifty-eight pointed out that they feared an increase in crime (assaults and burglaries), and 37 feared road safety issues. Twenty-one mention women in their answer, suggesting that they were more prone to being concerned about security problems. This argument

19. As explained in Table 2, we grouped here the municipalities "sparsely populated" and "very sparsely populated"

20. Age is an important factor to consider as older people are often more likely to vote than younger ones, so their opinion can have more weight in public policy decisions. Note that Willis et al. (2005) also examine the role of age in the willingness to pay for reduced light pollution and find it to be statistically insignificant.

supports our interpretation above of the interaction coefficient between gender and light extinction from 11 p.m. to 6 a.m. Other arguments were mentioned to a lesser extent, such as the reduction in visibility and the fear of falls or the cost of the policies. Informational campaigns on the consequences of changes in public lighting, particularly on safety, could therefore be useful in order to reassure the population, in addition to implementing the necessary measures to prevent an increase in crime.

4.3. Policy recommendations

Based on our results, we can draw recommendations for decision-makers. The most acceptable measure seems to be a change of the colour of the light from white/blue to orange. Switching off streetlights from 1 a.m. to 5 a.m. also seems to be rather easy to implement at least in periurban areas, and even in more urban areas, as the WTA of the anti-change for light extinction from 1 a.m. to 5 a.m. is very low. However, the reduction of light intensity and the light extinction from 11 pm to 6 am is very divisive. These measures should target the municipalities where acceptability is likely to be the greatest, for example, periurban areas in the MMA, according to our results. Based on the socioeconomic characteristics of the municipalities, it would be possible to design spatially targeted public policies that are both acceptable for the residents and where light mitigation is particularly needed for biodiversity.

Municipalities can also try to improve social acceptability. This can take the form of communication campaigns. The results from our survey to the question, "Why are you in favour of changing public lighting ?" (Figure 4) indicate that respondents are particularly sensitive to the arguments of energy savings and biodiversity preservation. The impacts on health and on star gazing seem to matter less. Municipalities can inform their citizens about the effects of the reduction of light pollution for these different aspects, including providing information on the costs and benefits involved. We saw that a large percentage of citizens are even willing to contribute to the financial cost that the change entails.

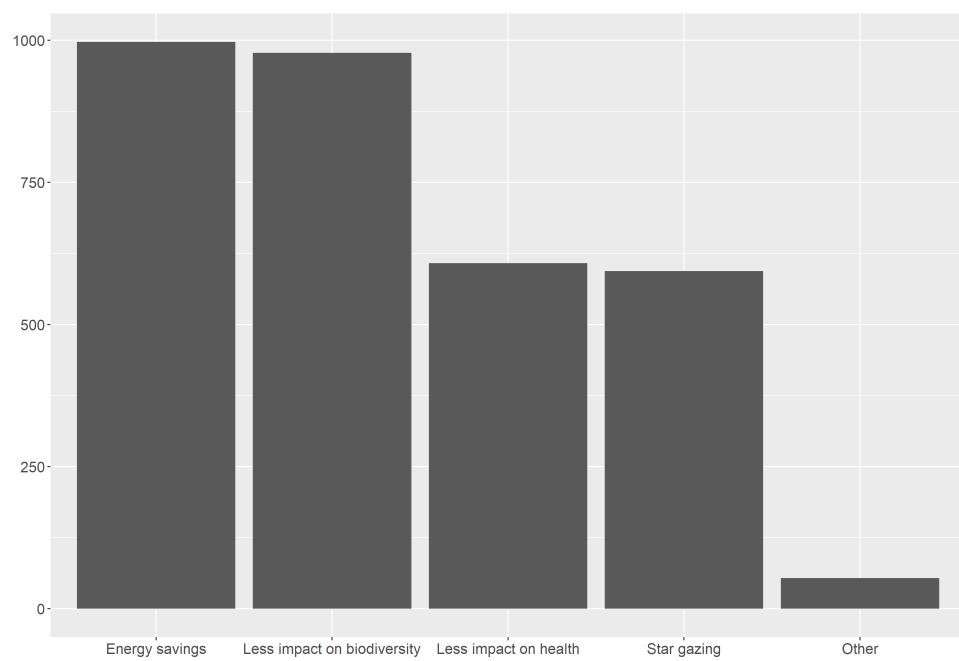

Figure 4 – Why are you in favour of changing public lighting ?

5. Conclusion

5.1. Summary

Our study investigates inhabitants' preferences regarding a public lighting shift to combat the harmful effects of light pollution. We use a *discret choice experiment* to measure the relative weight of different characteristics of public lighting - light intensity, light extinction, and colour - that influence the population's willingness to accept a change. We analyse the results with a latent class model. Our results indicate that, in general, respondents are willing to change public lighting. However, preferences for the different characteristics of street lighting are heterogeneous among the surveyed population. We identify two main groups of individuals. Respondents in the majority class (class 2, the "pro-change") have strong preferences for substantial changes in public lighting. They are in favour of orange-coloured light compared to white light. They are also in favour of light extinction from 1 a.m. to 5 a.m. and from 11 p.m. to 6 a.m. compared to no light extinction, as shown by the large associated WTPs (respectively 11 € and 6.3 € per year). On the contrary, individuals who belong to the minority class (class 1, the "anti-change"), although unsatisfied with the no change situation, are in average indifferent to the colour of the light, rather reluctant to switch lights off from 1 a.m. to 5 a.m. and very reluctant to switch them off from 11 p.m. to 6 a.m., as their negative WTP (-76.95 €) for this latter attribute shows. A vast majority of respondents (80%) are included in the pro-change class (class 2), which is rather reassuring about the possibility of implementing measures to mitigate light pollution. The inclusion of socioeconomic variables in our models permits identifying the characteristics of individuals that influence their decisions and that can explain the heterogeneity of the results. In the case of respondents from the Montpellier metropolitan area, we find that the density of the municipality is an important factor of social acceptability : the denser the municipality, the less willing inhabitants are to accept light extinction. This may be due to the fact that the population in denser areas is more prone to be outside at night and to move about by foot.

5.2. Limits

Our study suffers from one main limitation - the hypothetical bias. This drawback is very common in the DCE literature. In our case, it is difficult to know whether respondents can really imagine what it is like to walk down a street without lights, or with the lights dimmed. Street lighting is part of our daily lives and habits, so it is probably impossible to imagine all the consequences that light extinction would have on our habits. We have tried to limit the hypothetical bias as much as possible by describing in detail the context and the considered changes and by using concrete pictures and figures. In future research, it would be interesting and useful to simulate in the real-life the light change and let the population experience it - for example through night walks (Challéat and Lapostolle, 2018) - before making their choices, although it might be difficult to obtain a large sample of respondents for these field experiments. The cognitive bias, which is also common in the DCE literature, is rather limited in our case, as we limited the number of attributes to 4 with few levels.

5.3. Further research

Further research is needed in this field. First, we lack information and figures on the socioeconomic consequences of changes in public lighting, like the consequences on safety. Moreover, to our knowledge, there is no study that conducts a complete cost-benefit analysis of the modification of public lighting. This article, and particularly the associated WTP estimates, is a first step towards such analysis. The residents' preferences are indeed an important argument for (or against) the implementation of such policies that must be considered by mayors when they determine their actions on public lighting. In general, economic analyses related to light pollution are still very rare. Most economic analyses linked to light pollution seek to understand the factors that explain the spatial distribution of light pollution (Gallaway et al., 2010, 2013; Olsen et al., 2014). However, the authors of these articles do not attempt to make practical recommendations for limiting light pollution (Gallaway et al., 2010). Recently, Sordello et al. (2022) published a plea for the development of "dark infrastructures" in which they propose a 4-step method for local authorities to preserve or restore ecological continuities, taking into account the harmful effect of artificial light at night. Several articles, such as Olsen et al. (2014) and Pothukuchi (2021) stress the need for further research on the subject to design policies for light pollution planning and management. In particular, more interactions with local residents are needed to define the relevant attributes affecting the social acceptability of public lighting.

On a more methodological aspect, another scope for further research would be to explore the adequate statistical models to incorporate in the DCE estimates the protest answers and/ or nonresponses to the choice sets, in order to avoid selection bias. These methods have already been developed for contingent valuations, for example by Strazzera et al. (2003) or Brox et al. (2003), and would also be useful for DCEs.

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Appendix

Appendix A. Descriptive statistics on class membership

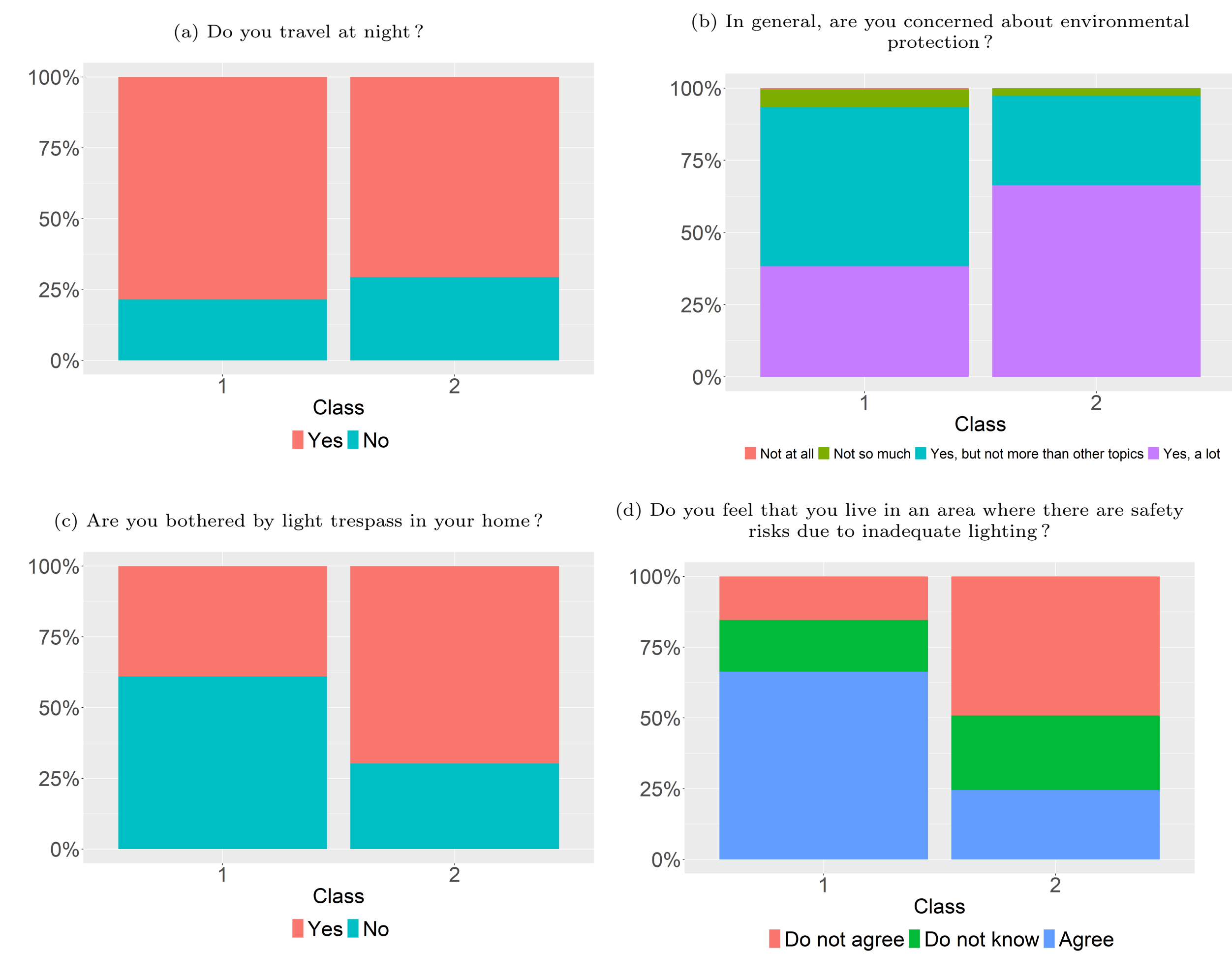

Figure Appendix A.1 – Descriptive statistics, differentiated by class

Appendix B. National sample (France)

Variable	Share in the sample	Share in total population (2018)
Gender		
Female	44.7%	52%
Male	54.3%	48%
Other	1.1%	-
Age		
19 – 30 y.o.	31.6%	17.5%
31 – 50 y.o.	49.2%	32.7%
51 – 65 y.o.	16.9%	24.6%
More than 66 y.o.	2.3%	25.2%
Socio-professional category		
Farmer	1.6%	0.8%
Craftmen, trader, entrepreneur	3.0%	3.5%
Managers and higher-educational professions	52.0%	9.5%
Intermediate professions	7.3%	14.1%
Employees	14.3%	16.1%
Workers	0.4%	12.1%
Pensioners	3.8%	26.9%
Others without professional activity	17.6%	17.0%

Table Appendix B.1 – Socio-economic comparison of the total sample and the population

	Dependent variable :	
	Choice	
	Class 1	Class 2
	Coefficient	Coefficient
	(S.E.)	(S.E.)
Attributes		
Intensity reduction	0.004**	0.013***
	(0.002)	(0.001)
Extinction2	0.307***	0.330***
	(0.072)	(0.061)
Extinction3	-1.401***	0.780***
	(0.101)	(0.071)
Colour	0.236***	0.254***
	(0.080)	(0.073)
Tax	-0.049***	-0.036***
	(0.010)	(0.010)
ASC	-1.430***	-1.986***
	(0.243)	(0.298)
Membership		
Gender2	Ref.	0.926***
		(0.221)
Gender3	Ref.	-0.023
		(0.860)
Age	Ref.	0.450**
		(0.189)
Communal density	Ref.	-0.190
		(0.130)
Children	Ref.	-0.289
		(0.276)
Time introduction	Ref.	-0.000
		(0.000)
Income	Ref.	0.168
		(0.135)
Biking	Ref.	0.106
		(0.259)
Constant	Ref.	-0.584
		(0.673)
N (obs.)	15363	
N (ind.)	569	
Log Likelihood	-3395	
AIC	6831	
CAIC	6943	
BIC	6992	
Preditive quality	97.5%	
Class membership (%)	25.5	74.5
Note :	*p<0.1 ; **p<0.05 ; ***p<0.01	

Table Appendix B.2 – Latent class model results - France