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White Paper

Outdoor Light-Emitting Diode (LED) Lighting and Human Health: A State of the Evidence Analytic Literature Review

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Abstract

Aim: to examine the state of the evidence on the effects of outdoor LED lighting on human health.

Method: we used rapid review methods. Our review included 27 peer-reviewed articles and six practice-based reports.

Results: the most developed literature related to street and area LED lighting, followed by LED traffic signals and pedestrian crossings, and outdoor screens and train station lighting.

Conclusions: we found that there is no one-size-fits-all approach for outdoor LED lighting. Lighting design can mitigate potential human health risks of outdoor LED lighting. However, trade-offs may be required to balance different users' needs and preferences for LED lighting, economic and energy costs, and other potential harms and benefits. Testing new outdoor LED lighting and gathering feedback before implementing changes can ensure the best fit for the specific setting and population.

Keywords: Light-emitting diode (LED) lighting; human health; outdoor lighting; rapid review methodology

Introduction

Growing awareness of climate change has increased the demand for energy-conserving technologies that result in lower greenhouse gas (GHG) emissions. Many municipalities have converted outdoor lighting to light-emitting diode (LED) technology because of the greater efficiency, the possibility for them to be dimmed centrally, and lower operational costs compared to conventional lighting[1].

The majority of streetlights in Edmonton, the capital city of the Canadian province of Alberta (2016 census population: 1,062,643),[2] were high-pressure sodium luminaires.[3] Edmonton's LED streetlight conversion, which began in 2011, is expected to reduce power consumption by 30% and GHG emissions by 6%.[3] Municipalities have also converted traffic signals to LED lights because of the energy benefits, lower costs and maintenance needs[4-6] and greater visibility in bad weather.[4] Edmonton's traffic signal conversion from incandescent to LED lights in 2006 resulted in a decrease in power consumption of about 60%.[3]

Although using LED lighting reduces energy use[7] and costs,[8] potential health impacts need to be considered. This is particularly relevant to mass-scale conversions from incandescent lighting that municipalities have undertaken for outdoor lighting. Human exposure to light at night, including from LED sources, can negatively affect mental and physical health.[8-11] Such exposure can result in exhaustion related to poor quality sleep,[12-14] changes in metabolism associated with obesity,[11,15-17] and an increased risk of depression,[14,18] breast cancer,[18] and prostate cancer.[8,9] Visible blue-spectrum light, which is more common in LED lighting than in other artificial light sources,[1,19] has been shown to have a disruptive effect on circadian rhythm via melatonin suppression[20,21] and may pose additional risks,[20,22-24] particularly to children, seniors, people who experience visual impairment or eye or skin conditions, and certain occupational groups.[19,25]

We used rapid review methods to find relevant information on the potential health consequences of exposure to outdoor LED lighting in urban and suburban environments and guide policy action in the area. Our secondary objective was to assess the health equity implications of the current evidence.

Methods

We used rapid review methods[26] to determine the scope of the relevant information on the effects of urban and suburban outdoor LED lighting on human health (i.e., social, physical, and mental). Rapid reviews have demonstrated their utility in the area of health-related decision-making policy and practice.[27-30]

This rapid review used a five-step process: 1) research question development; 2) search strategy development; 3) source appraisal; 4) evidence synthesis; and 5) identification of key practice implications and gaps. This study was undertaken by researchers at the Centre for Healthy Communities, School of Public Health, University of Alberta in partnership with municipal staff at the City of Edmonton department of Citizen Services.

Step 1: Research-Practice Question Development

We used the PICO framework[26] to guide the development of the research-practice question. Using this framework involves identifying the following:

- Population: humans (adults, children)
- Intervention: LED outdoor lighting in municipal areas (urban, suburban)
- Comparator: non-LED (e.g., incandescent) outdoor lighting in municipal areas (urban, suburban)
- Outcome: physical and mental health

Our preliminary research-practice question was:

What are the effects of outdoor LED lighting on human health (physical, mental) in urban and suburban settings? After running the preliminary search, we revised and finalized the research-practice question to include social health to our outcomes of interest.

Step 2: Search Strategy Development

An MLIS-trained Information Specialist built and conducted the searches of three databases (MEDLINE, Web of Science, and Google) using terminology that reflected the responses to the PICO framework. The first literature searches, which included physical and mental dimensions of human health, were conducted on October 22, 2018. Based on the results of the preliminary search, the research-practice question was revised to include social dimensions of human health (e.g., crime, belonging). The Information Specialist ran the revised searches in the three databases on January 17, 2019. See Supplementary Table S1. for the detailed search terms.

Step 3: Source Appraisal

Two reviewers, working independently, completed the primary and secondary article screening based on a priori inclusion and exclusion criteria (see Supplementary Table S2). We had developed the inclusion and exclusion criteria based on the PICO framework[26] and with consultation and feedback from the entire team.

After removing duplicates, the reviewers pooled the academic and practice-based articles retrieved through the initial and finalized searches (*n* = 2,720) for primary screening (i.e., based on title and abstract). Primary screening excluded 2,514. Two research team members assessed the full text of the remaining articles (*n* = 206) according to the inclusion and exclusion criteria (Supplementary Table S2), after exclusion of ineligible articles (*n* = 180) 26 articles were included. The reference lists for these 26 articles were reviewed and an additional 7 articles were identified for inclusion. In total, 33 articles (i.e., 27 peer-reviewed articles, 6 practice-based reports) were included in the analytic literature review.
See Figure 1 for the article selection process and results.

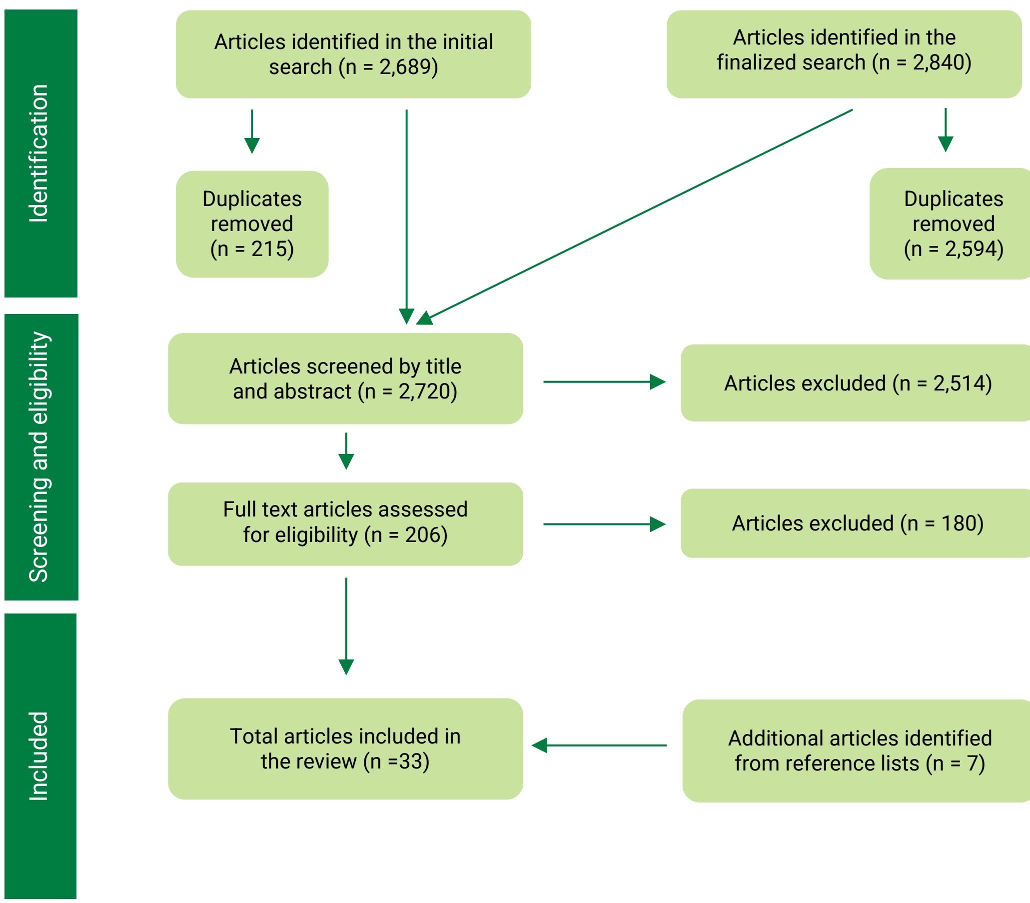

Figure 1. Article selection process and results

A single reviewer used the Mixed Methods Appraisal Tool (MMAT), 2018 version[31] to appraise the quality of the 27 academic research articles. Aligned with the instructions for the tool use, we did not exclude any articles based on the MMAT quality criteria question responses. We provide details of each article's MMAT criteria in the summary table (Table 1).

Step 4: Evidence Synthesis

A single reviewer extracted detailed content from the included articles and practice-based reports into an Excel file. We provide a summary of the extracted data per article in Table 1 for peer-reviewed articles and Table 2 for practice-based reports.

Step 5: Identification of Key Practice Implications and Gaps

Two research team members conducted detailed, independent readings of the selected articles and extracted data. They met to discuss their findings and group the articles according to LED lighting strategy: 1) street and area lighting; 2) traffic signals and pedestrian crossings; and 3) outdoor screens and train station lighting. They then consulted with a third research team member about key practice implications, literature gaps, and equity considerations. They discussed the findings and reached a consensus.

Table 1. Summary of academic research articles

Author, Year Objective	Geographical location Setting Population	Study details	Limitations[a]	Results and conclusions	Quality appraisal[b]
Bullough et al., 2000 Compared LED and incandescent traffic signals for human reaction times, color identification, frequency of missed signals, and subjective measures of brightness and noticeability.	Location not specified Laboratory with simulated daytime conditions Test 1: 10 participants aged 25–35 years; 50% female; with "normal" vision. Test 2: 30 participants; aged 22–54 years; 53% female.	Two tests compared red, yellow, and green incandescent and LED lights. In Test 1, reaction time and percentage of missed signals were measured based on the time between participants' releasing a switch and signal onset. In Test 2, color identification, perceived brightness, and noticeability were assessed based on participants' ability to identify colors and rate the signal's brightness and noticeability.	These results were based on laboratory-simulated daytime conditions with no terrain distractions and/or obstructions. Findings may not be applicable to nighttime conditions. Participants were younger and not representative of the diverse population of drivers. This study did not consider the time required for LED and incandescent lights to turn on, which differ, in relation to reaction time.	There were no statistically significant differences between LED and incandescent signals for reaction time, missed signals, color identification, brightness, or noticeability. For LED traffic signals, significantly higher illuminance was required for green and yellow to obtain similar reaction times, missed signals, brightness, and noticeability rating than for red LED traffic signals.	The study met 4 of the 5 criteria for nonrandomized studies. The alignment with the target population was unclear. The authors did not provide details on the sampling procedures and/or inclusion/exclusion criteria.
Djokic et al., 2017 Compared drivers' subjective impressions of HPS and LED streetlights.	Belgrade, Serbia Urban street used for field test of street lighting. 56 students from the University of Belgrade, aged 20–25 years, and possessing a driver's license.	An experimental field test was conducted to assess drivers' subjective impression of 2 street lighting installations based on survey results. Two 150 m long test zones, one with 6 LED lights and one with 6 adapted HPS lighting fixtures, were built. A buffer zone was created between the test zones. Drivers drove through each lighting installation twice, once with the streetlights at normal brightness and once with them dimmed.	None stated.	At normal brightness, LED street lighting was considered the better option in terms of luminance, luminance uniformity along the way, color of light, and the detection of obstacles. When the lights were dimmed or glare was present, the participants preferred HPS street lighting.	The study met 2 of the 5 criteria for nonrandomized studies. The alignment with the target population, completeness of the data, and intervention fidelity were unclear.

Author, Year Objective	Geographical location Setting Population	Study details	Limitations[a]	Results and conclusions	Quality appraisal[b]
Eustace et al., 2010 Assessed whether a change in traffic accidents had occurred at signalized intersections converted to LED signals.	Middletown, OH, USA 10 urban signalized Intersections: 8 converted to LED signals and 2 that had not been converted. Population not specified.	Data were collected on traffic accidents and average daily traffic before and after the lighting conversion. The Empirical Bayes method was used to estimate the expected number of crashes for post-treatments years had the conversion not occurred based on pre-conversion traffic data. This value was compared to the actual number of traffic accidents to assess any change in traffic accidents.	Difficulty with obtaining traffic data led to a small sample size and therefore a lack of generalizability of study findings. Due to urban development social factors, such as changes in employment, some intersections had abnormal traffic trends during the study period, which may have skewed the available data. The use of variables that account for traffic patterns changes could have produced a more accurate projection model.	The total number of traffic accidents increased by 71% after LED signal conversion, which suggested that traffic safety decreased with LED traffic signals.	The study met 3 of the 5 criteria for nonrandomized studies. The alignment with the target population was unclear and the authors did not control for confounding factors (e.g., changes in traffic patterns at intersections). They describe these factors in their study limitations.

Author, Year Objective	Geographical location Setting Population	Study details	Limitations[a]	Results and conclusions	Quality appraisal[b]
Huang et al., 2003 Compared the responses to red and yellow incandescent and LED traffic signals of different luminance of individuals with protan (i.e., red–green) color vision deficiency to individuals with normal color vision.	Location not specified. Laboratory with simulated daytime conditions. Normal color vision group: 3 male participants; age range 31–59 years; visual acuity of 20/20. Protan color vision deficiency group: 3 male participants; age range 33–57 years; visual acuity of 20/20.	Two tests were conducted to assess reaction time and color identification of 15 LED traffic signal conditions and 2 incandescent traffic signal conditions. Reaction time was based on the interval between signal onset and participants releasing a switch. In Test 1, participants performed a tracking task to simulate a driver's field of vision on a horizon line with signals located to the side. In Test 2, participants looked directly at the signals.	Limited generalizability due to small sample size.	In Test 1, the reaction time of participants with normal color vision decreased significantly with increasing luminance of LED traffic signals. Reaction times were longer for those with protan color vision deficiency. Participants with normal color vision had the longest reaction to yellow LED traffic signals with the lowest luminance time, whereas the reaction time of color vision–deficient participants was longest for yellow LED signals with the highest luminance. Participants with normal color vision were better able to identify colors, but both groups often misidentified traffic signals that had yellow LED with the lowest luminance. In Test 2, there were no differences in reaction time or color identification for those with normal color vision. The reaction time for red LED signals among color vision–deficient participants increased with shorter wavelengths (i.e., toward a more yellow color), and the shift decreased their ability to correctly identify signal color.	The study met 2 of the 5 criteria for non-randomized studies. The alignment with the target population, completeness of the data, and intervention fidelity were unclear.
Jami et al., 2011 Evaluated the traffic safety implications of full conversions of incandescent to LED lighting for traffic signals.	Memphis, TN, USA 8 intersections that had full LED replacements at approximately the same time and 2 intersection sites with no LED traffic signal replacement Population not specified	Data on traffic accidents and average daily traffic for 3 years before and after LED conversion for each site were compared. The Empirical Bayes method was used to estimate the expected number of crashes based on pre-conversion traffic data. Post-conversion traffic data were compared to the estimated model.	A lack of available data led to a small sample size. The results did not account for factors such as accident type and weather conditions.	There was a 47.3% increase in the number of crashes following the conversion to LED traffic signals. This indicated a reduction in traffic safety because of the LED traffic signals.	The study met all of the 5 criteria for nonrandomized studies.

Author, Year Objective	Geographical location Setting Population	Study details	Limitations[a]	Results and conclusions	Quality appraisal[b]
Jones, 2018b Examined the effect of LED street lighting retrofits on general life satisfaction.	USA 100 largest USA counties by population 312,525 survey respondents, aged 18+ years	The author used cross-sectional survey data from the US Centers for Disease Control and Prevention Behavioral Risk Factor Surveillance System for 2005–2010 and LED street lighting retrofit project data for the 100 largest counties by population. The author used a difference-in-difference model to compare individuals in intervention counties (i.e., counties with LED streetlight retrofits) with similar individuals in control counties (i.e., not using LED street lighting). A life satisfaction approach was used to evaluate association between residents' well-being and LED streetlight retrofits.	The study time frame was not long enough to assess major changes in health outcomes (e.g., breast cancer, prostate cancer) associated with LED street lighting because of the latency periods for these illnesses. It was not possible to spatially map out LED streetlights to individual survey responses. Some respondents may not live close to the streetlights and so the lights would have a limited impact on their life satisfaction. The life satisfaction approach provided an estimate of the effect of LED streetlights on only one measure of well-being.	Life satisfaction improvements were greater for young adults aged 18–24 years, senior citizens aged 75+ years, and individuals in fair or poor general health. Respondents living in counties where LED street lighting retrofitting had occurred had significantly higher life satisfaction than those in non-LED counties. The effect on life satisfaction was consistent over time. Increases in life satisfaction were positively associated with the number of streetlights replaced.	The study met all 5 of the criteria for non-randomized studies.
Jones, 2018a Investigated the mortality rates from breast cancer, prostate cancer, traffic accidents, and homicide of a prominent after a high-profile energy efficiency program replaced streetlights with high-efficiency LED lights.	Los Angeles, CA, USA The 2009 Los Angeles LED streetlight program replaced 67% of the total number of streetlights at an estimated cost of $57 million The mortality rates from breast cancer, prostate cancer, and traffic accidents are lower in the City of Los Angeles (in the county of Los Angeles) than the 100 largest counties in the USA by population (i.e., control group) while homicide rates are higher.	The impacts on mortality rates of the LED streetlight program was estimated with a constructed counterfactual approach by using a comparison group consisting of counties in the USA that shared common pre-treatment health trends. The findings were based on 1995–2014 data from annual county-level national mortality data from the US Centers for Disease Control and Prevention National Centre for Health Statistics.	The available data only allowed analysis of up to a 5-year latency period during which any LED-induced cancer mortality would be in the developmental stages and unaccounted for in mortality data. The constructed counterfactual approach limited the causal interpretation of the result. It was not possible to conclude that the observed changes were caused by the LED lighting program.	The LED streetlight program was associated with a lagged increase in breast cancer mortality. There were no increases in the rates of prostate cancer, traffic accidents, or homicide. When considering the effects on breast cancer mortality rates, the energy savings of the LED streetlight program were insufficient to provide a positive investment return. When the health impacts were considered, the program provided an −146.2% 10-year return. This compared to +118.2% when health outcomes were ignored.	The study met all 5 of the criteria for non-randomized studies.

Author, Year Objective	Geographical location Setting Population	Study details	Limitations[a]	Results and conclusions	Quality appraisal[b]
Kostic and Djokic, 2014 Compared pedestrians' subjective impressions of LED and MH ambient area lighting.	Belgrade, Serbia Paved pedestrian path in an urban park used for field testing ambient lighting. 112 participants, aged 20–30 years, 55% male, with healthy eyesight.	A pilot lighting project was conducted along a pedestrian path in a Belgrade park with 2 sequences of lighting installations, one with MH and one with LED lighting. The luminaries for both lighting types were identical and a uniform diffuser was applied to prevent participants from recognizing the light sources. Surveys were administered to gather participants' feedback on specific aspects of lighting and overall subjective impression of lighting.	The results have limited generalizability because the lighting installations could not encompass the range of conditions that are possible with MH and LED ambient area lighting.	Most participants preferred the MH lighting in terms of the illuminance uniformity, color, and feeling of comfort. Given that LED luminaires can provide luminance uniformities comparable to MH lighting, the findings of this pilot cannot be considered generalizable.	The study met all 5 criteria for nonrandomized studies. The study was described as a pilot. Participants were university students with good eyesight, i.e., not representative of the general population.
Kivimaki, 2013 Assessed the financial and secondary effects of retrofitting LED streetlights across 18 case-study cities to project the potential energy and maintenance effects of retrofitting LED lighting in São José dos Campos, Brazil.	Brazil, Canada, UK, USA 18 case-study cities USA: Anchorage, AK; Baltimore, MD; Boise, ID; Boston, MA; Brentwood, CA; Canton, OH; Chattanooga, TN; Fallon, NV; Jackson Township, NJ Canada: Mississauga, ON; North Bay, ON; Welland, ON UK: Lancashire and Salford Conceptual study: São José dos Campos, Brazil Population not specified	The author provided 18 case studies of cities where outdoor LED street-lighting programs were implemented. The case studies were based on questionnaires and interviews with city officials. The purpose was to assess the potential impacts of retrofitting LED streetlights and to inform a similar retrofitting strategy in the city of São José dos Campos.	Only 18 of 200 identified cities provided the majority of the needed data for the study. Data were not available from non-English speaking countries. Case-study cities and the LED lighting projects differed in size. This may have confounded the results. The information was mostly anecdotal, collected from city officials and project managers. Many of the retrofit projects were not completed when the questionnaires were being collected, so the secondary effects data were not yet available. The case-study cities were in countries that were not economically, politically, or geographically similar to Brazil, which limits the generalizability to the conceptual study.	According to survey and interview findings, light pollution decreased in all 18 case-study cities. Fewer than half of the case-study cities reported improvements in public safety as a result of improved nighttime visibility. Changes in traffic safety were rarely reported because of a lack of data. Public perception of LED streetlight retrofit projects was positive in most of the case-study cities. Although there were savings in maintenance and operational costs, the capital cost of LED lights was relatively high. The authors concluded that the long-term impact of LED lighting retrofits is unknown because of the newness of the technology.	The study met 4 of the 5 criteria for mixed-methods studies. The achievement of quality criteria for the methods used was unclear. The authors did not provide details on the methods used to collect the qualitative and quantitative data.

Author, Year Objective	Geographical location Setting Population	Study details	Limitations[a]	Results and conclusions	Quality appraisal[b]
Kuhn et al., 2013 Investigated the changes in residents' perception of light quality, visual accessibility, perception of danger, and energy use in the outdoor setting after retrofitting with LED area lighting.	Helsingborg and Luleå, Sweden Two housing cooperative residential areas with blocks of flats arranged around a yard open to people not residing in the area. Both areas were equivalent in terms of age of building, building developer, sociodemographics, presence of greenery, and degree of enclosure. Helsingborg: 29 participants; average age 63 years (range 41–94); 55% female Luleå: 31 participants; average age 66 years (range 20–85); 61% female	In both areas, yard, path, and entrance luminaires were replaced with LED lighting. Survey data were collected 1 year apart, before and after the lighting retrofit. Data collection occurred after sunset in February and March. On both occasions the ground was bare in Helsingborg and covered with snow in Luleå. Participants were instructed to take a walk in their yard in the evening and complete questionnaires related to their observations of lighting quality, visual accessibility, perceived danger, and perception of natural color of objects in the surroundings.	Despite the similarities between the areas, the presence of greenery, the building color and enclosure, and overall size may have led to differences in the lighting assessments. The 2 areas had different original light sources, which provided different points of references and thus different evaluations of the change in light. Also, lamps in Helsingborg were further apart than in Luleå, which may have made the Luleå area seem better lit. Women and older residents were over-presented in the study sample.	Residents' perceived visual accessibility improved. Perceived danger was low in both areas before and after the retrofit. In Luleå, there was an increase in the perceived quality of light, while in Helsingborg the results were mixed. The retrofitting reduced energy use by 41–76%, suggesting that LED area lighting retrofits might be a feasible alternative to conventional outdoor lighting in relatively safe areas.	The study met 2 of the 5 criteria for non-randomized studies. The study participants did not align with the target population. Older women were over-represented in the sample. The authors reported a high non-response rate. The completeness of the data and fidelity of the intervention were unclear.
Kurniawan et al., 2008 Evaluated the perceptions of brightness of different colored LED lights in fog.	Location not specified Laboratory with simulated nighttime foggy conditions 5 participants with normal color vision	The effects of fog on perceived brightness of 12 different colors of LED lights were determined by having participants stand in a dark room with a fog machine and the LED lights. Participants were asked to rate the brightness of each color for varying levels of fog density. A number of combinations of yellow, red, blue, and green LED lights were used.	None stated.	As fog density increased, the reported visibility for each color of LED light decreased in a linear fashion. Ranked from best to worst in terms of visibility in foggy conditions were 1) reddish blue and reddish yellow; 2) blueish red, yellow, yellowish red, and yellowish green; 3) green, greenish yellow, and red; and 4) blueish green, greenish blue, and blue.	The study met 4 of the 5 criteria for nonrandomized studies. The alignment with the target population was unclear. The authors did not provide details on the sampling procedures and/or inclusion/exclusion criteria.

Author, Year Objective	Geographical location Setting Population	Study details	Limitations[a]	Results and conclusions	Quality appraisal[b]
Lewin et al., 1997 Assessed the feasibility and implementation potential of colored LED lights for traffic signals.	USA Laboratory with "ideal" viewing conditions and in stationary vehicle and field observation Visibility test: 28 car drivers with normal vision Conspicuity test: 17 participants with normal vision and color vision deficiency. Field observation: the public.	A field observation assessed the visibility, conspicuity, or "attention getting." of red, orange, yellow, and green LED traffic signal lights compared to their incandescent counterparts For the visibility test, participants rated LED and incandescent signals. For the conspicuity test, participants compared the LED traffic signals that performed best in the visibility test to incandescent lights by identifying their type, color, and location (lights were positioned in 3 places) based on a quick glance from a stationary vehicle. Field observations of the LED traffic signals that performed best in the first 2 experiments were determined by observing vehicle and pedestrian violations at lights at 3 intersections. Finally, an economic analysis was performed for LED traffic signals.	Not enough color vision–deficient drivers were included in the study to generalize the experiences with different LED and incandescent traffic signal lights. The duration and number of intersection types evaluated were limited. Further investigation would require observing a wider range of intersection types over a longer period.	Based on the laboratory and field observations, red round, red arrow, and Portland orange (for pedestrian) LED lights were equally good or better than similar incandescent lights for traffic signals. Green and yellow LED lights performed poorly and were not recommended for use in traffic signals. Visibility and "attention getting" ability were proportional to light intensity, with a higher intensity required for yellow and green LED lights. Different types of LED traffic signal lights should be evaluated relative to incandescent traffic signals as they become available.	The article did not meet any of the 5 criteria for nonrandomized studies. All were unclear. The authors did not provide details of methods, including of participants and sampling. The completeness of the data, confounders, and fidelity to the intervention were not discussed.
Lin et al., 2014 Investigated the discomfort of glare produced by black-and-white LED billboards in relation to the following 4 factors: flicker frequency; panel luminance; viewing angle; and ambient illuminance.	Location not specified Laboratory with simulated nighttime conditions Experiment A (2 groups): 6 participants <40 years old, average age 22.3 years, 50% female; 6 participants >40 years old, average age 43.5 years, 50% male. Experiment B1 and B2: 6 participants; average age 21.0 years; 50% male. Experiment C: 81 participants; average age 21.6 years; 54% male.	Four experiments with varying levels of flicker frequency, luminance levels, viewing angles and ambient illuminance levels were performed with black-and-white LED lighting patterns on billboards. The de Boer rating scale was used to evaluate flicker glare and visual comfort in addition to post-experiment interviews. Experiment A involved testing flicker frequency, panel luminance, viewing angle, and ambient illuminance separately using a screen to flash patterns. Experiment B1 and B2 investigated the effect of flicker frequency in more detail by modifying flicker frequency. Experiment C investigated how visual comfort was affected by different levels of flicker frequency, luminance, and viewing angles.	None stated.	Results demonstrated that flicker comfort and overall display comfort were not significantly influenced by ambient illuminance but rather by flicker frequency, panel luminance, and viewing angle of the LED screen. The experiments confirmed that 15 Hz flicker frequency produced the most discomfort. In order to reduce discomfort, the authors recommended using a combination of smaller luminance (500 cd/m^2), smaller viewing angles (9.1°). and a flicker frequency of <6 Hz or >24 Hz.	The study met 3 of the 5 criteria for non-randomized studies. The completeness of the data and intervention fidelity were unclear.

Author, Year Objective	Geographical location Setting Population	Study details	Limitations[a]	Results and conclusions	Quality appraisal[b]
Lin et al., 2015 Investigated flicker glare and visual comfort from multicolored LED billboards.	Location not specified Laboratory with simulated urban nighttime conditions 84 participants, average age 21.7 years, 50% male, with normal or rectified vision without cataracts and no familial epilepsy	Participants sat 5 m away from a 1.6 × 1.28 m LED panel with red, green, and blue lights. Two factors were tested: flicker frequency at 7 levels and luminance at 4 levels. A 20-second-long display video was shown at different flicker frequencies and luminance levels in each session for a total of 28 sessions. Participants filled out a questionnaire about their experience at the end of each session. The number of blinks in each participant's right eye was recorded by electromyography (EMG) as an indication of visual tiredness.	Findings cannot be generalized to visual comfort ratings during daytime conditions.	Visual comfort was affected by flicker frequency and luminance of the LED screen. Visual tiredness was not influenced by either factor. Study results suggested that to maintain visual comfort in relation to LED billboards, the flicker frequency should be <3 Hz, and luminance level between 500 and 1600 cd/m^2.	The study met 2 of the 5 criteria for nonrandomized studies. The alignment with the target population, completeness of the data, and intervention fidelity were unclear.
Matsubayashi et al., 2013 Evaluated the effect of installing blue LED lights on train station platforms on the number of deaths by suicide at the train station.	Tokyo, Japan 11 train stations had blue lights installed at the edges of the platforms. These stayed on from sunset to sunrise. The effect of these lights on numbers of suicides was compared with 60 train stations without blue lights. Population not described.	Data from 71 train stations were collected by a railway company in Tokyo from 2000 to 2010. A difference-in-difference approach was used to evaluate the effect on the number of suicides before and after the installation of blue LED lights at 11 stations compared to stations without blue light fixtures.	Study used data from a single railroad company, which limits external validity. The underlying mechanism between blue LED lights and suicide prevention was not examined and a causal relationship cannot be inferred. The study cannot account for changes in suicides in other areas or by other methods.	At stations with blue LED lights, numbers of suicides decreased by 84%. Because blue LED lights are easier and less expensive to install than platform screen doors, they may be a cost-effective method for suicide prevention.	The study met 3 of the 5 criteria for nonrandomized studies. The alignment with the target population and the completeness of the data were unclear.
Matsubayashi et al., 2014 Tested whether the installation of blue LED lights as a suicide prevention method at train stations resulted in substitution phenomenon (i.e., more deaths by suicide at neighboring stations)	Japan 14 train stations with blue lights installed at edges of the station platform. Comparison group comprised 57 train stations without blue lights Population not described.	Suicide data from 2000 to 2014 were collected and analyzed to determine whether the installation of blue LED lights at train platforms influenced the incidence of suicides on train platforms. Data were analyzed based on the following factors: the existence of blue LED lights at a given station and relative location of stations in relation to others with blue LED lights.	This study did not consider location of suicides other than railway crossings or stations of other companies. The blue LED lights were only expected to work while they were turned on in the evening and night. Nighttime suicides only accounted for a limited percentage of suicides at train stations.	Results suggested that implementing blue LED lights on train station platforms decreased incidence of suicide by 74% at those stations. There was no evidence to suggest a systematic increase in suicides at neighboring train stations. The results suggest that the blue LED lights did not lose effectiveness in suicide reduction as people became accustomed to them over time.	The study met all of the 5 criteria for nonrandomized studies. The completeness of the data was unclear. The authors did not discuss missing data.

Author, Year Objective	Geographical location Setting Population	Study details	Limitations[a]	Results and conclusions	Quality appraisal[b]
Peña-García et al., 2015 Evaluated users' perceptions of different kinds of street lighting on pedestrians' sense of well-being (i.e., avoidance of stress, glare, headaches) and perceived safety in relation to illuminance and uniformity levels.	Granada, Spain Five streets in residential areas within the city center, with similar pedestrian and traffic flow with no intense commercial activities: 3 had HPS lighting; 1 had MH lighting; and 1 had LED lighting 275 pedestrians (55 pedestrians per street)	A survey with 11 questions was randomly administered to pedestrians as they were walking along the 5 streets. Data was collected on weekdays between 7:30 pm and 9 pm when the streetlights were turned on.	None stated.	Well-lit streets with uniform lighting tended to make people feel safer. Respondents felt safer in the white light, produced by LED or MH lighting but preferred the appearance of the warmer, yellow-toned light of HPS lighting.	The study met 3 of the 5 criteria for nonrandomized studies. The alignment with the target population and the completeness of the data were unclear.
Rahm and Johansson, 2018 Assessed participants' walking speed, visual perception, affective response, and evaluation of lighting quality for 3 pedestrian-area lighting installations.	Malmö, Sweden Laboratory with simulated pedestrian pathway Younger age group: 43 participants; average age 22 years (range 18–31); 47% female Older age group: 46 participants; average age 69 years (range 62–77); 54% female	A full-scale laboratory mock-up of a pedestrian pathway was created with 3 lighting installations: 1 ceramic MH lighting and 2 LED lighting. Participants' walking speed, visual perception (i.e., ability to recognize facial expressions, detect obstacles, and read a street signpost), affective response, and evaluation of the lighting quality were assessed. Each participant performed the test procedures once for each lighting application.	Facial recognition and sign reading tasks were conducted in the same location rather than several. The influence of differences in light distributions at various locations on visual tasks was not assessed.	Participants performed better in the visual tasks under the higher wattage LED lighting, which was perceived as brighter and more stimulating but less pleasant than the other 2 lighting installations. The younger age group performed better in terms of obstacle detection, identifying facial expressions, and reading signposts at a distance than the older age group. There were no significant differences between the lighting application and walking speeds for either group.	The study met 3 of the 5 criteria for nonrandomized studies. The completeness of the data and intervention fidelity were unclear.
Rea et al., 2017 Conducted photometric measurements and evaluations of perceived brightness and safety in 3 parking lots with different types of area lighting.	Seattle, WA, USA Three parking lots on the University of Washington campus with LED, HPS, and MH lighting 18 participants; average age 46 years; 39% female	Participants assessed the subjective perception of brightness and personal safety of the lighting conditions in the parking lots. The LED-lit parking lot was used as the reference condition and the other 2 parking lots were ranked in relation to the LED parking lot. Photometric measurements were made at all 3 sites.	None stated.	Most participants perceived the LED-lit parking lot as neither too bright nor too dark. They gave the same brightness rating for the HPS-lit parking lot. The MH-lit parking lot was rated as half as bright. Results showed that the LED lighting system had more benefits than the HPS lighting systems by appearing to be brighter and providing a greater sense of perceived safety.	The study met 2 of the 5 criteria for nonrandomized studies. The completeness of the data, handling of confounding factors, and intervention fidelity were unclear.

Author, Year Objective	Geographical location Setting Population	Study details	Limitations[a]	Results and conclusions	Quality appraisal[b]
Saraiji et al., 2016 Examined the effect of HPS, MH. and LED streetlight sources on pedestrian nighttime visibility for drivers.	Location not specified Isolated street on a university campus used as a field test 23 male drivers, age range 18–28 years, with normal vision	The experiment was conducted in 2 parts: 1) an unlit street to focus on the effects of oncoming car headlights on the detection distance of a pedestrian; 2) a lit street, with oncoming car headlights, to focus on the effect of changing the street lighting source on the detection of a pedestrian wearing different colored clothing. Drivers drove at between 35 and 40 km/h.	The findings have limited generalizability given the experimental conditions. Drivers were specifically focused on the task of looking for one pedestrian, and speeds were less than what would be typical in a real-life setting. The street lacked any other distractions for the drivers.	Detection distance on an unlit road was 52% shorter with oncoming car headlights than without the car headlights. With a lit road, pedestrian detection distance almost doubled. The detection distance was statistically similar for the streetlights that were LED and MH, both of which had better detection distance than with HPS streetlights.	The study met 2 of the 5 criteria for nonrandomized studies. The sample did not align with the target population. All participants were young men. The completeness of the data and intervention fidelity were unclear.
Srinivasan et al., 2013 Assessed whether the conversion of traffic signals from incandescent to LED bulbs had any effect on number of traffic accidents.	Charlotte, NC, USA. Converted sites: 282 intersections, included T-intersections and four-way intersections. Comparator sites: 3,375 stop sign–controlled intersections, included one-way or two-way streets in the vicinity of the sites that had the LED traffic light conversion and had available data on traffic volume. Population not specified	The authors used an Empirical Bayes model to compare the actual number of crashes that occurred after LED traffic signal conversion with an estimated that was based on pre-conversion traffic data. A comparison group of stop sign–controlled intersections was used to account for trends in traffic accidents and volume over time.	Because of limited data, the study was unable to account for effects of the LED signal failure such as reduced intensities or deactivation. Findings may not be generalizable to northern cities because Charlotte is a southern city with comparatively milder winters.	There were no statistically significant changes for crashes at T-intersections. At four-way intersections, the incidence of rear-ended crashes significantly decreased following the LED conversion. In addition, rear-end crashes during the day and night significantly decreased with the conversion to LED traffic signals, suggesting a potential safety benefit. The findings showed substantial differences between the intersection types in terms of traffic safety effects of LED traffic signals although the reasons for these differences was unknown.	The study met all of the 5 criteria for nonrandomized studies. The study included a natural experiment with city lights converted to LED so we can assume the intervention was administered as expected.

Author, Year Objective	Geographical location Setting Population	Study details	Limitations[a]	Results and conclusions	Quality appraisal[b]
Starr et al., 2004 Assessed the ability of color vision–deficient (color blind) drivers to accurately perceive whether green LED traffic lights were on or off under direct sunlight.	Woodbury, MN, USA Controlled field test at intersections under direct sunlight 4 male color vision–deficient participants; 4 non-color vision–deficient participants, 3 male; all aged 22–54 years	Six green LED traffic signal designs were compared to one incandescent signal across 7 intersections, with one design at each. Eight volunteers observed two signals at each of seven intersections, for a total of 112 observations. Differences in the LED designs included green tinted versus clear lenses; old (high LED count) versus new (low LED count) LED designs; and 2 different LED brands (i.e., brand A, brand B). While sitting in a stationary vehicle, participants indicated whether the unlit green LED signals, positioned in direct sunlight, were on.	The sample size was small and participants were Minnesota Department of Transportation workers who knew the light was off at the time. Only one incandescent signal was tested. Each design configuration was not equally represented in the experiment.	Twenty-five percent of observations gathered from color vision–deficient drivers and 4% of the observations collected from non-color vision–deficient drivers perceived the unlit green LED signals as being turned on. LED designs had opposing effects on the 2 groups of drivers. The clear lens, brand A, and older (high count) LED technology were more often misperceived by the color vision–deficient drivers. The tinted lens and newer (low count) LED technology were more often misperceived by the non-color vision–deficient drivers. The incandescent signal was never misperceived.	The study met 4 of the 5 criteria for a nonrandomized study. The completeness of the data was unclear.
Van Houten et al., 2001 Compared the relative conspicuity of various visual pedestrian signals for legally blind individuals with some vision.	Canada 130-foot-long pathway constructed outdoors to simulate pedestrian crosswalk 18 participants; age range 20–72 years; 33% male; legally blind based on criteria by Canadian National Institute for the Blind	Experimental design with a simulated crosswalk consisting of 8 lights: white incandescent “walk" signal; white and blue LED “walk” signals (with and without animated “eyes”); white incandescent “hand” (“do not walk”) signals; white LED “hand” signals; and blue LED “hand” signals. Participants were asked to identify the color and/or shape of signals from 130 feet. If unable to identify either the color or shape from that distance, they approached the signal until able to do so.	The study authors could not state with complete confidence that the animated eyes or additional LED lights increased the signals’ recognition distance. Participants were not always able to determine whether the white or orange light was from the pedestrian signal or from elsewhere. Increasing the size of the signals would likely increase the recognition distance; however, this may not be approved by the traffic engineering community.	The addition of animated eyes increased by 57% the distance at which legally blind participants were able to identify the pedestrian signal. No significant differences were observed between incandescent and LED signals without animated eyes, or between blue and white LED signals. Participants were able to identify the signal location and color from further away when they could identify the shape. None of the participants mistook the “walk” and animated eyes signal for “do not walk,” or vice versa. When the animated eyes were absent, many participants did mistake the “walk” symbol for the “do not walk” symbol and vice versa.	The study met 4 of the criteria for nonrandomized studies. The fidelity of the intervention was unclear.

Author, Year Objective	Geographical location Setting Population	Study details	Limitations[a]	Results and conclusions	Quality appraisal[b]
Van Houten et al., 2008 Examined the effects of installing pedestrian-activated yellow stutter-flash LED beacons on a pedestrian sign at a crosswalk.	Miami–Dade County, FL, USA Two crosswalks on multilane roads. The crosswalk on Northwest 67th Street traversed 4 lanes and a turning lane, posted speed was 40 mph, and annual daily traffic was 25,215 vehicles. The crosswalk on South Bayshore Drive traversed 4 lanes with a median island, posted speed was 35 mph, and annual daily traffic was 38,996 vehicles. Participants included staged and local pedestrians (e.g., residents and tourists) and drivers.	In the first test, data were collected for several sessions (20 pedestrians per session) prior to and after the installation of the pedestrian-activated stutter-flash LED beacon on 4 signs at each site. Data, collected during the day when it was not raining and at night, included drivers' yielding behaviors, evasive conflicts (i.e., driver suddenly stopped or swerved or pedestrian jumping, running, or suddenly stepped backward), pedestrians trapped on median, and drivers' yielding distance. Data were collected for a second test that added an LED-illuminated pad on the departure curb and first 4 feet of the crosswalk to the stutter-flash beacon.	None stated.	The use of the stutter-flash LED beacons on pedestrian crosswalk signs increased drivers' yielding behaviors, reduced the number of pedestrians trapped on the median, and reduced evasive conflicts. The addition of the illuminated departure pad did not have an effect on the percentage of drivers yielding at night.	The study met 2 of the 5 criteria for nonrandomized studies. The alignment with the target population, completeness of the data, and intervention fidelity were unclear.
Wood et al., 2018 Assessed the effect of dimming LED streetlights on drivers' reaction time and perceived visibility.	Australia Experimental closed-road circuit with lengthy straight section with 6 LED streetlights placed 50 m apart. 14 licensed drivers, 27–40 years old, 50% female, and with "good" vision based on driver's licensing criteria.	Participants drove several times around a closed-road circuit at night, with the LED streetlight intensity changing each time. Four intensities were measured: 100%, 75%, 50%, and 25%. Drivers were assessed on their ability to see and react to moving targets (human and non-human) under the different lighting conditions. Participants were asked whether the higher intensity LED street lighting provided better or worse visibility.	A lack of research in the area made it difficult to compare the study results with others studies. Experimental conditions made it difficult to extrapolate to normal road conditions. The sample size and participant demographics were not representative of the general public. Similar experiments with older participants need to be conducted.	Drivers' reaction times to pedestrians and obstacles had a small but nonsignificant delay under lower intensity levels of LED street lighting. The only statistically significant differences in reaction times were those between the highest and lowest intensities of LED street lighting (i.e., between 100% and 25%). Detection distance of the moving pedestrian was significantly higher with the greater intensity LED streetlights. There were no significant differences in drivers' detection distances between pedestrians standing under lighting versus not within a lit area. Nearly 80% of participants felt the 2 highest intensity lighting conditions provided the best visibility for driving.	The study met 2 of the criteria for nonrandomized studies. The participants did not align with the target population (see author limitations). The completeness of the data and intervention fidelity were unclear.

Author, Year Objective	Geographical location Setting Population	Study details	Limitations[a]	Results and conclusions	Quality appraisal[b]
Zalesinska, 2018 Determined the maximal permissible luminance and area for LED billboards that did not pose a significant threat to urban road traffic safety in relation to the location of the billboard in the driver's field of vision.	Location not specified Laboratory with car-driving simulator 175 participants, average age 23 years (range 21–25), licensed drivers, most having been driving for 3–4 years	Participants completed a simulated drive through a virtual city (i.e., making turns, speeding, and braking). Participants were evaluated on their reaction time to the sudden appearance of a moving obstacle (i.e., a human, a dog, or a ball) while an LED billboard was in the participant's field of view. The LED billboard was adjusted by the angle in the driver's field of view, size of image, and level of luminance.	The experimental simulator design lacked generalizability to other factors found in real road conditions (e.g., unpredictable behavior of other road users and different levels of traffic or weather conditions) that affect a driver's reaction time. The participants were younger and not representative of the general population.	Increase in LED billboard luminance, size of displayed images, and tilting the billboard toward a driver's field of vision resulted in a longer reaction time to obstacles. Luminance increased drivers' reaction time the most while the location of the LED billboard in relation to the driver's field of view had the least impact. Based on the findings, billboards that would not significantly decrease drivers' performance had luminance of 40 cd/m^2 with a surface area of 8.5 m^2 observed at a distance of 30 m or a surface area of 34 m^2 observed from a distance of 60 m.	The study met 2 of the 5 criteria for nonrandomized studies. The alignment with the target population, completeness of the data, and intervention fidelity were unclear.

Author, Year Objective	Geographical location Setting Population	Study details	Limitations[a]	Results and conclusions	Quality appraisal[b]
Zhu et al., 2013 Evaluated how LED streetlights with different CCT and luminance levels influenced people's perception of visual discomfort and glare.	Shanghai, China Laboratory with simulated street lighting conditions 18 participants, aged 23–29 years. 18 participants, aged 50–56 years. All had normal or corrected to normal visual acuity.	Participants were seated in front of a projector screen with their chin fixed to ensure their eyes were kept in the same position. The luminance of the screen represented the average luminance level on a road surface, and a few surroundings lights were added to the dark room to stimulate ambient lighting on the road. An LED light source, representing glare, with 2 levels of CCT, 3000 K and 6000 K, and 3 levels of surface luminance, was mounted on the top right corner of the screen at an angle of 10° to the horizontal line of sight to stimulate light cut off by the roof of a typical car. Participants judged the level of discomfort glare of the stimulated LED streetlight source as its parameters changed.	None stated.	An LED streetlight with a CCT of 3000 K was perceived to have less glare than one with a CCT of 6000 K. Participants perceived more glare when the light source had a higher average luminance and when directly looking into the light source rather than when seeing it in their periphery. No significant effect was found between participants' age and perceptions of glare, but this may be because of differences within the group rather than between the groups. Designs of LED luminaires that limit glare, especially when looking directly at the luminaire, may prevent pedestrians' visual discomfort. In addition, using LED street-lighting sources with lower CCT was recommended for reducing uncomfortable glare.	The study met 2 of the 5 criteria for nonrandomized studies. The alignment with the target population, completeness of the data, and intervention fidelity were unclear.

Note: CCT, correlated color temperature; HPS, high-pressure sodium; LED, light-emitting diode; MMAT, Mixed Methods Appraisal Tool; MH, metal halide

[a] As given by the study authors.

[b] Quality appraisal questions for nonrandomized studies:

- Are the participants representative of the target population?;
- Are the measurements appropriate regarding both the outcome and the intervention (or exposure)?;
- Are there complete outcome data?;
- Are the cofounders accounted for in the design and analysis?;
- During the study period, is the intervention administered (or exposure occurred) as intended?

[b] Quality appraisal for mixed methods studies:

- Is there an adequate rationale for using a mixed methods design to address the research question?;
- Are there different components of the study effectively integrated to answer the research question?;
- Are the outputs of the integration of qualitative and quantitative components adequately interpreted?;
- Are divergences and inconsistencies between quantitative and qualitative results adequately addressed?
- Do the different components of the study adhere to the quality criteria of each tradition of the method involved?[31]

Table 2. Summary of practice-based reports

Author, Year Objective	Geographical location Setting description Population	Study details	Limitations[a]	Results and conclusions
Connolly, 2016 Conducted a rapid, desktop HIA of the LED street lighting in Stockport, UK.	Stockport, UK Included an evidence review, so settings and populations for the primary studies varied.	The rapid, desktop HIA included a review of the evidence by a single reviewer. A literature search was conducted using search engines NHS Evidence and Google Scholar. Search terms included health impacts of LED lighting and artificial lighting.	None stated.	No evidence was found on the health impacts of LED street lighting. Health impacts from street lighting were based on exposure to artificial light at night and blue-color light. Health impacts of nighttime exposure to artificial light (in particular blue-spectrum light) included melatonin suppression, increased sleep onset latency (i.e., time to fall asleep), increased alertness, and disruption of circadian rhythm, which can negatively affect psychological, cardiovascular, and/or metabolic functions. Recommendations for lighting design include directing light downward to reduce the vertical dispersion of light; use of shielding to minimize direct and dispersed light from entering residential homes; and use of fixtures that keep the light source out of normal field of view.
FDS International, 2011 Assessed the awareness of the LED street lighting installations, identified residents' opinions, uncovered any issues related to the LED lighting, and determined whether there were barriers to widespread LED street lighting installations in London, UK.	London, UK Site 1: A201 Blackfriars Road between junction with Webber Road and Borough Road. Site 2: A40 Western Avenue in the vicinity of Leaver Gardens. Total participants: 402 drivers and residents aged ≥16 years; 56% male; most were white; the majority did not wear glasses or contact lens when driving; and had driven or walked past the sites within past 2 months.	Face-to-face interviews were conducted during the late afternoon and evening when street lighting was on. Participants were asked about their awareness of changes in street lighting; awareness of LED lighting trial; perception of new lighting installation; their preferences; and any problems or benefits caused by LED street lighting.	None stated.	Only 10% of participants noticed the change to LED street lighting. Of those aware of the change, most responded positively and preferred the LED lighting. One participant stated they did not like the change and were dazzled when they looked directly at the LED lights. No other participants experienced any problems or had issues with glare or reflection. Most participants (68%) were in favor of LED streetlights and over one-third stated that LED lighting was more energy efficient, better for the environment, and cheaper than conventional lighting.

Author, Year Objective	Geographical location Setting description Population	Study details	Limitations[a]	Results and conclusions
Kraus, 2016 The Council on Science and Public Health, American Medical Association, reported on the potentially harmful impacts of LED community lighting on human health and the environment to advise communities on lighting options.	Location, setting description, and population characteristics not applicable.	The report included a review of English language reports published between 2005 and 2016. These reports were identified as a result of a search in PubMed and Google Scholar databases using the following search terms: light; lighting methods; color; photic stimulation; adverse effects; circadian rhythm/physiology/radiation effects; radiation dosage/effects; sleep/physiology; ecosystem; community; street; and roadway lighting. Additional information and perspectives were provided by recognized experts in the field.	None stated.	Advantages of LED community lighting include decreases in energy consumption; lack of a requirement for warm-up; dimming capacity; longer lifetime; reduced maintenance costs; no toxic substances that may be released if the fixture becomes damaged; and no requirement for internal reflectors or glass covers. Disadvantages include a higher upfront cost than conventional lighting; emission of larger amount of blue/green light, which can increase light pollution; visual discomfort from glare, especially for older drivers; and greater potential impact on circadian rhythm physiology compared to HPS and MH lighting. To minimize the disadvantages of LED community lighting, light shielding should be installed to limit spread of light, lighting should be dimmed during off-peak hours, and a lower CCT should be used.
Miller et al., 2013 Reported on observations and results of an evaluation of different area lighting options in terms of pedestrian-scale responses and preferences.	Stanford University, CA, and Chautauqua Institution, NY, USA Stanford University: located in the foothills of the San Francisco's peninsula region. Campus building designs are a warm adobe wall finish with red Spanish tile roofs that are reflected in the outdoor lighting systems. The predominant area lighting system used 100 W HPS lamps in glass refractor post-top luminaires. Chautauqua Institution: located by Lake Chautauqua in western upstate New York. This compact, pedestrian-friendly community has dense housing. The community is environmentally conscious and concerned about preserving dark night skies. Existing street and pathway lighting systems include incandescent, mercury, and HPS lamps.	An iterative process was used to evaluate different luminaires to determine the best options for pedestrian-scale area lighting at both sites. Mock lighting options were installed to obtain feedback from residents, homeowners, and/or campus facilities groups on their preferences, luminaire appearance, lighting color temperature, and glare levels. Mock-ups were designed based on each location's needs and context.	Authors identified limitations with glare metrics as none worked reliably for pedestrian lighting. The authors recommended full-scale mock-ups whenever possible to gather feedback from users.	Based on feedback from both case studies, the authors found that users cared about the daytime appearance of the luminaires and preferred those that produced a soft-edge pattern of light and a warm color of light given the neighborhood characteristics. Glare was a significant factor for acceptability and horizontal illuminances could be used as long as glare was reduced. The authors recommended the following to mitigate glare, improve visual comfort and visibility, and make outdoor spaces more inviting: use lower lumen output luminaires and lower illuminances; use luminaires that spread luminance over a larger area such as indirect optics; use luminaires with less optical punch and less sharp cut-off in candlepower; and use luminaires that deliver warmer color light , i.e., <4,000 K.

Author, Year Objective	Geographical location Setting description Population	Study details	Limitations[a]	Results and conclusions
Ton et al., 2008 Compared HPS luminaires with LED area lights in a parking garage in terms of energy usage, lighting performance, and user satisfaction.	Portland, OR, USA Six-story parking garage with approximately 50,000 square feet of parking area, lit with 400 luminaires that operate 24 hours per day. 9 participants from security and maintenance divisions included 6 night shift staff who routinely walk/drive in area and 3 night staff who view area through security monitors.	Two types of LED lights, an older and newer version, were installed on different levels of the parking garage. The newer version had 30% more light output and used 8% less power. Wattage and photometric measurements were taken. Users' perceptions of the HPS- and LED-lit areas were gathered by survey. Survey questions included asking respondents if they noticed any lighting changes and their preferences to the lights. Economic costs were evaluated by calculating the paybacks (i.e., energy and material costs) for the LED lights versus the HPS.	Lack of generalizability because of small sample size.	The older LED lights produced similar illuminance levels as the HPS lights. The newer LED lights provided a slightly higher light level and more uniform light. The LED lights were whiter than the HPS lights. Over half of the survey participants thought the LED lights provided more light and improved visibility, and preferred the light color of the LED lights.
Vohra, 2013 Conducted an HIA of the LED street lighting in Trafford, UK.	Trafford, UK Trafford, located in the Greater Manchester area, with about 217,000 residents, with 22.4% <18 years and 16.2% >65 years	The HIA included a policy review of the Trafford LED street-lighting program, a brief community health profile, and a rapid non-systematic review of the current scientific literature on impacts of LED street lighting on health and well-being. Based on the literature review, the authors presented implications for Trafford's LED street-lighting program.	Literature specifically on LED street lighting and human health was lacking. The majority of the findings were based on literature focused on artificial lighting that included various lighting types. Opportunity costs and savings could not be accurately judged based on the results of the HIA.	The current evidence of the potential health and well-being impacts of LED street lighting was weak and mostly associated with animal, in vitro, and ecological cross-sectional studies. Artificial lighting, including indoor lighting and LED devices, have negative health impacts based on the intensity, duration, pattern, and characteristics of the light exposure. Compared with other types of lighting sources, LED lights can produce more blue-spectrum light. Exposure to the blue-spectrum light has been associated with circadian rhythm disruption, particularly in children.

Note: CCT, correlated color temperature; HPS, high-pressure sodium; LED, light-emitting diode; MMAT, Mixed Methods Appraisal Tool; MH, metal halide

[a] As stated by authors.

Results

Article Summary

We summarize the outcomes, study settings, and methods described in the articles retrieved in Table 3 Summary of study outcomes, geographic setting, and methods.

Table 3. Summary of study outcomes, geographic setting, and methods

Outcome (number of articles)	Study authors/year[a,b]	Geographical setting (if specified)
Traffic and pedestrian safety (*n* = 19)		
LED signal visibility (*n* = 5)	Starr et al., 2004	USA
	Bullough et al., 2000	–
	Kurniawan et al., 2008	–
	Lewin et al., 1997	USA
	Van Houten et al., 2001	Canada
Traffic accidents (*n* = 5)	Kivimaki, 2013[c,d,e]	Brazil, Canada, UK, USA
	Jones, 2018a [e]	USA
	Eustace et al., 2010	USA
	Jami et al., 2011	USA
	Srinivasan et al., 2013	USA
Drivers' detection of pedestrians/obstacles (*n* = 4)	Zalesinska, 2018	–
	Djokic et al., 2017	Serbia
	Saraiji et al., 2016	–
	Wood et al., 2018	Australia
Drivers' visual discomfort (*n* = 4)	Lin et al., 2015	–
	Lin et al., 2014	–
	Djokic et al., 2017	Serbia
	Zhu et al., 2013	China
Reaction time, missed signals, color identification of LED signals (*n* = 2)	Bullough et al., 2000	–
	Huang et al., 2003	–
Drivers' perception of lighting quality (*n* = 2)	Djokic et al., 2017	Serbia
	Wood et al., 2018	
Drivers' yielding behavior for pedestrians (*n* = 1)	Van Houten et al., 2008	USA
Public perception of street and area lighting, including parking lot safety and preferences (*n* = 9)	Kivimaki, 2013[c,d,e]	Brazil, Canada, UK, USA
	Miller et al., 2013 [d]	USA
	Rahm and Johansson, 2018	Sweden
	FDS International, 2011 [d]	UK
	Kostic and Djokic, 2014	Serbia
	Kuhn et al., 2013	Sweden
	Peña-García et al., 2015	Spain
	Rea et al., 2017	USA
	Ton et al., 2008 [d]	USA

Outcome (number of articles)	Study authors/year[a,b]	Geographical setting (if specified)
Pedestrian safety and preferences (*n* = 6)	Miller et al., 2013 [d]	USA
	Rahm and Johansson, 2018	Sweden
	FDS International, 2011[d]	UK
	Kostic and Djokic, 2014	Serbia
	Kuhn et al., 2013	Sweden
	Peña-García et al., 2015	Spain
Public safety (e.g., crime, homicide) (*n* = 2)	Kivimaki, 2013 [c,d,e]	Brazil, Canada, UK, USA
	Jones, 2018a [e]	USA
Area usage (*n* = 1)	Kivimaki, 2013 [c,d,e]	Brazil, Canada, UK, USA
Light pollution (*n* = 1)	Kivimaki, 2013 [c,d,e]	Brazil, Canada, UK, USA
Life satisfaction (*n* = 1)	Jones, 2018b [e]	USA
Suicide (*n* = 2)	Matsubayashi et al., 2013 [f]	Japan
	Matsubayashi et al., 2014 [f]	Japan
Breast cancer and prostate cancer mortality (*n* = 1)	Jones, 2018a [e]	USA
Melatonin suppression (*n* = 1)	Connolly, 2017[d,f,g]	UK
Other health impacts of LED street and area lighting (*n* = 4)	Vohra, 2013 [d,f,h]	UK
	Kraus, 2016 [d,f]	–
	Jones, 2018b [e]	USA
	Kivimaki, 2013 [c,d,e]	Brazil, Canada, UK, USA

Notes: HIA, health impact assessment; LED, light-emitting diode

[a] Unless indicated otherwise, these peer-reviewed academic articles used quantitative methods to understand the health impacts.

[b] Unless otherwise indicated, articles are engineering related and focus on lighting and transportation safety.

[c] Mixed methods multi-case study.

[d] Practice-based report.

[e] Economics related.

[f] Health related.

[g] Rapid desk-top HIA.

[h] Full HIA.

We identified potential positive and negative health impacts of LED street and area lighting installations. These benefits included an increase in life satisfaction, particularly among seniors;[32] improvements in traffic safety;[33] and increase in personal safety[34] and reduction in crime,[33] with residents and police reporting improved facial and vehicle recognition and elevated perceived safety due to improved visibility.[33,34]

Area residents generally perceived the installation of LED streetlights as a positive change.[33,35] Drivers reported that LED streetlights were comparable or better than other light sources (i.e., high-pressure sodium and metal halide) in terms of visibility of pedestrians and obstacles.[36,37] However, LED lights were not always the preferred lighting source because of reported glare,[36] dimming over time,[36,38] and light color.[39,40] In a rapid desktop HIA of street lighting, Connolly (2017)[41] found that exposure to bright light at night suppressed melatonin, but that outcome was not specific to LED lighting.

Kivimaki (2013)[33] reported a reduction in light pollution and "light trespass" (i.e., light into areas where no light is desired, such as bedrooms) with the introduction of LED street lighting in 18 case-study cities. In contrast, the Council on Science and Public Health[42] reported community complaints that high-intensity, blue-rich LED street and area lighting (i.e., 4,000 K correlated color temperature [CCT]) were "prison-like" and a source of discomfort that required heavy drapes to mitigate. Pedestrians who participated in a simulation of nighttime walking in a park reported bright LED streetlights (i.e., 3,810 K) as more stimulating and less pleasant than ceramic metal halide lighting.[43]

Traffic Signals and Pedestrian Crossings

Ten articles assessed health impacts of LED traffic signals and pedestrian crossings.[4, 5,44-51] Of these, three explored changes in traffic safety following conversion to LED traffic signals;[4,548] one evaluated the visibility of colored LED traffic signals in foggy conditions,[46] and another evaluated the effects of LED flashing lights at pedestrian crossings.[51] Most of the articles addressing traffic signals and pedestrian crossings evaluated the visibility of LED traffic signals among adults with normal vision[45,47] or with color vision deficiency (color blindness)[45,49] or limited vision.[50]

Findings on the relationship between the conversion to LED traffic signals and traffic accidents were inconsistent. Eustace et al., (2010)[4] and Jami et al., (2011)[5] reported an increase in traffic accidents after conversion to LED traffic signals, while Srinivasan et al., (2013)[48] found both increases and reductions in traffic accidents, depending on intersection type (i.e., four-way or T-intersection), crash type (i.e., rear-end, left-turn, angle, or head-on), and lighting conditions (i.e., dawn, dusk, or dark). These articles were limited by a lack of data on weather, visibility, traffic patterns, and other factors that could have contributed to traffic safety.

Van Houten et al., (2008)[51] reported that the addition of LED flashing lights at a pedestrian crossing improved driver yielding behaviors by over 60%, up from nearly zero when the crossing was marked only by signs. The addition of LED flashing lights also reduced evasive actions by drivers (i.e., suddenly stopping or swerving) and pedestrians (i.e., jumping, running, or suddenly stepping backward).

Outdoor Screens and Train Station Lighting

Five articles reported on health and LED lighting related to outdoor screens[52-54] and train station lighting.[55,56] The articles focusing on glare from LED billboard screens noted that visual discomfort from LED billboards was affected by luminance levels, flicker frequency, and location in drivers' field of view.[52-54]

The installation of blue LED lights on train platforms in Japan was associated with a reduction in incidence of suicides at those stations.[55,56] The blue LED lights were on from sundown to sunrise; however, the impact on suicide reduction was not limited to these times. The existing evidence could not demonstrate a causal relationship between blue-spectrum LED lighting on platforms and incidence of suicides at train stations nor the long-term effectiveness.[55-56]

Equity Considerations

Few of the included articles and/or reports discussed or evaluated equity-related factors[57] such as the possible differential impact of outdoor LED lighting based on sociodemographic factors (e.g., age, gender, disability). Exceptions were studies with seniors,[19,42,43] children,[19] and people who experience visual impairment.[19,45,49,50] These studies revealed that children and individuals without crystalline lenses or artificial lenses are unable to filter blue-spectrum light, common in LED lighting, and are more susceptible to its associated health risks.[19] Medical treatments and eye and skin conditions can also increase sensitivity to light and specifically to blue-spectrum light.[19] In addition, seniors and individuals who experience visual impairment are more susceptible to glare,[19,43] which can arise from LED lighting. Other population groups may benefit more from improved visibility at night, for example, seniors who tend to have difficulty with nighttime vision.[32]

The visibility of LED traffic signals and pedestrian crossings for people with visual impairments such as color vision deficiency or limited vision has implications for public safety. People who experience visual impairment may incorrectly identify a traffic signal or pedestrian crossing sign[45,49,50] and mistakenly enter an intersection. Van Houten et al., (2001)[50] compared the relative conspicuousness of different types of pedestrian crossing signals (i.e., "WALK" signals) among people who have some vision but have been designated as legally blind. The authors found no differences in visibility based on the lighting type (LED versus incandescent lighting, and white versus blue LED lights). However, they did report that the inclusion of "animated eyes" in a white and blue LED pedestrian crossing signal significantly improved the recognition distance.

No articles or reports considered the impact of outdoor LED lighting on populations with greater exposure, for example, outdoor workers, night shift workers, people experiencing homelessness, and/or people who live in urban, inner-city, and other densely populated locations (which are often underserved communities that can include racialized peoples, low-income earners, etc.).

Discussion

Projections indicate that outdoor municipal lighting will rely predominantly on LED technology in the coming decades.[1,7] Understanding the potential impact of LED lighting on human health is key to making informed decisions to reduce potential negative risks associated with LED light exposure, especially for far-reaching policies such as municipal lighting strategies. Research on the human health impacts of outdoor LED lighting is still emerging. The majority of the articles included in this analytic review on LED street and area lighting involved subjective assessments of lighting simulations or mock-ups,[36-39,43,58] and of existing light installations.[34,35,40,59,60]

The most thoroughly developed evidence was in relation to traffic safety and driver preferences,[35-38,60] followed by pedestrian safety and preferences.[35,40,43,58,59] The existing literature on street and area lighting has examined nighttime exposure to artificial light in general rather than specifically to LED lighting.

The evidence linking human health to outdoor LED light exposure has demonstrated benefits, such as improved public and traffic safety due to better visibility,[33,41] as well as risks, such as circadian rhythm disruption through the suppression of melatonin production.[19,41,42] Literature that focused on other human health outcomes was sparse and points to possibilities where outdoor LED lighting may be beneficial, such as improving "life satisfaction" among seniors,[32] and where it may be detrimental, for example, increasing breast cancer mortality.[62] The findings connecting outdoor LED lighting and human health are correlational, not causal, and highlight the need for more research and evaluation in the area.[36,62]

Although LED streetlights were often considered comparable or better than other light sources (i.e., high-pressure sodium and metal halide) in terms of their effects on visibility of pedestrians and obstacles, drivers and pedestrians also complained of glare,[36] dimming over time,[36,38] and light color.[39,40] Street and area lighting strategies need to balance improved visibility with users' preferences by directing lighting downward to minimize vertical dispersion of light;[41] shielding lights to minimize the amount of direct and dispersed light visible from residents' homes;[41] using luminaire designs that keep the light sources out of drivers' and pedestrians' normal field of view;[41,42] dimming lights;[42] using filters to block blue-spectrum light;[42] and using a correlated color temperature lower than 4,000 K.[42,61]

While some case studies found that city residents perceived their local area LED street lighting as decreasing light pollution and being less "trespassing",[33] residents in several US municipalities found bright LED lights a source of discomfort.[42] These contradictory findings emphasize the importance of community consultation to gather information on needs and potential impacts when evaluating the best fit of lighting for particular settings. Individual-level solutions for mitigating exposure to blue-spectrum and artificial light at night, such as wearing blue-blockers[23] or dimming indoor lights,[63] are not viable for curtailing outdoor lighting exposure. However, LED street and area lighting varies based on the precise type of fixture, intensity, and color spectrum of LED lights installed and whether they are dimmed at night.[33,58] The range of options allows for accommodating LED lighting to different settings and community uses.

LED billboards are approximately eight times brighter than light-box billboards and are more likely to contribute to light trespass and light pollution.[53] Based on the evidence from indoor and occupational screen exposure, risks can include photosensitive epilepsy, retinal damage, stress and annoyance, headaches and eyestrain, and circadian rhythm and sleep disruption.[64] Whether these risks translate to the outdoor setting is not known. The need for further assessment is particularly pressing given the increasing presence of LED screens in outdoor urban settings.[52,53] The possible health impacts of LED screens on segments of the population with higher exposure or greater sensitivity to the risks associated with LED screen exposure, for example, children,[64] also requires dedicated investigation. Lighting system installers have also been identified as being at higher risk of negative health impacts from blue-spectrum light.[25] Outdoor lighting encourages mobility and promotes public safety, including in the winter months when daylight hours are shorter.[43,65]

It is important to carefully weigh the possible positive and negative health impacts of outdoor LED lighting when determining the cost–benefit of proposed street and area lighting projects, traffic signals and pedestrian crossings, and outdoor screens. Consideration of the potential negative health impacts is essential, despite the limited outdoor LED-specific evidence to date, to mitigate worsening of health risks. Monitoring outdoor LED lighting strategies for possible health impacts will help to build the local evidence base and inform future municipal lighting strategies. Given that specific population groups (e.g., children, seniors, people who experience visual impairment, light-sensitive individuals) may be differentially affected by outdoor lighting and that light exposure levels vary, indicators should account for demographic characteristics and level of light exposure.

Equity-related factors were rarely considered, measured, and/or discussed in the literature that we reviewed. This is an area for researchers and evaluators to focus their efforts in the future. It is vital that we understand the physical, social, and mental health impact on diverse populations, particularly members of underserved groups, to ensure equitable outcomes result from municipal LED lighting conversions and usage.

Promising Practices

A number of promising practices emerged based on the findings of this analytic literature review. These included:

- Limit blue-spectrum light exposure by using specific LED lighting brands, blue-spectrum light-blocking filters, and a correlated color temperature of less than 4,000 K and considering lighting design (i.e., shielding) and dimming.[41,42,61]
- Develop contextually (i.e., setting and population) relevant outdoor lighting strategies rather than taking a one-size-fits-all approach. Test out new LED lighting in real-life settings and account for changes in weather[46,49] and seasonal variations in daylight,[43] and gather the perspectives of diverse users to ensure the best fit for residents' needs.[36-39,43,58]
- Assess, using detailed data, and monitor over the long term the impacts of LED street and area lighting.[32,42,62] Collect area-specific data on indicators, for example, pedestrian, cyclist, and driver concerns about glare or complaints about lighting;[19] other local stakeholders' concerns (e.g., environmental groups, health organizations, residents associations, business groups, public safety organizations);[19] compilations of relevant crime, safety, and road traffic statistics;[33] and traffic reports related to LED traffic signal conversion.[4,5,48]
- Assess the impacts of LED technologies that have received little attention to date, such as outdoor LED screens (e.g., billboards, sports fields, urban centers), and new technologies as they emerge.
- Consider the physical, social, and mental health impacts of outdoor LED lighting on populations who are underserved, particularly sensitive to lighting, and/or have greater exposure, such as children, seniors, people who work outdoors at night, and people who experience homelessness and/or precarious housing situations.

- Test the design of LED traffic signals for clarity and correct color identification in various environmental conditions among individuals with normal vision[44,45,47] and who experience visual impairment.[45,49] The visibility of colored LED lights used in traffic signals can be affected by environmental conditions such as fog[46] or direct sunlight[49] and by design features such as LED luminance,[44] lens, LED count, and LED lighting brand.[49]
- Install LED flashing lights at pedestrian crossings to improve pedestrian safety.[51]
- Test LED traffic signals and lights at pedestrian crossings as technology advances to determine the best design for the environmental settings and population.[44-47,49] Weather and lighting conditions, such as snow, ice, or short daylight hours in winter, may require specific considerations.
- Minimize glare from LED billboards (or screens) along roadways. Additional evaluations of various lighting and environmental conditions are required to inform LED-specific standards to minimize the visual discomfort for drivers and pedestrians.[52-54] This research could inform standards related to other outdoor LED screens such as those used at sports fields[64] or located throughout urban settings (e.g., on the exterior of buildings, for advertising).
- Evaluate the lighting output of LED lights as they dim over time.[38] Anticipate possible future changes and include these into any municipal procurement contracts to account for updates and modifications to LED lighting based on changing lighting technology and specifications as well as residents' needs.[19]

Limitations

The study designs of the articles included in this analytic literature review were broad and of varying quality, and most authors reported limitations to the study findings (listed in Tables 3 and 4). These included lack of generalizability, with findings not necessarily relevant or applicable to environmental conditions,[37,38,44,49,54] locations/settings,[4,33,43,55,56,65] lighting designs,[39,49,50,59] or populations[38,44,47,59] other than the one in which the study was conducted.

There were also limitations to our methodological approach. To maintain the scope of the rapid review, we restricted inclusion to articles and/or reports that evaluate LED lighting interventions. These often focus on study design and results rather than on intervention and implementation details. Articles that describe other lighting interventions, report on study protocols, and/or discuss theoretical or predictive models may contain detailed implementation information, and their exclusion represents a possible limitation. In addition, the inclusion of articles published only in English would introduce bias into the results.[66]

Conclusion

As municipalities transition to using LED lighting for outdoor environments, researchers and decision-makers need to consider all of the possible health impacts on diverse population groups based on the local geography and sociodemographic factors. Given the relationship between melatonin suppression and nighttime exposure to blue-spectrum light[19,41,42] this warrants careful evaluation.

Findings from this analytic review can be used to promote promising practices, inform planning, direct policy, and/or develop decision-making tools related to municipal lighting strategies. Focusing on the impact of outdoor LED lighting on underserved local populations will help guide the development of lighting strategies that promote health equity. This information would make a much-needed contribution to the evidence base connecting human health and outdoor LED lighting and also provide specific guidance for municipal planners and policy makers on how to best support residents' health.

The lighting quality and visibility and users' preferences for lighting can be affected by contextual factors,[40,58,59] environmental factors,[43,46,49] lighting characteristics and design,[34,36,38-40] and individuals' characteristics such as age and eyesight.[43] To ensure that lighting designs contribute to an age-friendly and visually accessible city, seniors and visually impaired individuals need to be consulted. An appropriate lighting design will balance users' needs and minimize negative health impacts relative to lighting levels and economic and energy costs.[4]

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Supplementary Materials

Supplementary Table S1. Detailed search strategy by database

INITIAL SEARCH **Database: Ovid MEDLINE(R) and Epub Ahead of Print, In-Process & Other Non-Indexed Citations and Daily 1946 to October 22, 2018** **Date executed: October 22, 2018** **Strategy:**	
1	Light/ae and (light emitting diode* or LED or LEDs).tw,kf. (113)
2	Lighting/ae and (light emitting diode* or LED or LEDs).tw,kf. (41)
3	((blue* or green* or red* or spectrum* or white*) adj3 (LED or LEDs)).ti. (449)
4	((blue* or green* or red* or spectrum* or white*) adj3 (LED or LEDs)).ab. /freq=2 (856)
5	((bulb* or emi* or frequenc* or kelvin* or lamp* or light* or lumina* or streetlight*) adj3 (LED or LEDs)).ti. (572)
6	((bulb* or emi* or frequenc* or kelvin* or lamp* or light* or lumina* or streetlight*) adj3 (LED or LEDs)).ab. /freq=2 (1456)
7	(((city* or urban) adj1 light*) and (LED or LEDs or light emitting diode*)).tw,kf. (2)
8	light emitting diode*.ti. (3512)
9 or/1-8	[Combined MeSH & text words for LED lighting] (5577)
10	Chronobiology Disorders/ (751)
11	Circadian Rhythm/ (67749)
12	Environmental Exposure/ (68593)
13	Equipment Safety/ (10009)
14	Eye Diseases/ (35841)
15	Melatonin/ (18223)
16	exp Migraine Disorders/ep (3048)
17	Oxidative Stress/ (115196)
18	Radiation/ (9330)
19	Radiation Dosage/ (45707)
20	Retina/ (70014)
21	Retinal Degeneration/ (9116)
22	Risk Assessment/ (232817)
23	Risk Factors/ (741460)
24	Sleep/ (47677)
25	"Sleep Initiation and Maintenance Disorders"/ (11536)
26	ae.fs. [adverse effects free-floating subheading] (1605430)
27	re.fs. [radiation effects free-floating subheading] (214725)
28	to.fs. [toxicity free-floating subheading] (395536)
29	(adverse adj2 (effect or effects or event or events or experience* or outcome or outcomes or reaction or reactions)).tw,kf. (377222)
30	carcinogen*.tw,kf. (132438)

31	chronobiolog*.tw,kf. (2608)
32	circadian.tw,kf. (45931)
33	(contrast* adj2 (decreas* or high* or increas* or low*)).tw,kf. (37084)
34	(cross* walk* or crosswalk*).tw,kf. (400)
35	((cycl* or disrupt* or disturb*) adj2 sleep*).tw,kf. (22921)
36	damag*.tw,kf. (554184)
37	danger*.tw,kf. (58009)
38	driving.tw,kf. (75898)
39	((effect* or impact*) adj2 health*).tw,kf. (67472)
40	((effect* or shift*) adj1 purkinje*).tw,kf. (69)
41	fatigu*.tw,kf. (85219)
42	glar*.tw,kf. (6002)
43	harm*.tw,kf. (155603)
44	hazard*.tw,kf. (210011)
45	human health*.tw,kf. (37414)
46	injur*.tw,kf. (750127)
47	((light* or lumin*) adj1 sensitiv*).tw,kf. (4096)
48	macular degeneration*.tw,kf. (18114)
49	melatonin*.tw,kf. (22305)
50	migraine*.tw,kf. (32025)
51	(night adj2 visi*).tw,kf. (942)
52	pedestrian*.tw,kf. (4732)
53	phototoxic*.tw,kf. (4947)
54	risk*.tw,kf. (1936281)
55	(safe* or unsafe*).tw,kf. (759771)
56	toxic*.tw,kf. (598759)
57	traffic*.tw,kf. (92062)
58	uninten*.tw,kf. (20323)
59 or/10-58	[Combined MeSH & text words for health impacts] (6514650)
60 and/9,59	[Combined concepts for LEDs & health impacts] (1524)
61	exp animals/ not humans/ (4506772)
62	(animal* or anthropod* or bovine* or calves or camel* or canine* or cat or cats or chimp* or dog or dogs or equine* or feline* or goat* or hamster* or horse* or insect* or llama* or mice* or monkey* or mouse* or pig or piglet* or pigs or porcine* or primate* or rabbit* or rat or rats or rodent* or sheep* or simian* or swine* or veterinar*).ti. (2234995)
63	60 not (61 or 62) [Exclude animal studies] (1187)
64	limit 63 to english (1144)
65	remove duplicates from 64 (1140)

Database: Web of Science - Science Citation Index Expanded (SCI-EXPANDED) --1900-present; Social Sciences Citation Index (SSCI), 1900–present

Date executed: October 22, 2018 **Strategy:**		
# 7	1,435	(#5 NOT #6) AND LANGUAGE: (English) Indexes=SCI-EXPANDED, SSCI Timespan=1980-2018
# 6	2,338,586	(TI=(animal* or anthropod* or bovine* or calves or camel* or canine* or cat or cats or chimp* or dog or dogs or equine* or feline* or goat* or hamster* or horse* or insect* or llama* or mice* or monkey* or mouse* or pig or piglet* or pigs or porcine* or primate* or rabbit* or rat or rats or rodent* or sheep* or simian* or swine* or veterinar*)) AND LANGUAGE: (English) *Indexes=SCI-EXPANDED, SSCI Timespan=1980–2018*
# 5	1,491	(#3 AND #4) AND **LANGUAGE**: (English) *Indexes=SCI-EXPANDED, SSCI Timespan=1980–2018*
# 4	2,316,557	TS=(carcinogen* or “circadian rhythm*” or “cross walk*” or crosswalk* or ((cycl* or disrupt* or disturb*) NEAR/2 sleep*) or driving* or ((effect* or impact*) NEAR/2 health*) or fatigu* or glare or “macular degeneration*” or melatonin* or migraine* or (night NEAR/2 visi*) or pedestrian* or traffic*) or TI=(damag* or danger* or harm* or hazard* or injur* or risk* or safe* or toxic* or unsafe*) *Indexes=SCI-EXPANDED, SSCI Timespan=1980–2018*
# 3	24,861	(#1 OR #2) AND **LANGUAGE**: (English) *Indexes=SCI-EXPANDED, SSCI Timespan=1980–2018*
# 2	46	(TS=(((city* or urban) NEAR/1 light*) and (LED or LEDs or “light emitting diode*”))) AND **LANGUAGE**: (English) *Indexes=SCI-EXPANDED, SSCI Timespan=1980–2018*
# 1	24,820	(TI=(((blue* or green* or red* or spectrum* or white*) NEAR/3 (LED or LEDs)) or ((bulb* or emi* or frequenc* or kelvin* or lamp* or light* or lumina* or streetlight*) NEAR/3 (LED or LEDs)) or “light emitting diode*”)) AND LANGUAGE: (English) *Indexes=SCI-EXPANDED, SSCI Timespan=1980–2018*
French Agency for Food, Environmental and Occupational Health & Safety (https://www.anses.fr/en)		
	Browsed A-Z index: Reviewed all documents belonging to keyword LED (Light-emitting diode) (3)	
Government of British Columbia (https://www2.gov.bc.ca/)		
	Search across site: (“LED light” OR “light emitting diode”) AND (health OR sleep OR traffic OR glare OR risk OR harm) – Reviewed first 5 pages of results. Nothing relevant to health (0)	
Illuminating Engineering Society (https://www.ies.org/)		
	Searched across site: LED lighting - Reviewed first 5 pages of results (3)	
Metropolitan Area Planning Council (https://www.mapc.org/)		
	Reviewed documents in resource library with tag “LED” (1)	
New York State Energy Research & Development (https://www.nyserda.ny.gov/)		
	led streetlights site: www.nyserda.ny.gov (1) Retrieved reference list on LED and health/environmental impact (76)	
Nova Scotia Department of Energy (https://energy.novascotia.ca/)		
	Searched across site: LED street | reviewed first 5 pages of result, zero results discussed health impacts (0)	
Portland Bureau of Transportation (https://www.portlandoregon.gov/)		
	Searched across site: LED street | Reviewed first 5 page of results (4)	
U. S. Department of Energy (https://www.energy.gov/)		
	Searched across site: “LED lighting” AND “human health” | Reviewed first 5 page of results (7)	
Google (https://www.google.ca/)		
	(“LED street light” | “LED street lighting” | “LED street lights” | “LED streetlight” | “LED	

	streetlighting" | "LED streetlighting") (glare | "human health" | "sleep disturbance" | "sleep disruption" | "pedestrian safety" | "traffic safety") Searched the first 5 pages of results (19)

FINALIZED SEARCH

Database: Ovid MEDLINE(R) and Epub Ahead of Print, In-Process & Other Non-Indexed Citations and Daily 1946 to January 17, 2019

Date executed: October 22, 2018

Strategy:

1	Light/ae and (light emitting diode* or LED or LEDs).tw,kf. (117)
2	Lighting/ae and (light emitting diode* or LED or LEDs).tw,kf. (41)
3	Lighting/td and (streetlight* or street light*).tw,kf. (2)
4	((blue* or green* or red* or spectrum* or white*) adj3 (LED or LEDs)).ti. (468)
5	((blue* or green* or red* or spectrum* or white*) adj3 (LED or LEDs)).ab. /freq=2 (886)
6	((bulb* or emi* or frequenc* or kelvin* or lamp* or light* or lumina* or streetlight*) adj3 (LED or LEDs)).ti. (591)
7	((bulb* or emi* or frequenc* or kelvin* or lamp* or light* or lumina* or streetlight*) adj3 (LED or LEDs)).ab. /freq=2 (1496)
8	(((city* or urban) adj1 light*) and (LED or LEDs or light emitting diode*)).tw,kf. (2)
9	light emitting diode*.ti. (3621)
10	white light LED*.tw,kf. (76)
11 or/1-10	[Combined MeSH & text words for LED lighting] (5790)
12	Chronobiology Disorders/ (758)
13	Circadian Rhythm/ (68086)
14	Community Health Planning/ (4968)
15	Community Participation/ (16140)
16	exp Crime/ (126614)
17	Environmental Exposure/ (69533)
18	Equipment Safety/ (10083)
19	Eye Diseases/ (35964)
20	Melatonin/ (18444)
21	exp Migraine Disorders/ep (3103)
22	Oxidative Stress/ (118017)
23	Radiation/ (9352)
24	Radiation Dosage/ (46148)
25	Retina/ (70427)
26	Retinal Degeneration/ (9184)
27	Risk Assessment/ (236509)
28	Risk Factors/ (751880)
29	Safety/ (38289)
30	Safety Management/ (19217)
31	Sleep/ (48328)

32	“Sleep Initiation and Maintenance Disorders”/ (11734)
33	“Social Determinants of Health”/ (1867)
34	Social Isolation/ (12553)
35	ae.fs. [adverse effects free-floating subheading] (1622830)
36	re.fs. [radiation effects free-floating subheading] (216307)
37	to.fs. [toxicity free-floating subheading] (400358)
38	(adverse adj2 (effect or effects or event or events or experience* or outcome or outcomes or reaction or reactions)).tw,kf. (385077)
39	(assault* or “break-in*” or “break and enter*” or drug* or graffiti* or robber* or solicitation or theft* or violen*).tw,kf. (1588449)
40	((belong* or cohes* or isolat*) adj2 (communit* or neighbo* or social*)).tw,kf. (10865)
41	carcinogen*.tw,kf. (133696)
42	chronobiolog*.tw,kf. (2634)
43	circadian.tw,kf. (46508)
44	(contrast* adj2 (decreas* or high* or increas* or low*)).tw,kf. (37546)
45	(criminal* or crime*).tw,kf. (34584)
46	(cross* walk* or crosswalk*).tw,kf. (416)
47	((cycl* or disrupt* or disturb*) adj2 sleep*).tw,kf. (23379)
48	damag*.tw,kf. (562170)
49	danger*.tw,kf. (58731)
50	driving.tw,kf. (77651)
51	((effect* or impact*) adj2 health*).tw,kf. (69119)
52	((effect* or shift*) adj1 purkinje*).tw,kf. (69)
53	fatigu*.tw,kf. (86744)
54	glar*.tw,kf. (6106)
55	harm*.tw,kf. (159052)
56	hazard*.tw,kf. (215097)
57	human health*.tw,kf. (38664)
58	injur*.tw,kf. (761039)
59	((light* or lumin*) adj1 sensitiv*).tw,kf. (4159)
60	macular degeneration*.tw,kf. (18437)
61	melatonin*.tw,kf. (22591)
62	migraine*.tw,kf. (32391)
63	(night adj2 visi*).tw,kf. (970)
64	pedestrian*.tw,kf. (4842)
65	phototoxic*.tw,kf. (5003)
66	(place-making or placemaking).tw,kf. (49)
67	risk*.tw,kf. (1973889)
68	(safe* or unsafe*).tw,kf. (774662)
69	“sense of place”.tw,kf. (118)

70	social health*.tw,kf. (2563)
71	toxic*.tw,kf. (607027)
72	traffic*.tw,kf. (93453)
73	uninten*.tw,kf. (20803)
74	or/12-73 [Combined MeSH & text words for health impacts] (7664101)
75	and /11,74 [Combined concepts for LEDs & health impacts] (1613)
76	exp animals/ not humans/ (4538357)
77	(animal* or anthropod* or bovine* or calves or camel* or canine* or cat or cats or chimp* or dog or dogs or equine* or feline* or goat* or hamster* or horse* or insect* or llama* or mice* or monkey* or mouse* or pig or piglet* or pigs or porcine* or primate* or rabbit* or rat or rats or rodent* or sheep* or simian* or swine* or veterinar*).ti. (2248830)
78	75 not (76 or 77) [Exclude animal studies] (1263)
79	limit 78 to english (1218)
80	remove duplicates from 79 (1213)

Database: Web of Science - Science Citation Index Expanded (SCI-EXPANDED) --1900-present; Social Sciences Citation Index (SSCI) –1900–present
Date executed: January 17, 2019
Strategy:

#9	1,623	(#7 not #8) AND LANGUAGE: (English) *Indexes=SCI-EXPANDED, SSCI Timespan=1980–2019*
#8	2,358,020	(TI=(animal* or anthropod* or bovine* or calves or camel* or canine* or cat or cats or chimp* or dog or dogs or equine* or feline* or goat* or hamster* or horse* or insect* or llama* or mice* or monkey* or mouse* or pig or piglet* or pigs or porcine* or primate* or rabbit* or rat or rats or rodent* or sheep* or simian* or swine* or veterinar*)) AND **LANGUAGE**: (English) *Indexes=SCI-EXPANDED, SSCI Timespan=1980–2019*
#7	1,693	(#3 and #6) AND **LANGUAGE**: (English) *Indexes=SCI-EXPANDED, SSCI Timespan=1980–2019*
#6	3,764,074	(#4 or #5) AND **LANGUAGE**: (English) *Indexes=SCI-EXPANDED, SSCI Timespan=1980–2019*
#5	1,625,711	(TS=(assault* or “break-in*” or “break and enter*” or drug* or graffiti* or robber* or solicitation or theft* or violen* or ((belong* or cohes* or isolat*) NEAR/2 (communit* or neighbo* or social*)) or crime* or criminal* or “place making” or placemaking or “sense of place” or “social health*”)) AND **LANGUAGE**: (English) *Indexes=SCI-EXPANDED, SSCI Timespan=1980–2019*
#4	2,284,963	(TS=(carcinogen* or “circadian rhythm*” or “cross walk*” or crosswalk* or ((cycl* or disrupt* or disturb*) NEAR/2 sleep*) or driving* or ((effect* or impact*) NEAR/2 health*) or fatigu* or glare or “macular degeneration*” or melatonin* or migraine* or (night NEAR/2 visi*) or pedestrian* or traffic*) or TI=(damag* or danger* or harm* or hazard* or injur* or risk* or safe* or toxic* or unsafe*)) AND LANGUAGE: (English) *Indexes=SCI-EXPANDED, SSCI Timespan=1980–2019*
#3	25,481	(#1 or #2) AND **LANGUAGE**: (English) *Indexes=SCI-EXPANDED, SSCI Timespan=1980-2019*
#2	232	((TS=((((city* or urban) NEAR/1 light*) or “street light*” or streetlight*) and (LED or LEDs or “light emitting diode*”)))) AND **LANGUAGE**: (English) *Indexes=SCI-EXPANDED, SSCI Timespan=1980-2019*

#1	25,327	((TI=(((blue* or green* or red* or spectrum* or white*) NEAR/3 (LED or LEDs)) or ((bulb* or emi* or frequenc* or kelvin* or lamp* or light* or lumina* or streetlight*) NEAR/3 (LED or LEDs)) or "light emitting diode*"))) AND **LANGUAGE**: (English) *Indexes=SCI-EXPANDED, SSCI Timespan=1980-2019*
Google (https://www.google.ca/)		
	(LED street light) (assault | break in | community belonging | crime | drug | glare | graffiti | "human health" | place making | robbery | social isolation | "sleep disturbance" | "pedestrian safety" | "sense of place" | social health | theft | "traffic safety" | violence) Searched the first 5 pages of results (4)	

Supplementary Table S2. Inclusion and exclusion criteria for article selection

Characteristic	Inclusion	Exclusion
Study Design	Scoping reviews; systematic review; meta-analysis; primary research studies (i.e., qualitative/ethnographic, quantitative, mixed-methods); case studies; cross-sectional studies; implementation studies; measurement/evaluation/impact studies (outcome and process) and/or practice-based reports	Comments; editorials; letters; theoretical papers; abstracts only
Population, Location	Humans Urban; suburban; municipal; city Outdoor and/or simulations of outdoors	Animals; plants Rural Indoor
Intervention and/or Evaluation	Related to impact of outdoor LED lighting on human health (social, physical, and mental)	Not related to outdoor LED lighting and the impact/effect on an aspect of human health (social, physical, and mental)
Outcome	All outcomes and process and/or implementation measures (e.g., program, process, implementation, evaluation, measurement, impact, effectiveness, equity, feasibility) of the impact/effect of outdoor LED lighting on human health	Studies that do not include outcome or process measures
Other	English; full text available	Whole books; thesis/dissertation abstracts; research protocols