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Associations of Positive and Negative Perceptions of Outdoor Artificial Light at Night with Nighttime Outdoor Behaviors and Health: Self-Reported Data Analyses on Urban and Suburban Residents in Japan

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Abstract: Nighttime light guarantees outdoor work, leisure, and other activities, and its convenience and security greatly improve the quality of human life. However, the negative effects of outdoor artificial light at night (ALAN) on humans are also being proven. This study aimed to examine the relationships between outdoor nighttime lighting and human behaviors (i.e., outdoor nighttime behaviors such as jogging and meeting friends) and health (i.e., physical and mental health, including sleep quality and stress) through how individuals feel about outdoor ALAN (i.e., ALAN perceptions) in their living environment. Two online questionnaire surveys were conducted among residents of Tokyo (Survey 1, N = 2000) and Tsukuba City (Survey 2, N = 500), Japan. Structural equation modeling results show that both positive and negative ALAN perceptions increase nighttime outdoor behavior in both surveys. In Survey 1, this association led to a deterioration in sleep quality and physical and mental health. The current findings contribute to understanding the controversial relationships between the pros and cons of nighttime light perceptions and behaviors and health. They also contribute to designing better nighttime lighting in outdoor public and private spaces with relevant restrictions by balancing the benefits and harms of outdoor ALAN.

Keywords: nighttime light; light pollution; sleep quality; mental health; safety

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1. Introduction

The invention of electric lighting has removed limitations and enabled humans to work, travel, and conduct different activities after dark [1]. Artificial lighting has considerably contributed to supporting economic activities [2], especially in human laboring sectors such as the medical, manufacturing, service, and leisure industries. Along with this revolution, artificial light at night (ALAN) has completely changed human life patterns and enabled around-the-clock human activities [3,4]. Furthermore, ALAN on roads, urban streets, and public spaces is known to increase perceived safety and comfort [5] and reduce crimes after dark [6]. Due to the rapid development of lighting technology, including the light-emitting diode (LED), the great convenience of nighttime brightness has allowed the use of ALAN to expand rapidly worldwide. Consequently, more than 80% of the world's population lives under artificially bright skies [7], and ALAN continues to expand both in spatial extent and intensity due to population density and economic growth [8].

In addition to the positive aspects of ALAN, however, negative side effects (i.e., light pollution) have also been noted by some researchers. Light pollution is defined as excessive or obtrusive artificial light due to improperly installed lighting [9]. It is known that light pollution eliminates darkness in animal habitats and changes animal behaviors and health

conditions [10]. According to IDA, almost all species could be influenced by the adverse side effects of ALAN [11]. The universality of the impacts of ALAN on a wide range of biomass, ecosystems, species, and animal behaviors has also been highlighted [8]. For example, ALAN disturbs the physical health of insects [12], amphibians [13], birds [14], and mammals [15]. Furthermore, excessive or improper outdoor ALAN disturbs biological rhythms [14] and depression-like behaviors against stress [15] among animals.

Humans' physical and mental health, well-being, and various decision-making processes are also threatened by outdoor ALAN [16]. ALAN could cause sleep problems [17–19], obesity [20], breast cancer [21,22], autism spectrum disorder in children [23], depressive symptoms [24–26], and degraded subjective well-being [27]. The negative impacts of ALAN are estimated to cost the United States (US) nearly USD 7 billion annually due to the costs of health care, unnecessary energy for lighting, lost opportunities for stargazing, etc. [9].

The International Committee of Illumination (CIE) published a guideline (CIE150: 2017) aiming at minimizing the negative side effects of ALAN by avoiding obtrusive light from outdoor lighting installations [28]. This guideline classifies the negative impacts of light on human perceptions, such as discomfort, stress, and distraction, and these perspectives have been introduced to outdoor ALAN regulations and guidelines in several countries, such as Croatia, France, Japan, South Korea, and the US. These guidelines, however, primarily ignore the relationships between human perceptions of ALAN and nighttime behaviors, which could eventually induce health and well-being issues [16]. On the one hand, several studies have reported a positive association between feeling safe with street lighting in the dark and nighttime outdoor behavior such as walking, jogging, cycling, and traveling [4,5,29]. On the other hand, outdoor ALAN could confound the positive associations between urban green space and human health, such as stress and circadian disruption [30].

Moreover, street lighting at night may increase perceived safety but not affect outside behaviors, including meeting friends [31]. This means that outdoor ALAN may (or may not) encourage people to engage in outdoor physical and social activities at night and eventually cause health issues. However, little is known about how humans perceive outdoor ALAN, how these perceptions influence outdoor nighttime behavior for different purposes (not only physical exercises but also daily necessities and socializing), and how the behaviors might impact physical and mental health. Outdoor ALAN could have controversial, i.e., favorable and adverse, influences on human behaviors and health. It is crucial to understand the associations between human perceptions, behaviors, and health under outdoor ALAN for the optimal design of outdoor lighting; however, little research has thus far been conducted hereon.

The present study aimed to examine the relationships among human perceptions of outdoor ALAN (i.e., ALAN perceptions), nighttime outdoor behaviors, and physical and mental health. We assumed that ALAN perceptions could be associated with nighttime outdoor behaviors and physical and mental health improvement. We propose two manipulation hypotheses in the present study. First, people who positively perceive outdoor ALAN are more likely to go out at night than those with negative perceptions, who may feel reluctant to do so. Second, people with positive perceptions of outdoor ALAN could engage in physical activities and achieve improved physical and mental health, including subjective sleep quality, while negative perceptions would have the opposite effect.

2. Study Areas

Questionnaire surveys were conducted in two different areas in Japan during the period 24–28 December 2021: Tokyo (Survey 1, N = 2000) and Tsukuba (Survey 2, N = 500). Tokyo was selected because it is the most urbanized area in the country and the financial, political, and commercial capital, with approximately 13.51 million residents and a population density of 6402.6 persons/km^2 [32]. Tsukuba, as a rural and suburban area, was selected for comparison with Tokyo. It is located approximately 60 km north of Tokyo, and it accommodates a population of 226,963 (a population density of 851.7 persons/km^2). The average

radiance in Tokyo and Tsukuba during the survey period was 34.24–34.76 nW/(cm^{2}sr) and 18.42–18.7 nW/(cm^{2}sr), respectively [33], which indicates that Tokyo is generally brighter than Tsukuba.

3. Survey 1

The aim of Survey 1 was to examine the associations between the evaluation (i.e., brightness, visibility, glare, etc.) and perceptions (i.e., safety, convenience, and amenity for positive perceptions; discomfort, stress, and distraction for negative perceptions) of outdoor ALAN, physical and mental health conditions (including sleep quality and quantity), and outdoor behaviors at night (e.g., exercise, dining out, and grocery shopping) in Tokyo.

3.1. Methods

3.1.1. Participants and Study Area

An online questionnaire survey was conducted for 2000 adults (i.e., 20 years old or older) living in Tokyo via a commercial, web-based survey company (Rakuten Insight, Inc., Tokyo, Japan). The participants were recruited from a large, pre-existing online panel owned by the survey company. Considering the purpose of the study, 593 respondents who had never or hardly ever engaged in any nighttime outdoor behaviors asked in the questionnaire and two respondents with no postal code response were removed from the analysis, which resulted in a usable sample of n = 1405. Approximately half of the respondents (54.45%) were male, and the mean age of the respondents was 47.68 years (SD = 16.58). Most (63.06%) of the respondents had a bachelor's degree or higher, and 53.96% were employees in the private or public sectors. The mean annual household income was 6.98 million JPY, or USD 61,220 (SD = 4.58 million JPY, or USD 40,170) as of the survey period. Approximately one out of five (18.01%) identified themselves as shift workers.

3.1.2. Questionnaire Design

The questionnaire consisted of four sections. The first section asked about sleep, based on the assumption in previous studies [17,34,35] that sleep is sensitive to light exposure at night, which should be related to health conditions. The respondents were asked about their sleep quality and quantity, complaints of insomnia, and daytime sleepiness using the Athens Insomnia Scale [36] and the Epworth Sleepiness Scale [37].

The second section asked about the respondents' health status based on the question from the World Health Organization's (WHO) World Health Survey on overall health. The respondents were asked to rate their overall physical and psychological health using a 5-point Likert scale ranging from "Very bad" to "Very good". This section also included the Perceived Stress Scale [38] and the Center for Epidemiologic Studies Depression Scale (CESD) [39] to measure mental health conditions.

In the third section, the respondents were asked about their knowledge of, concerns about, and perceptions of outdoor ALAN. This section was initiated by a question on urbanization in the respondents' neighborhood for a rough classification of the outdoor light environment. The respondents were asked to choose one from the four illustrative images as classified in the Japanese government's Guidelines for Countermeasures against Light Pollution (3rd revised edition) [40], namely, dark district (i.e., rural, primarily agricultural farm and forest landscape with a few houses), low bright district (i.e., suburban landscape with some agricultural farms, houses, roads, some cars, and trees), moderate bright district (i.e., suburban to urban landscape with houses, several-story buildings, shops, main roads, train station, some urban greens) and high bright district (i.e., urban landscape with high-rise buildings, large stores, main roads, many cars, larger-scale train station, and some urban greens), which largely associates with urbanization levels. They were also asked for the 7-digit postal code of their residence to link subjective and objective (i.e., satellite data) brightness. The respondents were then asked to rate their knowledge of and concerns about the effects of outdoor ALAN on humans (two items: visibility and discomfort; and reduced

sleep quality due to disturbed life rhythm), plants and animals (three items: changes in animals' nocturnal activities; changes in wildlife activity patterns and the ecosystem; and decreases in the quality and quantity of crop harvests), and the starry sky (one item: decrease in star visibility) according to the above-mentioned guidelines, using a 5-point Likert scale ("Do not know at all" or "Not at all concerned" to "Know very well" or "Highly concerned").

In the same section, the respondents were also asked to evaluate the brightness levels of the nighttime lighting environments of residential and commercial areas in their walking-distance neighborhoods. For each area, seven nighttime-landscape photos were shown to the respondents for them to choose one that was closest to the light situations in their neighborhood; in the photos, only brightness was modified using the original photo taken in Tokyo by the authors after dark, between 5.30 pm and 6.30 pm, in November 2021. The respondents were also asked to evaluate the level of outdoor nighttime brightness, visibility, and glare in the areas on a 5-point Likert scale ranging from "dark" to "bright", "invisible" to "visible", and "not glaring" to "glaring", respectively, and light color to choose the closest out of the five images based on the Japanese government light pollution guidelines ranging from warm, orangish to cool, pale colors. They were then asked to rate the positivity (i.e., safety, convenience, and amenity) and negativity (i.e., discomfort, stress, and distraction) of the outdoor nighttime light conditions in their neighborhood. These items were developed based on light-pollution guidelines [28,40] and were asked on a 5-point Likert scale ranging from "Strongly disagree" to "Strongly agree."

In the fourth section, the respondents were asked about their outdoor behaviors at night. The items for nighttime outdoor behaviors were developed based on two pilot surveys. In the first pilot survey, we asked 29 university-student participants (male, n = 11) living in Japan an open-ended question about types of nighttime outdoor behaviors to extract a pilot set of 20 items that the participants commonly indicated. We then conducted the second pilot survey (with 200 Tokyo residents recruited through a consumer panel) to test the frequency of these 20 behaviors (also using an open-ended question on nighttime behavior). Through this procedure, we combined similar behaviors, such as walking and walking the dog, and dropped behaviors that occurred only occasionally, such as sending packages and smoking cigarettes. Consequently, we obtained 20 items as a tentative behavior set, which we used in Surveys 1 and 2. The respondents were asked to rate the frequency of the behaviors in the evening after dark (e.g., going out for exercises, dining out, meeting friends and families, and grocery shopping) using a 7-point scale (1 = "Never," 2 = "Once or twice in half a year," 3 = "Once or twice every 2 to 3 months," 4 = "Once or twice a month," 5 = "Once or twice a week," 6 = "Three to four times a week," and 7 = "Almost every day"). The complete list of behavior items is shown in Table 1. The respondents were instructed to answer all the questions based on their walk-distance neighborhood situations under a completely dark sky in December (around 8 pm) to avoid the influence of seasonal differences in darkness and climate among the respondents' neighborhoods. The descriptive statistics for the collected data are also summarized in Table 1.

Table 1. Descriptive statistics for Survey 1.

	Mean, %	***SD***	**Min**	**Max**
Demographic characteristics				
Gender (%)				
Male	54.45			
Female	45.55			
Age (years)	47.68	16.58	20	90
Education (%)				
Junior high school	1.49			
Senior high school	16.30			

Table 1. *Cont.*

	Mean, %	*SD*	Min	Max
Junior college	19.15			
University	54.23			
Graduate school	8.76			
Others	0.07			
Income (household annual, million JPY)	6.98	4.58	2	20
Shiftwork (yes %)	18.01			
Occupation (%)				
Civil servant	4.56			
Company employee	49.40			
Freelance	4.48			
Self-employed	4.84			
Part-time job	12.10			
Student	2.63			
Homemaker	9.04			
Unemployed	11.17			
Others	1.78			
Neighborhood environment				
Urbanization	3.22	0.65	1	4
Noise	2.43	1.00	1	5
Light environment of residential street	4.10	1.42	1	7
Light environment of shop street	4.90	1.35	1	7
Objective brightness, radiance (nW/(cm^{2}sr))	25.47	6.03	1.24	35.64
Outdoor ALAN evaluation and perceptions				
Subjective brightness	3.17	0.76	1	5
Visibility	3.66	0.86	1	5
Light color	3.11	1.11	1	5
Glare	2.43	0.93	1	5
Knowledge	2.50	0.87	1	5
Concern	2.82	1.00	1	5
Positive perceptions	3.37	0.66	1	5
Negative perceptions	2.20	0.86	1	5
Sleep and health				
General Health	3.37	0.94	1	5
Insomnia	1.83	0.61	1	4
Sleepiness	1.98	0.62	1	4
Depression	1.80	0.50	1	4
Stress	2.57	0.60	1	5
Nighttime outdoor behaviors				
Go out walking	2.46	1.91	1	7
Go out jogging	1.67	1.38	1	7
Go out biking	1.74	1.48	1	7
Go out exercising	1.54	1.29	1	7
Exercise in outdoor sports facilities (e.g., soccer fields)	1.47	1.16	1	7
Exercise in indoor sports facilities	1.84	1.63	1	7
Go out to the park	1.98	1.56	1	7
Go out to see the night view of the city	1.78	1.35	1	7
Go out to see the starry sky	1.76	1.32	1	7
Go out for a meal or drink	2.98	1.51	1	7
Go out to indoor amusement venues (e.g., karaoke, cinema)	1.83	1.30	1	7
Go out to public baths or hot springs	1.84	1.28	1	7
Go out for a drive	1.86	1.36	1	7
Go out to a convenience store	3.67	1.70	1	7
Go out to a supermarket	3.48	1.73	1	7
Go out to a department store or shopping mall	2.27	1.50	1	7
Meet friends, families, or relatives outside home	2.55	1.45	1	7

Table 1. *Cont.*

	Mean, %	*SD*	Min	Max
Visit the homes of friends, families, or relatives	2.12	1.36	1	7
Go to the workplace or school to study or work	2.82	2.32	1	7
Go to cafes or libraries to study or work	1.86	1.43	1	7

Note: *SD* = standard deviation. Cronbach's α values for knowledge and concern were 0.84 and 0.91, respectively.

3.1.3. Data Analysis

Analyses were conducted in three steps. First, the 20 behavior items were entered into an exploratory factor analysis to group nighttime outdoor behaviors. The factor-loading threshold for retaining variables and factor extraction was set at 0.5. Second, Pearson correlation analysis was performed to examine the correlation between the evaluations of outdoor ALAN (i.e., brightness, visibility, light color, and glare) and its positive and negative perceptions (i.e., safety, convenience, amenity, discomfort, stress, and distraction), concern and knowledge, nighttime outdoor behaviors, mental and physical health conditions, and demographic characteristics. Knowledge of and concern about outdoor ALAN were calculated as the means of six items involving effects on humans, nature, and starry skies. In this part, *t*-tests for gender comparison were also performed to explore how gender, as one of the key demographic factors in health research, could explain individual situations in outdoor ALAN and the factors considered in this study. Third, structural equation modeling (SEM) was performed to examine the associations among ALAN perceptions, nighttime outdoor behaviors, and mental and physical health conditions. All the data were analyzed using Stata 15.0 software (StataCorp LLC, College Station, TX, USA).

3.2. Results

3.2.1. Factor Analysis of Nighttime Outdoor Behaviors

As a result of the factor analysis, the nighttime outdoor behaviors were categorized into three factors: "outdoor activities" (Items 1–5, 7–9), "outdoor traveling for indoor activities" (Items 10, 11, 16–18), and "essential outings" (Items 14, 15), as shown in Table 2. We used these three factors for further analysis to investigate their relationships with nighttime lighting environments.

Table 2. Factor loadings of nighttime outdoor behavior items (Survey 1).

	F1	F2	F3
F1: Outdoor Activities			
1. Go out walking	**0.634**	−0.389	0.491
2. Go out jogging	**0.750**	−0.043	−0.037
3. Go out biking	**0.645**	0.054	0.004
4. Go out to exercise	**0.757**	0.137	−0.107
5. Exercise in outdoor sports facilities	**0.727**	0.227	−0.175
7. Go out to the park	**0.636**	−0.079	0.390
8. Go out to see the night view of the city	**0.684**	0.098	0.071
9. Go out to see the starry sky	**0.750**	0.010	−0.016
F2: Outdoor traveling for indoor activities			
10. Go out for a meal or drink	−0.097	**0.667**	0.156
11. Go out to indoor amusement venues	0.339	**0.508**	0.025
16. Go out to a department store or shopping mall	0.108	**0.523**	0.339
17. Meet friends, families, or relatives outside home	−0.028	**0.752**	0.099
18. Visit the homes of friends, families, or relatives	0.189	**0.637**	0.009
F3: Essential outings			
14. Go out to a convenience store	−0.112	0.164	**0.766**
15. Go out to a supermarket	−0.072	0.167	**0.733**
Mean (SD) of behavior frequency scores in each factor	1.80 (1.04)	2.35 (1.07)	3.58 (1.51)

Notes. n = 1405. Bold font indicates measurement variables for respective factors. Items 6, 12, 13, 19, and 20 were omitted due to low factor loadings (<0.5) in the initial factor analysis.

3.2.2. Correlations and Gender-Comparison

The correlation-analysis results in Table 3 show that objective brightness was positively correlated with subjective brightness ($r = 0.24$, $p < 0.001$), visibility ($r = 0.22$, $p < 0.001$), cool light color ($r = 0.14$, $p < 0.001$), glare ($r = 0.08$, $p < 0.01$), and positive perceptions ($r = 0.19$, $p < 0.001$). Objective brightness was not significantly correlated with any ALAN perceptions, health, sleep, or behaviors; thus, it was not included in the SEM analysis. All the light-evaluation items (brightness: $r = 0.30$; visibility: $r = 0.34$; and cool light color: $r = 0.13$; ps < 0.001) were positively correlated with positive perceptions. Visibility was negatively correlated with negative perceptions ($r = -0.17$, $p < 0.001$), while glare showed a positive correlation with negative perceptions ($r = 0.41$, $p < 0.001$). All three behavioral factors were positively correlated with negative perceptions (outdoor activities: $r = 0.31$; outdoor traveling for indoor activities: $r = 0.23$; essential outings: $r = 0.08$; ps < 0.001), while no significant correlations were found between behaviors and positive perceptions.

Table 4 shows gender comparison *t*-test results. While having no statistical difference in both objective and overall subjective brightness, female respondents tend to evaluate their neighborhood residential and shopping street light environments as brighter (residential $M_{\text{Male}} = 4.03$, $M_{\text{Female}} = 4.18$, $d = 0.11$, $t = 1.98$; shopping $M_{\text{Male}} = 4.84$, $M_{\text{Female}} = 4.98$, $d = 0.11$, $t = 1.96$, ps = <0.05) regardless of living in less urbanized areas ($M_{\text{Male}} = 3.18$, $M_{\text{Female}} = 2.26$, $d = 0.12$, $t = 2.28$, $p < 0.05$) than their male counterparts. Females were more concerned about light pollution ($M_{\text{Male}} = 2.71$, $M_{\text{Female}} = 2.96$, $d = 0.26$, $t = 4.83$, $p < 0.001$), had better overall health ($M_{\text{Male}} = 3.30$, $M_{\text{Female}} = 3.44$, $d = 0.15$, $t = 2.89$, $p < 0.01$), and had lower levels of depression ($M_{\text{Male}} = 1.83$, $M_{\text{Female}} = 1.77$, $d = 0.12$, $t = 2.18$, $p < 0.05$) than males. They stayed outside at night less than males in all the behavioral scenes except some related to essential and socialization purposes.

Table 3. Correlation matrix of the analyzed variables (Survey 1).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1. Age	1																						
2. Education	−0.09 **	1																					
3. Income	−0.08 **	0.23 ***	1																				
4. Urbanization	−0.02	0.04	0.10 ***	1																			
5. Light environment of residential street	0.12 ***	0.01	0.08 **	0.33 ***	1																		
6. Light environment of shop street	−0.04	0.07 *	0.11 ***	0.27 ***	0.51 ***	1																	
7. Objective brightness	−0.02	0.02	0.08 **	0.43 ***	0.22 ***	0.23 ***	1																
8. Subjective brightness	0.01	0.02	0.07 *	0.32 ***	0.43 ***	0.38 ***	0.24 ***	1															
9. Visibility	0.11 ***	0.02	0.06 *	0.26 ***	0.35 ***	0.32 ***	0.22 ***	0.52 ***	1														
10. Light color	0.10 ***	−0.03	0.03	0.20 ***	0.40 ***	0.29 ***	0.14 ***	0.30 ***	0.26 ***	1													
11. Glare	−0.18 ***	0.02	0.08 **	0.14 ***	0.19 ***	0.15 ***	0.08 **	0.35 ***	0.08 **	0.16 ***	1												
12. Positive perceptions	0.11 ***	0.03	0.06 *	0.22 ***	0.24 ***	0.20 ***	0.19 ***	0.30 ***	0.34 ***	0.13 ***	0.001	1											
13. Negative perceptions	−0.20 ***	−0.01	−0.04	−0.02	−0.01	−0.01	−0.002	0.04	−0.17 ***	0.01	0.41 ***	−0.23 ***	1										
14. Knowledge	−0.10 ***	0.02	−0.01	0.01	0.02	0.04	0.03	0.09 ***	−0.01	0.03	0.32 ***	−0.07 **	0.42 ***	1									
15. Concern	−0.07 **	0.01	0.01	0.002	−0.02	0.01	0.03	0.03	0.01	−0.05	0.18 ***	−0.04	0.32 ***	0.61 ***	1								
16. Insomnia	−0.19 ***	−0.002	−0.04	−0.02	−0.05	−0.01	−0.03	0.01	−0.12 ***	0.02	0.17 ***	−0.07 *	0.25 ***	0.19 ***	0.17 ***	1							
17. Sleepiness	−0.26 ***	0.02	−0.01	−0.05	−0.07 **	−0.01	−0.01	0.03	−0.10 ***	−0.04	0.16 ***	−0.06 *	0.19 ***	0.17 ***	0.10 ***	0.46 ***	1						
18. General health	0.09 ***	0.04	0.12 ***	0.04	0.09 **	0.07 **	0.06 *	0.07 **	0.16 ***	−0.01	−0.04	0.16 ***	−0.13 ***	−0.07 **	−0.03	−0.52 ***	−0.21 ***	1					
19. Depression	−0.30 ***	0.04	−0.03	0.004	−0.07 *	0.01	−0.01	0.01	−0.15 ***	0.002	0.20 ***	−0.06 *	0.32 ***	0.26 ***	0.17 ***	0.56 ***	0.41 ***	−0.36 ***	1				
20. Stress	−0.12 ***	0.05 *	−0.002	0.02	−0.04	−0.01	0.03	0.06 *	0.004	−0.003	0.10 ***	0.06 *	0.15 ***	0.21 ***	0.23 ***	0.36 ***	0.24 ***	−0.16 ***	0.54 ***	1			
21. Outdoor activities	−0.21 ***	0.08 **	0.07 **	−0.05	−0.02	0.04	0.02	0.05	−0.15 ***	0.02	0.26 ***	<0.01	0.31 ***	0.25 ***	0.13 ***	0.27 ***	0.24 ***	−0.05	0.42 ***	0.24 ***	1		
22. Outdoor traveling for indoor activities	−0.25 ***	0.06 *	0.06 *	−0.001	0.02	0.06 *	0.05	0.05	−0.07 **	−0.002	0.19 ***	0.004	0.23 ***	0.17 ***	0.08 **	0.22 ***	0.20 ***	−0.02	0.35 ***	0.24 ***	0.62 ***	1	
23. Essential outings	−0.14 ***	−0.03	−0.01	0.05	0.05	0.06 *	0.05 *	0.09 **	0.05	0.05	0.11 ***	0.05	0.08 ***	0.07 *	0.02	0.15 ***	0.08 **	−0.09 ***	0.18 ***	0.13 ***	0.34 ***	0.49 ***	1

Note: n = 1405. Significant at *** $p < 0.001$, ** $p < 0.01$, and * $p < 0.05$.

Table 4. Unpaired *t*-test results by gender (Survey 1).

	Male (n = 765)		Female (n = 640)		d (Effect Size)	t	p
	Mean, %	*SD*	Mean, %	*SD*			
Demographic characteristics							
Age (years)	48.05	16.61	47.23	16.55	0.05	0.92	0.360
Education (bachelor's degree or above %)	74.12 (M = 0.74)	0.43	49.84 (M = 0.50)	0.50	0.52	9.69	0.000
Income (household annual, million JPY)	7.28	4.66	6.98	4.58	0.15	2.71	0.007
Occupation (employed in private or public sector %)	63.01 (M = 0.63)	0.48	43.13 (M = 0.43)	0.50	0.41	7.59	0.000
Shiftwork (yes %)	17.78 (M = 0.18)	0.38	18.28 (M = 0.18)	0.39	0.13	0.24	0.807
Objective brightness	25.30	6.12	25.68	5.91	0.06	1.18	0.237
Outdoor ALAN evaluation and perceptions							
Subjective brightness	3.18	0.77	3.17	0.74	0.02	0.29	0.770
Visibility	3.63	0.84	3.70	0.88	0.07	1.33	0.184
Light color	3.15	1.10	3.07	1.12	0.07	1.30	0.193
Glare	2.45	0.93	2.41	0.89	0.04	0.72	0.473
Knowledge	2.48	0.87	2.53	0.98	0.06	1.07	0.286
Concern	2.71	0.99	2.96	1.00	0.26	4.83	0.000
Positive perceptions	3.37	0.65	3.38	0.68	0.01	0.14	0.887
Negative perceptions	2.19	0.91	2.20	0.81	0.01	0.15	0.877
Neighborhood environment							
Urbanization	3.18	0.67	2.26	0.63	0.12	2.28	0.023
Noise	3.62	0.99	3.50	1.01	0.12	2.17	0.031
Light environment of residential street	4.03	1.40	4.18	1.43	0.11	1.98	0.048
Light environment of shop street	4.84	1.35	4.98	1.34	0.11	1.96	0.050
Health and sleep							
General health	3.30	0.96	3.44	0.91	0.15	2.89	0.004
Insomnia	1.85	0.62	1.81	0.59	0.08	1.46	0.145
Sleepiness	1.99	0.63	1.96	0.60	0.05	0.89	0.372
Depression	1.83	0.52	1.77	0.47	0.12	2.18	0.030
Stress	2.57	0.64	2.58	0.55	0.01	0.22	0.827
Nighttime outdoor behaviors							
Go out walking	2.66	1.94	2.23	1.85	0.23	4.24	0.000
Go out jogging	1.92	1.55	1.36	1.07	0.41	7.69	0.000
Go out biking	1.95	1.61	1.49	1.26	0.31	5.86	0.000
Go out to exercise	1.72	1.44	1.33	1.04	0.31	5.73	0.000
Exercise in outdoor sports facilities	1.62	1.29	1.29	0.95	0.29	5.36	0.000
Exercise in indoor sports facilities	1.91	1.63	1.76	1.61	0.09	1.75	0.080
Go out to the park	2.16	1.61	1.78	1.48	0.25	4.60	0.000
Go out to see the night view of the city	1.92	1.44	1.62	1.22	0.22	4.09	0.000
Go out to see the starry sky	1.87	1.39	1.63	1.24	0.18	3.33	0.001
Go out for a meal or drink	3.12	1.54	2.81	1.46	0.20	3.73	0.000
Go out to indoor amusement venues	1.94	1.39	1.70	1.17	0.19	3.51	0.001
Go out to public baths or hot springs	1.98	1.37	1.67	1.14	0.24	4.52	0.000
Go out for a drive	2.05	1.47	1.63	1.18	0.31	5.79	0.000
Go out to a convenience store	3.84	1.70	3.47	1.69	0.22	4.07	0.000
Go out to a supermarket	3.52	1.72	3.44	1.75	0.05	0.84	0.400
Go out to a department store or shopping mall	2.28	1.50	2.26	1.51	0.02	0.31	0.758
Meet friends, families, or relatives outside home	2.58	1.49	2.51	1.41	0.04	0.83	0.409
Visit the homes of friends, families, or relatives	2.09	1.35	2.15	1.36	0.05	0.90	0.368
Go to the workplace or school to work or study	2.94	2.34	2.68	2.30	0.11	2.11	0.035
Go to cafes or libraries to study or work	1.96	1.52	1.74	1.30	0.15	2.87	0.004

Note: *SD* = standard deviation.

3.2.3. SEM on Outdoor ALAN Perceptions, Behaviors, and Health

The SEM result is shown in Figure 1. It yielded a relatively good fit to the model (RMSEA = 0.047, CFI = 0.934). Positive ALAN perceptions were found to be positively

associated with brightness (β = 0.23, $p < 0.001$) and visibility (β = 0.32, $p < 0.001$) and negatively associated with glare ($\beta = -0.15$, $p < 0.001$). Negative ALAN perceptions were found to be negatively associated with visibility ($\beta = -0.20$, $p < 0.001$) and positively associated with glare (β = 0.30, $p < 0.001$). Negative perceptions had positive associations with all three behavioral factors: outdoor activities (β = 0.54, $p < 0.001$), outdoor traveling for indoor activities (β = 0.42, $p < 0.001$), and essential outings (β = 0.26, $p < 0.001$). Positive perceptions were positively associated only with essential outings (β = 0.18, $p < 0.01$) among the behavioral factors. In addition, outdoor activities and outdoor traveling for indoor activities were negatively associated with sleep quality ($\beta_{\text{outdoor activities}} = -0.16$, $p < 0.001$; $\beta_{\text{outdoor traveling}} = -0.09$, $p < 0.05$) and mental health ($\beta_{\text{outdoor activities}} = -0.23$, $p < 0.001$; $\beta_{\text{outdoor traveling}} = -0.13$, $p < 0.001$). Essential outings were negatively associated with general health ($\beta = -0.12$, $p < 0.001$). Negative perceptions had negative associations with sleep quality ($\beta = -0.26$, $p < 0.001$), general health ($\beta = -0.10$, $p < 0.01$), and mental health ($\beta = -0.24$, $p < 0.001$). Positive perceptions were negatively associated only with general health (β = 0.16, $p < 0.001$).

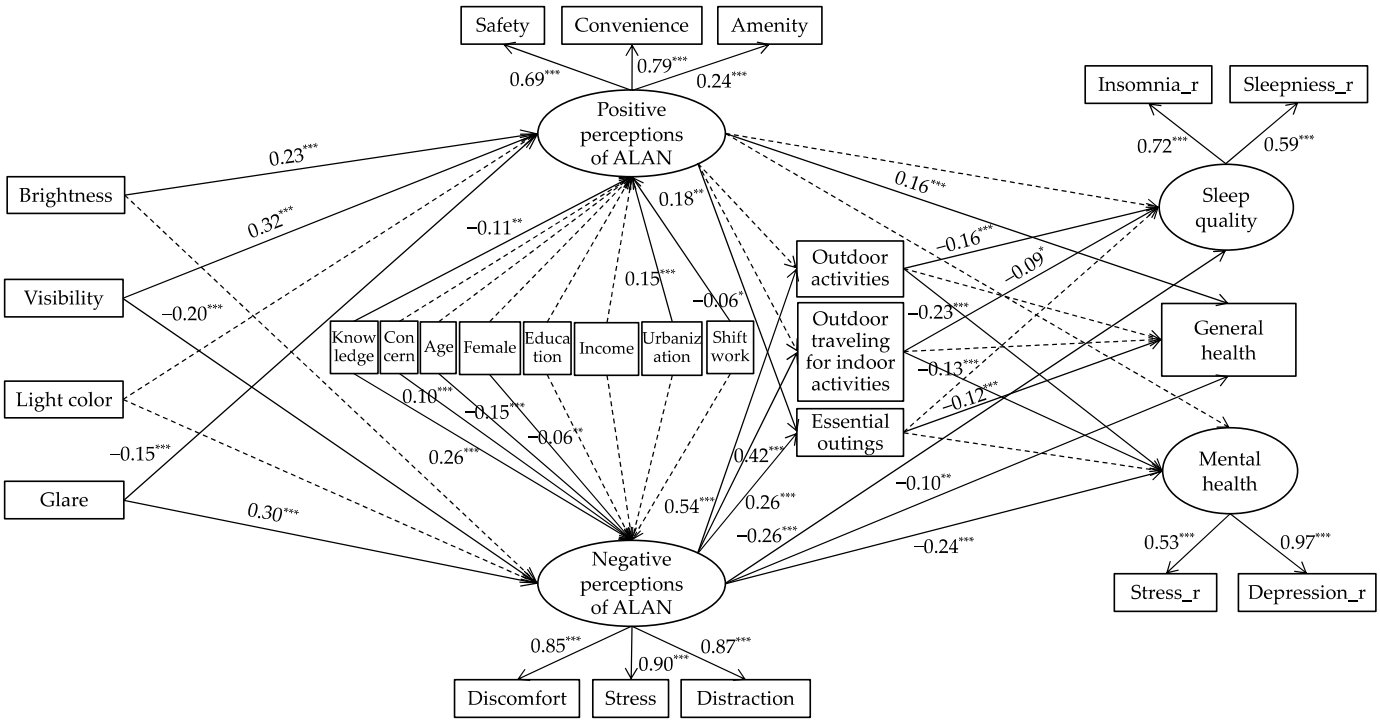

Figure 1. Structural associations of outdoor ALAN evaluation and perceptions, nighttime outdoor behaviors, sleep quality, and general and mental health (Survey 1). Notes: n = 1405, χ^2 (176) = 730.03, $p < 0.001$, RMSEA = 0.047, CFI = 0.934. Significant at *** $p < 0.001$, ** $p < 0.01$, and * $p < 0.05$. Solid and dotted lines indicate significant and insignificant paths, respectively. "_r" at the end of the measurement variable name indicates reversed item.

Positive ALAN perceptions were also explained by three demographic factors, namely, knowledge ($\beta = -0.11$, $p < 0.01$), urbanization (β = 0.15, $p < 0.001$), and shiftwork ($\beta = -0.06$, $p < 0.05$). Negative perceptions had positive associations with knowledge (β = 0.26, $p < 0.001$) and concern (β = 0.10, $p < 0.001$) and negative associations with age ($\beta = -0.15$, $p < 0.001$) and being female ($\beta = -0.06$, $p < 0.01$).

3.3. Discussion for Survey 1

From the factor analysis of the Survey 1 behavior data, we found that nighttime outdoor behaviors could be considered in three categories: outdoor activities, outdoor traveling for indoor activities, and essential outings. Outdoor activities primarily involve physical exercises, which are generally considered to improve health [41]. While the

behaviors in this category can be performed with or without accompanying persons, they can also enhance social relationships if performed in a group of people. The second behavior category, outdoor traveling for indoor activities, predominantly comprises meeting friends and families. This behavior may thus contribute to psychological well-being and social capital through enriching personal and group connections [42,43]. The last behavior category, essential outings, specifically comprises going out to purchase daily commodities. The behaviors in this category were practiced much more frequently than those in the other two behavior categories, which is reasonable considering the necessity and availability of the grocery-shopping behaviors and the weaker influence of personal preference on behaviors compared to the other two behavior categories.

The significant correlational relationships between the evaluation and perceptions of outdoor ALAN suggest that visibility is the most important aspect of lighting that can cause both positive and negative perceptions about outdoor nighttime lighting. Also, brightness and (warmer) light color are associated with positive perceptions, and glare is associated with negative perceptions only. Visibility is considered essential in outdoor lighting as it can directly affect accident and crime safety as well as enjoying the nightscape.

The SEM result supports our assumption about the unfavorable effects of outdoor ALAN on perceptions and health. On the one hand, the current results confirm significant associations of outdoor ALAN with general and mental health and sleep, which are consistent with previous findings [44]; that is, people are healthier when they feel safer and sense more convenience under outdoor nighttime light. On the other hand, there were positive associations of negative ALAN perceptions (i.e., discomfort, stress, and distraction) with all three nighttime outdoor behavioral factors, which is contrary to our hypothesis. This suggests that feeling more uncomfortable or stressed about outdoor nighttime light could facilitate going out at night for any purpose, which would result in worse sleep quality and health. This finding is controversial but intriguing and will be discussed under general discussion.

4. Survey 2

The aim of Survey 2 was to examine the associations between ALAN perceptions, human health, and nighttime outdoor behaviors in Tsukuba City, Japan. In this survey, we expected to replicate the main results of Survey 1 and elaborate on any results that were unique to Tokyo or Tsukuba, which would enable us to discuss the differences in the concerned associations based on the city characteristics.

4.1. Methods

4.1.1. Participants and Study Area

An online questionnaire survey was conducted to collect data from 500 adults living in Tsukuba via a commercial, web-based survey company in December 2021. The questions asked in the questionnaire and respondents' recruitment were the same as those for Survey 1. Descriptive statistics of the valid sample are shown in Table 5. Among the respondents, 177 who had never or hardly ever engaged in any nighttime outdoor behaviors and three respondents with no postal code response were omitted, resulting in a usable sample size of 320. Slightly more than half (57.81%) of the respondents were male, and the respondents' mean age was 45.17 years (*SD* = 15.76). Most respondents (62.50%) had a bachelor's degree or higher, and 50.94% were public- or private-sector employees. The respondents' mean annual household income was 6.62 million JPY, or USD 58,060 (*SD* = 4.30 million JPY, or USD 37,710) as of the survey period. Some 20.31% of the respondents worked day and night shifts.

Table 5. Descriptive statistics for Survey 2.

	Mean, %	*SD*	Min	Max
Demographic characteristics				
Gender (%)				
Male	57.81			
Female	42.19			
Age (years)	45.17	15.76	20	85
Education (%)				
Junior high school	0.94			
Senior high school	22.50			
Junior college	14.06			
University	40.94			
Graduate school	21.56			
Income (household annual, million JPY)	6.62	430	2	20
Shiftwork (yes %)	20.31			
Occupation (%)				
Civil servant	10.31			
Company employee	40.63			
Freelance	2.81			
Self-employed	3.44			
Part-time job	15.00			
Student	8.12			
Homemaker	6.88			
Unemployed	10.00			
Others	2.81			
Neighborhood environment				
Urbanization	2.39	0.64	1	4
Noise	2.02	0.84	1	5
Light environment of residential street	2.73	1.07	1	7
Light environment of shop street	3.73	1.39	1	7
Objective brightness, radiance (nW/(cm^{2}sr))	9.64	4.82	1.42	19.09
Outdoor ALAN evaluation and perceptions				
Subjective brightness	2.53	0.75	1	5
Visibility	2.85	0.96	1	5
Light color	2.50	1.01	1	5
Glare	2.04	0.86	1	5
Knowledge	2.52	0.98	1	5
Concern	2.84	1.05	1	5
Positive perceptions	2.98	0.81	1	5
Negative perceptions	2.13	0.79	1	4.33
Sleep and health				
General Health	3.49	0.86	1	5
Insomnia	1.73	0.52	1	3.88
Sleepiness	1.98	0.55	1	4
Depression	1.74	0.45	1	3.9
Stress	2.53	0.58	1	4.29
Nighttime outdoor behaviors				
Go out walking	2.19	1.79	1	7
Go out jogging	1.53	1.20	1	7
Go out biking	1.62	1.39	1	7
Go out to exercise	1.44	1.11	1	7
Exercise in outdoor sports facilities (e.g., soccer fields)	1.47	1.18	1	7
Exercise in indoor sports facilities	1.71	1.46	1	7
Go out to the park	1.73	1.34	1	7
Go out to see the night view of the city	1.49	0.96	1	7
Go out to see the starry sky	1.78	1.28	1	7
Go out for a meal or drink	2.75	1.40	1	7
Go out to indoor amusement venues (e.g., karaoke, cinema)	1.69	1.17	1	7
Go out to public baths or hot springs	1.80	1.27	1	7
Go out for a drive	1.97	1.30	1	7

Table 5. *Cont.*

	Mean, %	*SD*	Min	Max
Go out to a convenience store	3.40	1.64	1	7
Go out to a supermarket	3.48	1.63	1	7
Go out to a department store or shopping mall	2.44	1.45	1	7
Meet friends, families, or relatives outside home	2.37	1.44	1	7
Visit the homes of friends, families, or relatives	2.18	1.40	1	7
Go to the workplace or school to work or study	3.00	2.36	1	7
Go to cafes or libraries to study or work	1.68	1.31	1	7

Note: *SD* = standard deviation. Cronbach's α values for knowledge and concern were 0.88 and 0.92, respectively.

4.1.2. Data Analysis

The collected data were analyzed in the same three steps as in Survey 1: factor analysis on nighttime outdoor behaviors, correlation analysis, and SEM on the association of outdoor ALAN evaluation with perceptions, nighttime outdoor behavior, and health.

4.2. Results

4.2.1. Factor Analysis of Nighttime Outdoor Behaviors

The factor analysis yielded three factors for nighttime outdoor behaviors: "outdoor activities" (Items 2–6, 8, 9, 11, 12), "outdoor traveling for indoor activities" (Items 10, 14–17, 19), and "light exercises" (Items 1, 7), as shown in Table 6.

Table 6. Factor loadings for nighttime outdoor behavior items (Survey 2).

	F1	F2	F3
F1: Outdoor Activities			
2. Go out jogging	**0.694**	−0.147	0.260
3. Go out biking	**0.672**	0.053	−0.003
4. Go out to exercise	**0.850**	−0.151	0.195
5. Exercise in outdoor sports facilities	**0.840**	−0.175	0.074
6. Exercise in indoor sports facilities	**0.611**	−0.026	−0.071
8. Go out to see the night view of the city	**0.681**	0.084	0.234
9. Go out to see the starry sky	**0.669**	−0.054	0.312
11. Go out to indoor amusement venues	**0.609**	0.217	−0.091
12. Go out to public baths/hot springs	**0.620**	0.237	0.057
F2: Outdoor traveling for indoor activities			
10. Go out for a meal or drink	0.123	**0.519**	−0.087
14. Go out to a convenience store	−0.249	**0.818**	0.255
15. Go out to a supermarket	−0.252	**0.795**	0.319
16. Go out to a department store or shopping mall	0.072	**0.732**	0.110
17. Meet friends, families, or relatives outside home	0.211	**0.626**	−0.201
19. Commuting to work or school	−0.058	**0.599**	0.112
F3: Light exercises			
1. Go out walking	0.306	0.153	**0.597**
7. Go out to the park	0.397	0.181	**0.577**
Mean (*SD*) of behavior frequency in each factor	1.61 (0.87)	2.80(1.10)	1.96(1.31)

Notes. n = 320. Bold font indicates measurement variables for respective factors. Items 13, 18, and 20 were omitted due to low factor loadings (<0.5) in the initial factor analysis.

4.2.2. Correlations and Gender-Comparison

The results of the correlation analysis are shown in Table 7. Objective brightness was positively correlated with subjective brightness (r = 0.24; $p < 0.001$), visibility (r = 0.13; $p < 0.05$), positive perceptions (r = 0.14; $p < 0.05$), and knowledge (r = 0.13; $p < 0.05$). It was found to be weakly or not correlated with ALAN perceptions, health, sleep, and behaviors and thus was not included in SEM analysis. Positive correlations were found between positive perceptions and brightness (r = 0.50, $p < 0.001$), visibility (r = 0.46, $p < 0.001$), cool

light color ($r = 0.23$, $p < 0.001$), and glare ($r = 0.21$, $p < 0.001$). Glare ($r = 0.33$, $p < 0.001$) was positively correlated with negative perceptions. Furthermore, positive and negative perceptions were positively correlated with outdoor activities ($r_{positive} = 0.17$, $p < 0.01$; $r_{negative} = 0.31$, $p < 0.001$) and light exercises ($r_{positive} = 0.17$, $p < 0.01$; $r_{negative} = 0.12$, $p < 0.01$).

Table 8 reports the gender difference in the analyzed items. There was no gender difference in objective or subjective brightness. Females were higher in general health and sleepiness compared to males (general health $M_{Male} = 3.41$, $M_{Female} = 3.59$, $d = 0.21$, $t = 1.87$, $p < 0.1$; sleepiness $M_{Male} = 1.92$, $M_{Female} = 2.07$, $d = 0.28$, $t = 2.47$, $p < 0.01$). No statistical difference was found in nighttime behaviors except for a few exercise-related items (i.e., lower in females).

Table 7. Correlation matrix of the analyzed variables (Survey 2).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1. Age	1																						
2. Education	−0.15 **	1																					
3. Income	−0.02	0.23 ***	1																				
4. Urbanization	−0.02	<0.01	0.11 *	1																			
5. Light environment of residential street	0.11 *	−0.03	0.13 *	0.30 ***	1																		
6. Light environment of shop street	−0.12 *	−0.03	0.15 **	0.34 ***	0.46 ***	1																	
7. Objective brightness	−0.12 *	0.22 ***	0.19 ***	0.42 ***	0.19 ***	0.31 ***	1																
8. Subjective brightness	0.03	0.02	0.10	0.32 ***	0.49 ***	0.42 ***	0.24 ***	1															
9. Visibility	0.19 ***	−0.06	−0.03	0.23 ***	0.46 ***	0.31 ***	0.13 *	0.60 ***	1														
10. Light color	0.08	0.003	−0.01	0.15 **	0.33 ***	0.25 ***	0.10	0.31 ***	0.32 ***	1													
11. Glare	−0.11	0.06	0.08	0.11 *	0.30 ***	0.28 ***	0.07	0.48 ***	0.38 ***	0.29 ***	1												
12. Positive perceptions	0.20 ***	−0.04	0.11	0.23 ***	0.38 ***	0.23 ***	0.14 *	0.50 ***	0.46 ***	0.23 ***	0.21 ***	1											
13. Negative perceptions	−0.17 ***	0.24 ***	0.10	0.09	0.04	0.08	0.09	0.11	0.02	0.09	0.33 ***	−0.02	1										
14. Knowledge	−0.02	0.25 ***	0.14 *	0.04	0.08	0.07	0.13 *	0.12 **	0.04	0.02	0.20 ***	0.07	0.27 ***	1									
15. Concern	<0.01	0.27 ***	0.13 *	−0.04	−0.01	0.03	0.09	0.07	0.003	−0.02	0.12 *	0.04	0.22 ***	0.61 ***	1								
16. Insomnia	−0.14 *	−0.03	−0.17 **	−0.004	−0.08	−0.04	−0.02	−0.01	−0.04	−0.11 *	0.07	−0.05	0.11 *	0.09	0.10	1							
17. Sleepiness	−0.28 ***	0.01	0.02	−0.05	−0.12 *	−0.02	−0.01	−0.03	−0.09	−0.06	0.07	−0.08	0.07	0.08	0.11	0.46 ***	1						
18. General health	0.01	−0.02	0.06	0.07	0.11	0.10	0.02	0.07	0.01	0.06	−0.10	0.13 *	−0.14 *	−0.09	−0.02	−0.41 ***	−0.18 ***	1					
19. Depression	−0.21 ***	0.06	0.01	−0.04	−0.14 *	0.10	0.02	0.05	−0.02	0.002	0.21 ***	−0.09	0.18 ***	0.15 **	0.12 *	0.44 ***	0.34 ***	−0.37 ***	1				
20. Stress	−0.003	0.20 ***	0.04	−0.04	−0.06	−0.001	0.09	0.02	0.02	−0.06	−0.001	−0.01	0.12 *	0.25 ***	0.31 ***	0.28 ***	0.24 ***	−0.22 ***	0.51 ***	1			
21. Outdoor activities	−0.21 ***	0.10	0.08	−0.05	0.06	0.25 ***	0.04	0.34 ***	0.21 ***	0.15 **	0.35 ***	0.17 **	0.31 ***	0.18 **	0.13 *	0.07	0.11 *	−0.02	0.41 ***	0.20 ***	1		
22. Outdoor traveling for indoor activities	−0.27 ***	−0.02	0.08	−0.004	0.06	0.12 *	−0.04	0.17 **	0.04	−0.06	0.12 *	0.08	0.04	0.14 *	0.08	0.04	0.19 ***	0.03	0.12 *	0.13 *	0.45 ***	1	
23. Light exercises	0.04	0.05	0.07	−0.04	0.11	0.14 ***	0.01	0.30 ***	0.15 **	0.17 **	0.23 ***	0.17 **	0.12 *	0.16 **	0.10	0.06	0.06	0.003	0.26 ***	0.20 ***	0.55 ***	0.42 ***	1

Note: $n = 320$. Significant at *** $p < 0.001$, ** $p < 0.01$, and * $p < 0.05$.

Table 8. Unpaired *t*-test results by gender (Survey 2).

	Male (*n* = 185)		**Female (*n* = 135)**		***d* (Effect Size)**	***t***	***p***
	Mean, %	***SD***	**Mean, %**	***SD***			
Demographic characteristics							
Age (years)	47.21	16.41	42.39	14.43	0.31	2.73	0.007
Education (bachelor's degree or above %)	71.89 (*M* = 0.72)	0.45	49.63 (*M* = 0.50)	0.50	0.47	4.16	0.000
Income (household annual, million JPY)	6.86	4.25	6.58	4.30	0.16	1.44	0.151
Occupation (employed in private or public sector %)	62.7 (*M* = 0.63)	0.48	34.81 (*M* = 0.35)	0.48	0.58	5.11	0.000
Shiftwork (yes %)	18.92 (*M* = 0.19)	0.39	22.22 (*M* = 0.22)	0.42	0.08	0.72	0.470
Objective brightness	9.69	4.85	9.56	4.78	0.03	0.23	0.819
Outdoor ALAN evaluation and perceptions							
Subjective brightness	2.54	0.79	2.52	0.69	0.03	0.26	0.796
Visibility	2.84	0.95	2.85	0.97	0.01	0.08	0.937
Light color	2.52	1.06	2.48	0.95	0.04	0.33	0.745
Glare	2.06	0.87	2.02	0.85	0.04	0.38	0.702
Knowledge	2.50	1.01	2.42	0.93	0.18	1.62	0.107
Concern	2.77	1.06	2.93	1.03	0.15	1.34	0.182
Positive perceptions	3.00	0.81	2.95	0.80	0.07	0.59	0.557
Negative perceptions	2.11	0.81	2.16	0.77	0.06	0.52	0.601
Neighborhood environment							
Urbanization	2.36	0.58	2.43	0.71	0.11	1.01	0.314
Noise	3.97	0.85	3.99	0.83	0.03	0.26	0.794
Light environment of residential street	2.74	1.06	2.71	1.08	0.03	0.24	0.808
Light environment of shop street	3.65	1.36	3.85	1.41	0.15	1.30	0.196
Health and sleep							
General health	3.41	0.84	3.59	0.88	0.21	1.87	0.063
Insomnia	1.70	0.47	1.79	0.58	0.17	1.52	0.128
Sleepiness	1.92	0.53	2.07	0.57	0.28	2.47	0.014
Depression	1.72	0.48	1.77	0.42	0.11	0.93	0.351
Stress	2.53	0.57	2.54	0.59	0.02	0.17	0.862
Nighttime outdoor behaviors							
Go out walking	2.38	1.90	1.92	1.59	0.26	2.31	0.021
Go out jogging	1.68	1.34	1.32	0.94	0.31	2.71	0.007
Go out biking	1.76	1.51	1.41	1.17	0.25	2.22	0.027
Go out to exercise	1.51	1.19	1.34	0.99	0.15	1.33	0.183
Exercise in outdoor sports facilities	1.61	1.34	1.28	0.87	0.28	2.49	0.013
Exercise in indoor sports facilities	1.78	1.51	1.61	1.38	0.12	1.03	0.302
Go out to the park	1.79	1.36	1.66	1.32	0.10	0.86	0.393
Go out to see the night view of the city	1.50	0.96	1.47	0.96	0.02	0.21	0.831
Go out to see the starry sky	1.79	1.24	1.75	1.31	0.04	0.32	0.748
Go out for a meal or drink	2.73	1.36	2.77	1.47	0.03	0.26	0.799
Go out to indoor amusement venues	1.72	1.20	1.65	1.14	0.06	0.54	0.586
Go out to public baths or hot springs	1.86	1.29	1.72	1.22	0.11	0.98	0.326
Go out for a drive	2.04	1.33	1.87	1.25	0.13	1.11	0.267
Go out to a convenience store	3.46	1.68	3.30	1.59	0.10	0.91	0.366
Go out to a supermarket	3.38	1.68	3.62	1.54	0.15	1.30	0.196
Go out to a department store or shopping mall	2.44	1.48	2.44	1.41	0.005	0.04	0.968
Meet friends, families, or relatives outside home	2.40	1.49	2.32	1.36	0.06	0.50	0.617
Visit the homes of friends, families, or relatives	2.19	1.45	2.16	1.34	0.02	0.21	0.832
Go to the workplace or school to work or study	2.95	2.36	2.06	2.36	0.05	0.40	0.687
Go to cafes or libraries to study or work	1.75	1.36	1.59	1.24	0.12	1.07	0.286

Note: *SD* = standard deviation.

4.2.3. SEM on Outdoor ALAN Perceptions, Behaviors, and Health

The SEM result is shown in Figure 2. SEM yielded an acceptable model fit (RMSEA = 0.059, CFI = 0.875). Positive ALAN perceptions were positively associated with brightness (β = 0.49,

$p < 0.001$), visibility ($\beta = 0.27$, $p < 0.001$), and cool light color ($\beta = 0.13$, $p < 0.05$). Negative ALAN perceptions were positively associated only with glare ($\beta = 0.34$, $p < 0.001$). Both positive and negative perceptions were positively associated with outdoor activities ($\beta_{positive} = 0.28$, $p < 0.001$; $\beta_{negative} = 0.34$, $p < 0.001$) and light exercises ($\beta_{positive} = 0.30$, $p < 0.001$; $\beta_{negative} = 0.14$, $p < 0.05$). In addition, light exercises were negatively associated with mental health ($\beta = -0.27$, $p < 0.001$). Positive perceptions were positively associated with sleep quality ($\beta = 0.27$, $p < 0.01$), general health ($\beta = 0.16$, $p < 0.05$), and mental health ($\beta = 0.23$, $p < 0.01$). Negative perceptions were negatively associated with general health ($\beta = -0.14$, $p < 0.05$). Positive ALAN perceptions had positive associations with age ($\beta = 0.20$, $p < 0.01$), whereas negative perceptions had positive associations with education ($\beta = 0.19$, $p < 0.001$).

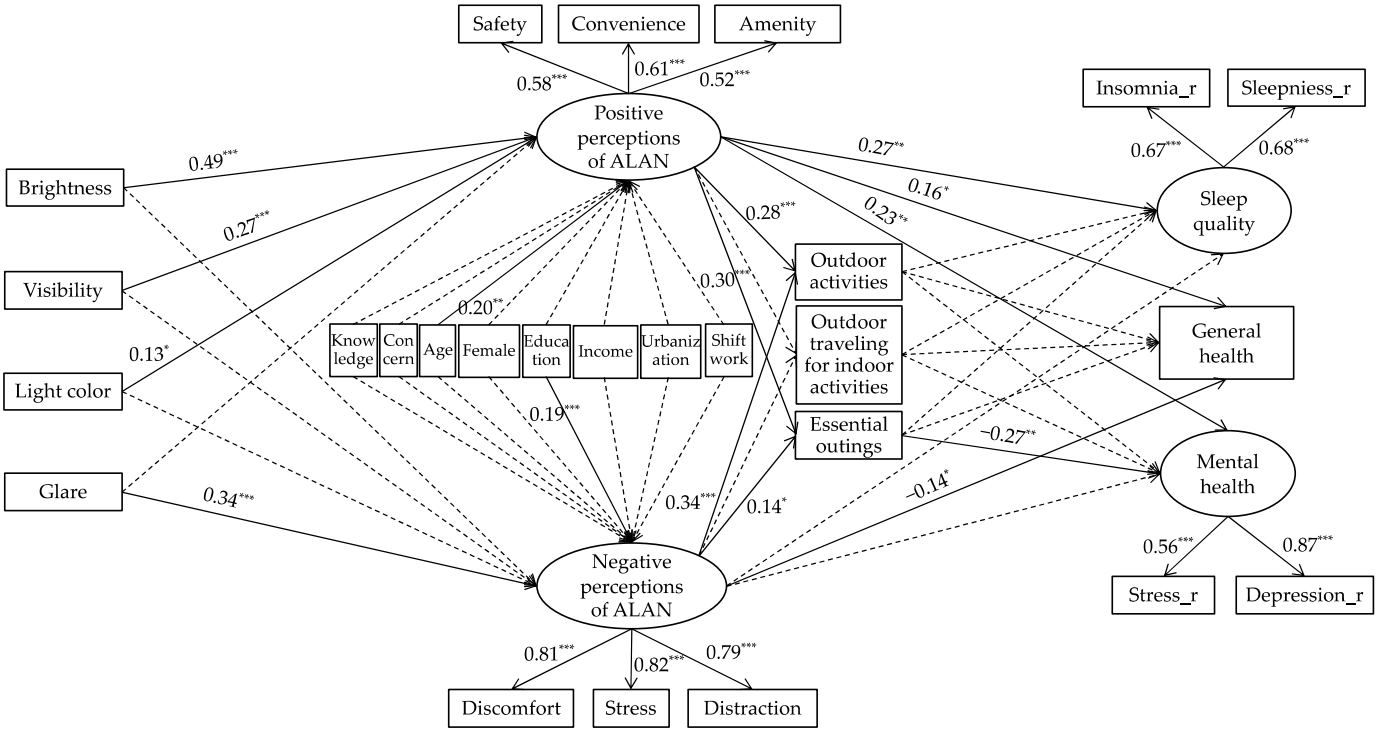

Figure 2. Structural associations of outdoor ALAN evaluation with perceptions, nighttime outdoor behaviors, sleep quality, and general and mental health (Survey 2). Notes: $n = 320$, χ^2 (185) = 390.06, $p < 0.001$, RMSEA = 0.059, CFI = 0.875. Significant at *** $p < 0.001$, ** $p < 0.01$, and * $p < 0.05$. Solid and dotted lines indicate significant and insignificant paths, respectively. "_r" at the end of the measurement variable name indicates a reversed item.

4.2.4. T-Test on the Two Cities

Table 9 reports the descriptive statistics and *t*-test results for the Tokyo and Tsukuba survey data on demographic characteristics, objective and subjective brightness, ALAN evaluation and perceptions, neighborhood environment, sleep and health, and nighttime outdoor behaviors. The objective brightness in Tokyo is much higher than in the Tsukuba area ($M_{Tokyo} = 25.47$, $M_{Tsukuba} = 9.64$, $d = 2.27$, $t = 43.92$, $p < 0.001$). The Tokyo respondents perceived higher brightness ($M_{Tokyo} = 3.17$, $M_{Tsukuba} = 2.53$, $d = 0.85$, $t = 13.7$, $p < 0.001$) and visibility ($M_{Tokyo} = 3.66$, $M_{Tsukuba} = 2.85$, $d = 0.93$, $t = 14.97$, $p < 0.001$), cooler lighting colors ($M_{Tokyo} = 3.11$, $M_{Tsukuba} = 2.50$, $d = 0.56$, $t = 9.01$, $p < 0.001$), and more glare ($M_{Tokyo} = 2.43$, $M_{Tsukuba} = 2.04$, $d = 0.42$, $t = 6.82$, $p < 0.001$) than the Tsukuba respondents. The respondents in Tokyo had more positive perceptions about outdoor nighttime light than those in Tsukuba ($M_{Tokyo} = 3.37$, $M_{Tsukuba} = 2.98$, $d = 0.57$, $t = 9.25$, $p < 0.001$), while there was no significant difference in negative perceptions between the two cities. The neighborhood environments of the two cities were also significantly different, with Tokyo being more urbanized ($M_{Tokyo} = 3.22$, $M_{Tsukuba} = 2.39$, $d = 1.30$, $t = 20.65$, $p < 0.001$), noisier

(M_{Tokyo} = 2.43, $M_{Tsukuba}$ = 2.03, d = 0.42, t = 6.79, $p < 0.001$), and having a brighter residential (M_{Tokyo} = 4.10, $M_{Tsukuba}$ = 2.73, d = 1.00, t = 16.30, $p < 0.001$) and shopping street environment (M_{Tokyo} = 4.90, $M_{Tsukuba}$ = 3.73, d = 0.86, t = 13.90, $p < 0.001$). Additionally, the Tokyo respondents reported a higher insomnia score (M_{Tokyo} = 1.83, $M_{Tsukuba}$ = 1.73, d = 0.17, t = 2.71, $p < 0.01$) and worse physical health (M_{Tokyo} = 3.37, $M_{Tsukuba}$ = 3.49, d = 0.13, t = 2.08, $p < 0.05$).

Table 9. Unpaired *t*-test results for the Tokyo and Tsukuba survey data.

	Tokyo (n = 1405)		**Tsukuba (n = 320)**		***d* (Effect Size)**	***t***	***p***
	Mean, %	***SD***	**Mean, %**	***SD***			
Demographic characteristics							
Gender (male %)	54.45 (M = 0.54)	0.50	57.81 (M = 0.58)	0.49	0.07	1.09	0.275
Age (years)	47.68	16.58	45.17	15.76	0.15	2.45	0.014
Education (bachelor's degree or above %)	63.06 (M = 0.63)	0.48	62.50 (M = 0.63)	0.48	0.01	0.19	0.852
Income (household annual, million JPY)	6.98	4.58	6.62	4.30	0.08	1.28	0.202
Occupation (employed in private or public sector %)	53.96 (M = 0.54)	0.50	50.94 (M = 0.51)	0.50	0.06	0.97	0.330
Shiftwork (yes %)	18.01 (M = 0.18)	0.38	20.31 (M = 0.20)	0.40	0.06	0.96	0.337
Objective brightness	25.47	6.03	9.64	4.82	2.27	43.92	0.000
Outdoor ALAN evaluation and perceptions							
Subjective brightness	3.17	0.76	2.53	0.75	0.85	13.70	0.000
Visibility	3.66	0.86	2.85	0.96	0.93	14.97	0.000
Light color	3.11	1.11	2.50	1.01	0.56	9.01	0.000
Glare	2.43	0.93	2.04	0.86	0.42	6.82	0.000
Knowledge	2.50	0.87	2.52	0.98	0.02	0.40	0.691
Concern	2.82	1.00	2.84	1.05	0.01	0.21	0.834
Positive perceptions	3.37	0.66	2.98	0.81	0.57	9.25	0.000
Negative perceptions	2.20	0.86	2.13	0.79	0.08	1.21	0.226
Neighborhood environment							
Urbanization	3.22	0.65	2.39	0.64	1.30	20.65	0.000
Noise	2.43	1.00	2.02	0.84	0.42	6.79	0.000
Light environment of residential street	4.10	1.42	2.73	1.07	1.00	16.30	0.000
Light environment of shop street	4.90	1.35	3.73	1.39	0.86	13.90	0.000
Health and sleep							
General health	3.37	0.94	3.49	0.86	0.13	2.08	0.037
Insomnia	1.83	0.61	1.73	0.52	0.17	2.71	0.007
Sleepiness	1.98	0.61	1.98	0.55	0.01	0.09	0.935
Depression	1.80	0.50	1.74	0.45	0.12	1.88	0.060
Stress	2.57	0.60	2.53	0.58	0.07	1.16	0.245
Nighttime outdoor behaviors							
Go out walking	2.46	1.91	2.19	1.79	0.15	2.37	0.018
Go out jogging	1.67	1.38	1.53	1.20	0.10	1.65	0.100
Go out biking	1.74	1.48	1.62	1.39	0.10	1.40	0.162
Go out to exercise	1.54	1.29	1.43	1.11	0.10	1.37	0.170
Exercise in outdoor sports facilities	1.47	1.16	1.47	1.18	0.01	0.09	0.929
Exercise in indoor sports facilities	1.84	1.63	1.71	1.46	0.10	1.39	0.164
Go out to the park	1.98	1.56	1.73	1.34	0.16	2.63	0.009
Go out to see the night view of the city	1.78	1.35	1.49	0.96	0.23	3.71	0.000
Go out to see the starry sky	1.76	1.32	1.78	1.28	0.01	0.21	0.835
Go out for a meal or drink	2.98	1.51	2.75	1.40	0.15	2.50	0.013
Go out to indoor amusement venues	1.83	1.30	1.69	1.17	0.11	1.73	0.083
Go out to public baths or hot springs	1.84	1.28	1.80	1.27	0.03	0.50	0.620

Table 9. *Cont.*

	Tokyo (n = 1405)		Tsukuba (n = 320)		d (Effect Size)	t	p
	Mean, %	*SD*	Mean, %	*SD*			
Go out for a drive	1.86	1.36	1.97	1.30	0.08	1.35	0.176
Go out to a convenience store	3.67	1.70	3.40	1.64	0.16	2.60	0.009
Go out to a supermarket	3.48	1.73	3.48	1.63	0.001	0.01	0.992
Go out to a department store or shopping mall	2.27	1.50	2.44	1.45	0.11	1.85	0.064
Meet friends, families, or relatives outside home	2.55	1.45	2.37	1.44	0.12	2.01	0.045
Visit the homes of friends, families, or relatives	2.12	1.36	2.18	1.40	0.04	0.68	0.496
Go to the workplace or school to work or study	2.82	2.32	3.00	2.36	0.08	1.24	215
Go to cafes or libraries to study or work	1.86	1.43	1.68	1.31	0.12	1.96	0.050

Note: *SD* = standard deviation.

There were significant differences between Tokyo and Tsukuba in some nighttime outdoor behaviors. The frequency was higher among the Tokyo respondents in several behaviors: go out walking (M_{Tokyo} = 2.46, M_{Tsukuba} = 2.19, d = 0.15, t = 2.37, $p < 0.05$), go to the park (M_{Tokyo} = 1.98, M_{Tsukuba} = 1.73, d = 0.16, t = 2.63, $p < 0.01$), go out to see the city night view (M_{Tokyo} = 1.78, M_{Tsukuba} = 1.49, d = 0.23, t = 3.71, $p < 0.001$), go out for a meal or drink (M_{Tokyo} = 2.98, M_{Tsukuba} = 2.75, d = 0.15, t = 2.50, $p < 0.05$), go to a convenience store (M_{Tokyo} = 3.67, M_{Tsukuba} = 3.40, d = 0.16, t = 2.60, $p < 0.01$), meet friends/families (M_{Tokyo} = 2.55, M_{Tsukuba} = 2.37, d = 0.12, t = 2.01, $p < 0.05$), and go to the cafes/libraries to study/work (M_{Tokyo} = 1.86, M_{Tsukuba} = 1.68, d = 0.12, t = 1.96, $p < 0.05$).

4.3. Discussion for Survey 2

Survey 2 aimed to duplicate Survey 1, which was conducted in Tokyo, and to confirm and compare the results on the relationships between outdoor ALAN perceptions, nighttime outdoor behaviors, and health. Survey 2 obtained three types of nighttime outdoor behaviors: outdoor activities, outdoor traveling to indoor activities, and light exercises, with the last categorization different from that in Survey 1. Obtaining light exercises (i.e., walking and outings to the park) as a distinctive factor among the three in Survey 2 is reasonable, considering the much higher availability of space and accessibility of this type of activity in Tsukuba compared to Tokyo. Tsukuba is well-furnished with pedestrian-only streets with a total length of 48 km in the central area, relatively wide sidewalks, and as many as 146 parks, many of which are accessible through the pedestrian-only streets, while some are also equipped with walking and jogging tracks [45].

The SEM result confirms the associations between outdoor ALAN evaluation, its positive and negative perceptions, nighttime outdoor behavior, and health. On the one hand, the current results confirm positive associations of positive ALAN perceptions with health, including sleep; that is, when respondents felt outdoor ALAN was safer and more convenient, the quality of their general and mental health and sleep was higher. On the other hand, positive associations were found between negative ALAN perceptions (i.e., discomfort, stress, and distraction) and two nighttime outdoor behavioral factors, outdoor activities, and light exercises, contrary to our initial hypothesis. This will be discussed based on the results of Surveys 1 and 2 in the next section.

5. General Discussion

In this study, we examined how residents' perceptions of outdoor ALAN affected their nighttime outdoor behaviors, sleep quality, and physical and mental health using the questionnaire-response datasets for Tokyo and Tsukuba, Japan. The general findings from structural analyses of the two samples suggest that brightness and visibility increase positive ALAN perceptions, enhancing nighttime outdoor behaviors and general and mental health. They also suggest that glare increases negative ALAN perceptions, deteriorating general health but enhancing behaviors. The association of positive ALAN perceptions

with nighttime outdoor behaviors confirms previous research findings [4,46]. To the best of our knowledge, this study is the first to report structural associations between (both positive and negative) outdoor ALAN perceptions, nighttime outdoor behaviors, and health in multiple cities.

The most interesting finding in this study is that negative perceptions of outdoor ALAN, i.e., discomfort, stress, and distraction, could enhance nighttime outdoor behaviors in both study areas, which was initially assumed to be the opposite. We believe there are two possible reasons for this controversial result. First, it is known that feeling negative can make people go out at night more often and for a longer time to relieve stress [47]. When stimulated by light while outside, melatonin production is suppressed, making the body more excited and alert, which could consequently negatively impact their health and sleep quality due to increased difficulties in keeping an appropriate sleep–wake cycle. Negative feelings caused by outdoor ALAN may also lead to this general coping behavior, i.e., going out to refresh. Because people often need to work or study during the day, the evening is the best time to schedule activities that they enjoy to relieve stress. The second possibility is the opposite causality between negative perceptions and behavior. Outdoor ALAN typically includes streetlights, vehicular headlights, residential lights, parking lots, sporting venues, and lights from commercial districts, shops, or business offices [10,19,24]. These lighting facilities assist people in accessing and experiencing necessary or leisure activities. Outdoor ALAN may thus boost outings during the evening, particularly in urbanized commercial districts equipped with different types of lighting, which would increase exposure to outdoor nighttime light and would thus eventually make people perceive outdoor ALAN negatively.

Furthermore, the opposite and mixed causality are also possible among health factors, including sleep, behaviors, and ALAN perceptions. For example, people with insomnia or other sleep problems are more likely to go out at night, such as jogging or walking, because exercise is considered one of the behavioral therapies for poor sleep or sleep disorders [48]. As a result, this type of individual may become more aware of nearby outdoor lighting conditions and have a more salient sense of pros and cons toward outdoor ALAN than individuals whose health conditions are moderate and who have no proactive reasons for going out at night. The associations of negative ALAN perceptions with nighttime outdoor behaviors may be interdependent and recursive in daily life. They may also be explained by interactions with other socio-environmental factors related to urbanization, such as noise, business, greens, and typical activities.

Another interesting result is that nighttime outdoor behaviors, regardless of their purpose, could inhibit sleep quality and physical and mental health in both study areas. We had initially assumed that health-related outings, such as walking and jogging, could enhance physical and mental health as part of daily exercise during the available time after returning home, as it is widely known that exercises, to a certain extent, benefit the physical and mental health status [42]. However, nighttime outdoor behaviors reduce sleep quality and physical and mental health, and this phenomenon is more pronounced in urban cities with higher outdoor ALAN levels. It is possible that going out at night, per se, increases exposure to outdoor ALAN and disrupts the brain's production of melatonin, leading to poorer sleep quality, eventually inducing stress and depression, and deteriorating physical health. Indeed, a previous study suggested that morning exercise might be better for sleep than evening exercise in regulating circadian rhythms [49]. Our findings thus imply that the adverse effects of nighttime light exposure could mask the health benefits of physical exercise and social relationships. These findings suggest the importance of designing the minimum required lighting at night to avoid excessive light exposure while maintaining the positive effects of nighttime outings at both the district and social scales.

This study also found that the residents in the two cities did not care considerably about the light color to which they were exposed (i.e., blue/white to yellow/orange) compared with the other light indicators, namely, brightness, visibility, and glare. The light color had no significant effect on positive or negative perceptions of outdoor ALAN,

whereas the other three indicators did. This may be because people often consider light sources brighter or darker than color when explicitly evaluating them. Therefore, according to the residents' evaluation, illuminance, visibility, and the glare of lighting should draw more attention to outdoor lighting design than light colors. However, some attention must be paid to light color in both research and practice regarding nighttime light because the desirable color temperature may differ depending on community characteristics, lighting purposes, and times of the day/night (e.g., [50]).

The two surveys in this study provide interesting implications for differences in outdoor nighttime light situations and behaviors by area. According to the *t*-test results, Tokyo (Survey 1) was significantly brighter than Tsukuba (Survey 2) based on the residents' evaluation, which is generally consistent with the objective brightness, i.e., satellite nighttime light data. Tokyo's residents go out relatively more frequently at night (e.g., exercising, eating out, shopping, and meeting people) than Tsukuba's residents. Furthermore, the factor analyses of nighttime outdoor behaviors yielded similar but different sets of behavioral factors in the two cities. The common behavioral factors in the two samples were outdoor activities and outdoor travel compared to indoor activities. For the behavioral factor unique to each city, on the one hand, residents in Tokyo tend to engage in essential outings at night to buy groceries at supermarkets or convenience stores. This may be because small-volume and more frequent grocery shopping on foot is more common and feasible in urban areas during the evening than in Tsukuba, where large-volume shopping by car during the daytime is common. The *t*-test results also showed that going to convenience stores at night occurred more frequently in Tokyo than in Tsukuba.

On the other hand, we obtained the factor of light exercises (i.e., going for a walk in the park or jogging) from the Tsukuba sample. This may be because this kind of exercise in the neighborhood is quite popular and feasible at night on the well-deployed pedestrian-only streets and relatively wide sidewalks in the city. These results suggest that living in different light environments and other urban and suburban characteristics tend to lead to area-specific uniqueness in lifestyles and, thus, what people do outside after dark. We also found that residents of Tokyo and Tsukuba differ in sleep quality and general health, and this may be due to the differences in outdoor ALAN but also urbanization, noise, and other urban characteristics in the two areas. These results show that outdoor ALAN can affect all aspects of human life, leading to different outcomes in different cities.

Furthermore, our *t*-test results for gender comparison in each city imply that gender is one of the key demographic variables to understand the influence of outdoor ALAN on human behavior and health in different living environments. The SEM result for Tsukuba (Survey 2) yielded fewer significant associations in the model than that for Tokyo (Survey 1), particularly regarding the associations between behaviors and health. This may be because of the relatively darker nighttime environment and low frequency of the behavior compared with Tokyo, which blurred the associations between outdoor lighting and nighttime activities. This implies that relationships between outdoor nighttime lighting and residents' perceptions and behaviors differ by city. Further investigation of this topic at the individual level and in other cities is necessary.

The findings in the current study suggest a few practical implications for balancing the pros and cons of outdoor nighttime light. First, lighting regulations should consider the effects of outdoor nighttime light on human behaviors and physical and mental health. Therefore, urban planners and policymakers should be aware of the potential impacts of outdoor nighttime lighting on human health and behavior and develop lighting strategies that promote healthy, safe, and sustainable urban environments. Current restrictions are mainly aimed at starry skies, visual safety and discomfort, and energy efficiency. This study sheds light on the importance of human health in designing outdoor nighttime lighting by demonstrating that both positive and negative perceptions of lighting could influence human behaviors and health. More specifically, glare is viewed as a negative factor in the subjective evaluation of lighting, while brightness and visibility are positively appreciated. This suggests that compromising regulations to lower glare while making people feel safe

and comfortable is necessary from a human health perspective. By practicing sustainable outdoor lighting, including smart lighting technologies and lighting regulations, the benefits of lighting can be balanced with the necessity to maintain natural darkness to improve sleep quality and overall health among humans as well as the natural ecosystem. Second, stakeholders in policy design, such as government officials, urban planners, and activists, should consider diversity in outdoor nighttime lighting situations, perceptions, behaviors, and health among residents at the district and municipality levels. This study found significant differences in these two aspects between Tokyo (i.e., urban areas) and Tsukuba (i.e., suburban and rural areas), as well as the interrelationship between these factors. It is thus essential to consider the local uniqueness and characteristics, including residents' perceptions and needs for outdoor nighttime lighting, in planning street lighting and lighting regulations. Overall, balancing the benefits of outdoor ALAN with its potential drawbacks is crucial to ensuring a sustainable and harmonious coexistence with the natural environment.

This study has a few limitations. First, the investigation of outdoor ALAN perceptions, nighttime outdoor behaviors, sleep quality, and health is based on self-reported responses and may not capture the respondents' accurate situations in lighting environments and behaviors. A detailed investigation of this matter is required, for example, through objective data measurement of light exposure, behaviors, and health. Second, we analyzed only the nighttime light environments of neighborhood residences and shop streets and did not consider those in indoor and outdoor activities (e.g., home, offices, commuting, stores, and sports fields) and the duration of the activities. Light exposure and its influence on humans are not separated by time or place but are continuous and cumulative [51]. A detailed, longitudinal investigation of residents in selected districts is necessary to clarify this relationship further, including interrelations. Panel data or experimental studies are also essential to clarify the causal associations between nighttime light, perceptions, and behaviors, which were not determined by the cross-sectional dataset in the current study. Finally, this study considered only the overall urbanization level as well as the (sub)urban characteristics of the studied cities. Future studies should consider diverse factors related to quality of life, such as environmental pollution, landscape, and traffic busyness, to provide a more elaborate picture of human life in urban settings, including outdoor ALAN.

6. Conclusions

This study revealed the potential benefits and harms of outdoor ALAN to human health and behaviors through outdoor ALAN perceptions among residents in the Tokyo metropolitan area and Tsukuba City in Japan based on investigations of their structural associations. The current findings shed light on the controversial relationships between the pros and cons of nighttime light perceptions and behaviors and health; the findings contribute to a better design of nighttime lighting in outdoor public and private spaces with relevant restrictions by balancing the benefits and harms of outdoor ALAN.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Research Ethics Board of the University of Tsukuba (Approval number 2021R525).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to institutional restrictions.

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