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Light painting photography makes particulate matter air pollution visible

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The World Health Organization estimates that air pollution causes approximately seven million premature deaths worldwide each year. Solutions to air pollution are well known, yet this rarely equates to easily actionable. Here we demonstrate how art science collaboration can successfully highlight the issue of air pollution and create wider civic discourse around its amelioration. We document a light painting photographic technique that uses data from calibrated low-cost particulate matter sensors to measure and depict air pollution. We also use a postcard technique to grasp individuals' sentiments regarding air pollution. The photographs from three countries, Ethiopia, India and United Kingdom, visually highlight the importance of location and occupation upon human exposure. The photographs are used as a proxy to communicate and create dialogues, spaces and places about air pollution. The sentiment analysis shows how this approach can foster awareness and create agency for stakeholders to take actions to tackle air pollution.

Air pollution is one of the main threats to both environmental and human health, and is a leading cause of premature death globally[1]. Indeed, the World Health Organization estimates 99% of the global population breathe polluted air, causing ~7 million premature deaths worldwide each year[2,3]. The situation is particularly challenging in Asia, where air pollution remains a problem in countries like India and China, despite many air quality policies and actions[4,5]. Similarly, African countries have been experiencing exponential deterioration in air quality over the last five decades, with several cities presenting levels of pollution 5–10 times higher than World Health Organization recommendations[6]. Particulate matter (PM) is the air pollutant most responsible for human morbidity and mortality. It has multiple impacts upon physical health and is responsible for diseases including heart disease, stroke and cancers[7]. A growing body of literature highlights that PM not only affects physical, but also mental and cognitive health[8,9]. As a consequence of the increasing evidence of the harmful effects of air pollution even at relatively low concentrations, in 2021, the World Health Organization decided to revise its air quality guidelines and reduce its recommendations for $PM_{2.5}$ annual concentrations from 10 to 5 μg m-3 and PM_{10} from 20 to 15 μg m-3[10].

Knowledge, perceptions and attitudes towards air pollution are key factors for achieving air pollution exposure reductions through behavioral change[11]. Moreover, perceptions of environmental harms are key determinants to changes in behavior[12]. Previous work on air pollution has highlighted the need for raising awareness of both the problem of air pollution and potential solutions with which to achieve reductions, especially in low-income settings[13,14].

From an epidemiological perspective, the serious impacts of poor air quality upon morbidity and mortality are well understood. However, this body of knowledge is rarely translated into individual perceptions of air quality. Multiple interacting processes can cause public indifference to the issues of air pollution. First, the ubiquity of air pollution can cause disempowerment and subsequent ambivalence to its presence. Secondly, in most situations, air pollution is invisible. Unlike some other environmental hazards, (e.g. flooding), air pollution is difficult for the public to observe and react to. The individual PM particles are too small to be seen by the naked

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eye. However, PM scatters and absorbs light, resulting in hazes and loss of visibility under sufficiently high concentrations[15]. When hazes appear, air pollution becomes the subject of media and public interest (see for example the London smogs of the 1950s and contemporary Asian smogs). But when the observable hazes diminish, so does the newsworthiness of air pollution, despite its still present threat. Thirdly, individual agency over air pollution exposure is limited. This limitation is especially true with respect to outdoor pollution, with multiple sources that an individual has no control over[16]. Indoor air pollution offers more agency to individuals who can choose how to generate heat and light within dwellings. However, this agency is often limited by economic and infrastructure constraints[17] and lack of access to alternatives. Finally, excluding the most susceptible, the wider day-to-day risks of air pollution are small for the overall population, resulting in a correspondingly low motivation for individual changes in behavior. Furthermore, other contemporary issues, like access to food, water and housing, are more immediate.

Collaboration between the arts and sciences can be a useful tool for both informal knowledge dissemination and fostering citizen engagement and/or activism[18]. Art experiences are aligned with the affective domain of learning[19]. Art provides engagement, and elicits emotions and changes in attitude, while science education emphasizes cognitive understanding through logic[20], creating reciprocal pathways for public engagement[21]. By holistically drawing from both the affective and cognitive domains, such collaboration encourages a more intuitive understanding of subjects. In this sense, art-science collaboration can be particularly effective in the context of climate change and environmental issues[22]. Art science collaboration can provide innovative, challenging and provocative ways to engage communities and, despite not providing solutions, can help in stimulating individuals' perceptions, behavioral changes and raising awareness of the climate crisis[23–26]. This project was devised to creatively represent air pollution in different contexts and, by doing so, to provide places and spaces for discourse. The project follows the concepts of eco-didacticism[21,22,27,28] and aims to make invisible air pollution visible. This approach will provide an easy-to-comprehend artistic engagement tool to compare air pollution in different contexts. The team required artists and scientists to produce output that was scientifically robust, but also visually arresting, which could be understood by those uneducated in scientific practices.

Light painting is a photographic technique using long exposure times. Its effect is that only objects that are very still or bright are recorded in the final image. The technique was pioneered by Étienne-Jules Marey and Georges Demeny in 1889 as part of a research program using photography as a scientific tool to investigate biological motion. It was used for similar purposes by the Gilbreths to scientifically record the movements of clerical and factory workers as part of their time and motion research studies before being taken up and popularized by photographic artists such as Vilho Setälä, Man Ray, Wynn Bullock and Gijon Mili. Digital light painting uses digitally controlled light sources to create and control the effect within the image[20]. It was developed by Steve Mann as a means of visualizing sensor data[29], and further advanced in recent work of Timo Arnall in the visualization of Wi-Fi strength[30].

We applied digital light painting to visualize air pollution. Low-cost air pollution sensors that have previously been shown to provide accurate measurements were used to measure PM mass concentrations[31,32]. The real time signal from the sensor was used to control a moving Light Emitting Diode (LED) array, which was programmed to rapidly flash as a function of PM concentration. A relevant location was then chosen in which a story about air pollution could be told. A long exposure photograph is taken with the artist moving the LED array in front of the camera within the chosen scene. The duration of an individual LED flash is sufficiently short so that the flash becomes a dot on the photograph. The artist is not observed in the photo because they are moving, whereas the light flashes from the LED array are seen because they are bright. The photographs represent the PM concentration by creating an equivalency between the measured PM particles and the number of light dots in the photographs. This creates in the camera a visualization of the pollution, thus creating an affective visual metaphor of the PM being put under a microscope and lit up. The strength of the metaphor is that it allows for pollution levels to be instantly visually understood. Furthermore, it allows for easy comparisons between different locations.

Results

Once developed, the light painting technique was used to document the levels of air pollution in multiple and contrasting international contexts. Port Talbot in Wales was the initial focus of the project. The interest came from the tension between the economic benefits of the Port Talbot steelworks in the community, being the city's largest employer, and the environmental consequences of having one of the largest steelworks in Europe and a major source of local pollution[33]. Figure 1 shows the light painting for Port Talbot. The scene shows the Prince Street air quality monitoring site situated in front of the steelworks. Port Talbot Steelworks is an integrated steelmaking plant, using imported iron ore and coal as the major inputs. The air quality

Fig. 1 | Light paintings in Port Talbot, United Kingdom. Photo from the Prince Street air quality monitoring site with Tata Steelworks in the background - $PM_{2.5}$ 30 − 40 μg m-3.

monitoring and light painting were performed at 9 pm (dusk) on 27/07/2017 and measured $PM_{2.5}$ concentrations in the range of 30–40 μg m-3. The $PM_{2.5}$ hourly average value measured at the regulatory Automatic Urban and Rural Network monitoring site for the same time was 24 μg m-3. There were large variations within the same day with no clear diurnal cycle: the mean average for the day (±1σ) was 21.9 ± 13.0 μg m-3.

Figure 2 presents a diptych of two light paintings both taken in children's playgrounds in India, but ~500 km distant from each other. The left-hand image is taken in Delhi, a megacity with an estimated population of 32 million in 2022, often observed to be one of the cities with the worst air quality globally[34]. The right-hand image was taken in Palampur, a hill station in the state of Himachal Pradesh which has some of the cleanest air in India. The images were taken within 5 days of each other. The Delhi air pollution was recorded in the range of 500–600 μg m-3, at least 40 times greater than the World Health Organization's guideline values (15 μg m-3) for 24 h mean average[35]. The $PM_{2.5}$ values measured at the Palampur playground were in the range of 30–40 μg m-3, a factor of at least 12.5 times less than that measured in Delhi, highlighting how air pollution concentrations depend upon location, thereby setting up intra-country environmental inequalities.

Figure 3 presents a diptych from Ethiopia, this time exploring how air pollution can vary dramatically between indoor and outdoor locations. Ethiopia, and more generally East African countries, are undergoing rapid economic development, industrialization and socio-demographic transition, with associated increases in ambient air pollutant levels[36]. The two light paintings were taken in the capital of Ethiopia, Addis Ababa, in 2020 within days of each other. The left-hand image shows an image taken outdoors on the Airport Road, an area of the capital that is well developed, with high-quality surfaces both on the road and surrounding pavement. Measured $PM_{2.5}$ concentrations were in the range of 10–20 μg m-3, a relatively low range observed by many cities around the world. Data from the https://www.airnow.govair website measuring $PM_{2.5}$ in Addis Ababa indicates this value is not unusual for the season. The outdoor image is juxtaposed with the indoor image, taken of a kitchen using multiple large biomass stoves for food preparation for a canteen. Even with a large room volume and reasonable ventilation to the outside, the $PM_{2.5}$ concentrations measured in the room were in the range of 150–200 μg m-3, a factor of ~10–20 times greater than what was measured nearby outdoors. The diptych visually makes apparent the vast differences in exposure to PM, which is dependent on where you live, work, and how you travel between these locations.

Figures 4 and 5 provide an example of how the light painting technique can be used as an engagement and advocacy tool for air quality data visualization and create spaces and places for discussion about air pollution. The light painting images from Addis Ababa, shown in Fig. 3, were printed onto posters (Fig. 4) and postcards (Fig. 5), with supplementary information about the air pollution situation in Addis Ababa, both within indoor and ambient environments. They also provided simple messages on how to reduce personal air pollution contributions and exposure to provide the observers with potential agency. The posters were placed in areas around the Addis Ababa Institute of Technology to engage with the student body. After discussions with the students about the posters, a postcard technique for real-time data collection was used to grasp their thoughts on the air pollution situation in Addis Ababa. The team distributed five types of postcards depicting photos of both ambient and household air pollution situations and asked students about what they thought about air pollution, what actions could be taken to address air pollution, and who should address air pollution. The postcards returned a set of 63 responses comprising 143 statements that were analyzed using the behavioral change wheel technique[37]. This qualitative analysis provides insights into the 'capability', 'opportunity, and 'motivation' of the students regarding air pollution. The thematic analysis of the statements collected reveals a good level of awareness among the students of both household and ambient air pollution: "Addis air quality is poor" (Postcard_C15), and its causes. Students highlighted the impacts on the environmental impacts and health effects of exposure to air pollution and the associated types of diseases, including respiratory diseases, cancer and eye issues. They also identified as main causes of ambient air pollution transport-related air pollution and waste burning. Transport-related air pollution was predominantly associated with motorized traffic congestion, poor maintenance and the performance of vehicles' engines, and polluting second-hand imported vehicles: "The exhaust in cars, I feel sorry for people walking on the street who have to breathe in, and for children as well" (Postcard_C9). Students identified waste burning as a cause of air pollution both in terms of industrial waste disposal: "We have to decrease industrial waste" (Postcard_CW3), and household waste disposal, especially related to burning plastic: "I wish people could stop burning their trash and dispose of their waste properly" (Postcard_C8). They reported smoke from industrial factories and people smoking as contributors to ambient air pollution.

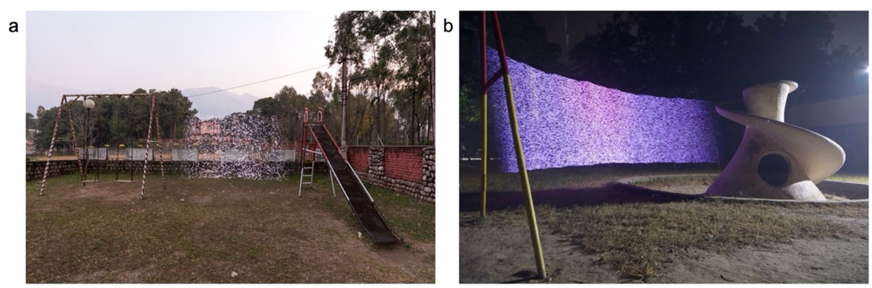

Fig. 2 | Light paintings in two Indian playgrounds. **a** Children's playground in Palampur (CSIR-IHBT), India, measured $PM_{2.5}$ 30–40 μg m-3. **b** Nursery playground in Delhi (IIT Delhi), India, measured $PM_{2.5}$ 500–600 μg m-3.

Fig. 3 | Light paintings in Addis Ababa, Ethiopia. **a** Airport Road, Addis Ababa, Ethiopia - $PM_{2.5}$ 10–20 μg m-3. **b** Indoor Biomass Burning Kitchen, Addis Ababa, Ethiopia—$PM_{2.5}$ 150–200 μg m-3.

Fig. 4 | Air pollution awareness campaign in Addis Ababa, Ethiopia. Posters with light paintings from Addis Ababa located at a bus stop outside the Addis Ababa Institute of Technology.

Indoor air pollution was mainly associated with the burning of domestic fuels, particularly charcoal for indoor cooking: "It will be good if we use alternatives to charcoal indoors" (Postcard_A5).

In the context of advocating for change, students identified relevant stakeholders, suggesting they have the knowledge to engage with and bring about change, advocating for top-down measures to raise awareness to tackle air pollution: "The United Nations and other authorities should give awareness to people and make an effort to solve this global problem" (Postcard_A17); "The government should give awareness to the people about air pollution. Alternatives for charcoal should be used" (Postcard_A8). Similarly, they suggested the government intervention to tackle transport-related air pollution: "I wish the government of Ethiopia can reduce the toxic gas released by cars" (Postcard_C8); "The government should stop importing second-hand cars" (Postcard_CW1). Nonetheless, very few students identified mitigation mechanisms, suggesting a limited lack of knowledge of solutions. They focused particularly in addressing the need to plant more trees to tackle air pollution: "We should plant more plants in the cities to reduce air pollution" (Postcard_C5), but also to tackle deforestation for wood burning: "If we cut trees, we have to plant two-thirds of what we cut" (Postcard_A1). Moreover, they mentioned measures to reduce transport-related air pollution, especially in terms of incentivizing the use of more sustainable transport modes, including building more non-motorized transport infrastructure for walking and cycling, better car emissions regulation for imported cars, improvements in vehicles' maintenance and fleet electrification: "Access to cheaper auto parts would decrease emissions, same with consistent electricity and CO_2" (Postcard_C16). Similarly, electrification and the incentivization for the use of more sustainable forms of power were suggested to reduce the use of charcoal for domestic use: "Promote and encourage people to use electricity for cooking" (Postcard_CW2).

Due to air pollution being ingrained in external factors (e.g., industry) and solutions requiring governmental influence, participants reported little individual opportunity to combat air pollution; nor were they able to express the physical or social opportunities they had to reduce pollution. Nonetheless, the students' motivations and aspirations to reduce air pollution were high, although reported with broad comments: "I want to move around freely without getting polluted" (Postcard_A19); "We want to see a clean city, green and clean residential areas" (Postcard_A1). Overall, the postcards were a useful medium for initiating discussions around air pollution and indicated that there are still multiple barriers faced by individuals to improve air quality in Addis Ababa, despite their knowledge of the presence of air pollution and its impacts upon human and ecological health.

Discussion

The Air of the Anthropocene project has experienced widespread recognition across multiple stakeholders, including publications in the New Scientist[38], The Guardian[39], Quest[40], Source Magazine[41], and gallery shows in Los Angeles, Belfast, and Birmingham. The project has also been utilized to raise air pollution awareness by UN International Organization for Migration (IOM), the Foreign, Commonwealth, and Development Office (FCDO) and UN-Habitat. For example, UN-Habitat commissioned four pollution light painting posters, see Fig. 6 for one of the commissioned light painting posters. The posters incorporated a light painting with accompanying text. The four light paintings all contained different messages that provided both information about air pollution and steps to reduce exposure to the air pollution. The use of the light painting provided the initial interest to create the place of discussion, where the additional messaging could be introduced. The four light paintings were displayed during the Kampala Capital City Authority (KCCA) "Placemaking awareness raising event" (Kampala, Uganda 17th–19th January 2018).

The work of Ostrom on common pool resources highlights that environmental management is more likely to be successful when four conditions hold[16,42]: (1) the environmental problem is visible, (2) the cause and effect relationships are understood, (3) the problem is reversible, and (4) management of the environmental resource (the air in this case) results in clear benefits to key constituencies. The Air of the Anthropocene project aimed at making invisible air pollution visible and to provide an easy-to-comprehend artistic engagement tool to compare air pollution in different contexts. By doing so, it fulfils the first of Ostrom's conditions by making something that was largely invisible visible. It allows for the causes and effects of air pollution to be more readily understood and helps to achieve the second condition. By providing a visual understanding of air pollution that is accessible to a wide array of stakeholders, who do not necessarily have a scientific background, the light painting approach can help to demonstrate that the third and fourth criteria can hold for air pollution.

Due to its photographic art science connotation, the Air of the Anthropocene differs from more recent air quality community engagement projects[43,44], creating spaces and places for discussion about air pollution, and thereby raising awareness, in an innovative manner. The project uses art, in this case, photography, as a proxy to communicate and create dialogs about the issues associated with air pollution. The visual depiction of PM and the associated storytelling highlighting the causes, contexts, and levels of air pollution, can make the issues of air pollution more tangible and understandable by the community. The use of photography, thanks to the power of images, has also the function of evoking people's emotions and stimulating reflections upon the contextual environmental conditions. Moreover, as Addis Ababa's example shows, this approach can foster awareness, space and places for dialogs, agency and community action, allowing different stakeholders to share their perspectives, solutions and take actions to tackle air pollution.

Measuring and understanding the impacts of art science collaboration in the context of climate change and environmental-related projects is challenging, due to the intrinsic long-term time scale associated with behavioral change[22]. Nonetheless, the approach presented in this paper can

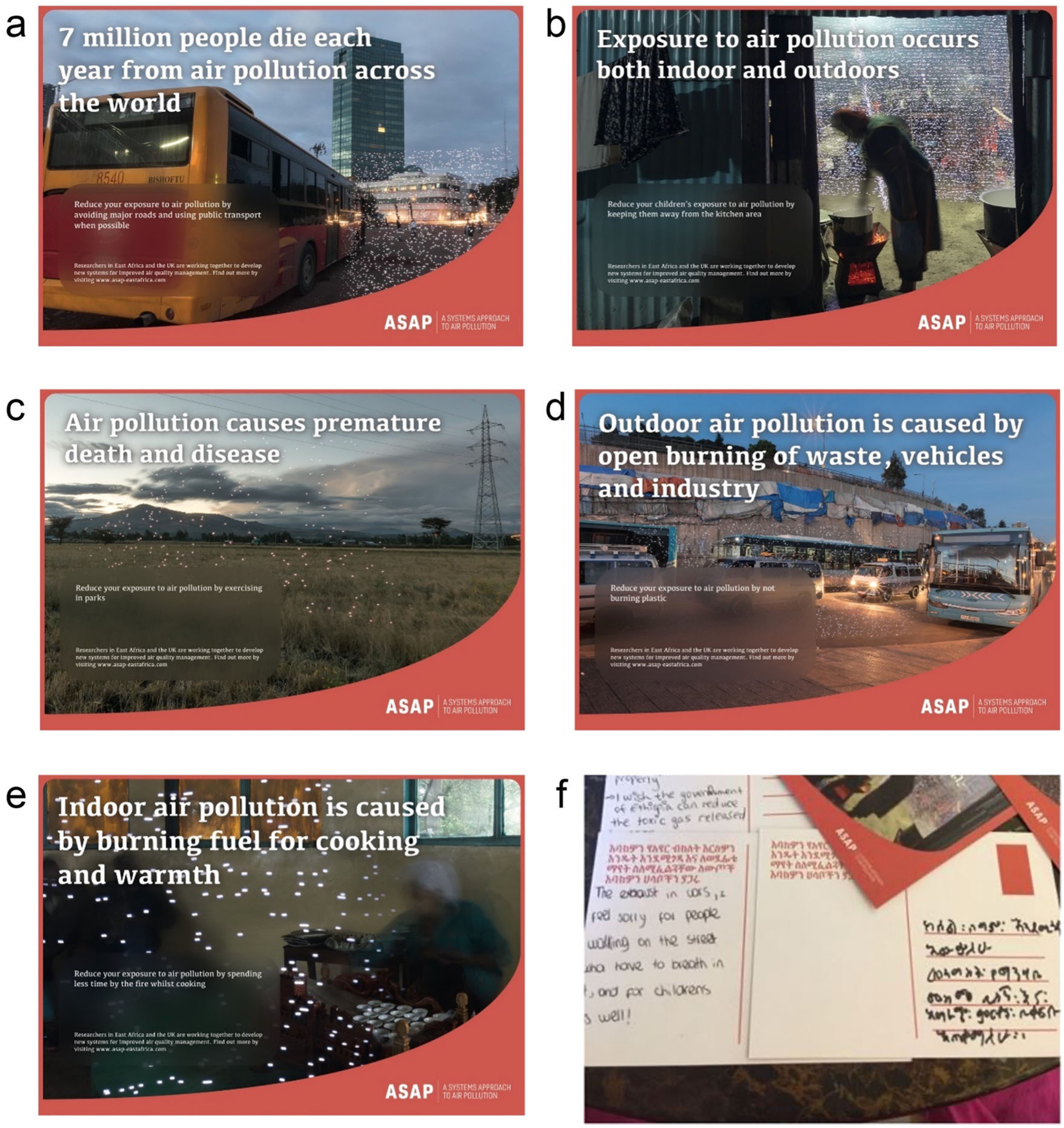

Fig. 5 | Illustrated types of postcards produced for awareness campaign and data collection. a Depicts the level of air pollution on Airport Road, Addis Ababa, Ethiopia, recording $PM_{2.5}$ levels of 10–20 μg m-3; **b** Depicts the level of air pollution of biomass burning in a commercial kitchen at the University of Addis Ababa, Ethiopia, recording $PM_{2.5}$ levels of 150–200 μg m-3; **c** Depicts level of air pollution in an open area; **d** Depicts level of air pollution at a bus station in Addis Ababa, Ethiopia; **e** Depicts level of air pollution during a traditional Ethiopian coffee ceremony; **f** Example of back of postcard with student's statements.

enhance individual and communities experience, emotions and reflections upon the relationships between spaces and environmental issues. The paper highlights the need for a holistic approach to understanding perceptions of air pollution, efforts to monitor pollution, efforts to communicate findings and ultimately efforts to affect change through interventions. It demonstrated that artistic interventions in scientific practice can create informative discussions, activate public engagement, and can become part of the air quality management toolkit. To quote John Butler "Art changes people and people change the world".

In the future, this collaboration between art and science strives to develop open-sourced techniques that will generate new tools to effectively engage and empower communities to measure air quality and create air pollution narratives. For example, expanding the digital representation technique beyond lens-based techniques into augmented reality camera use is a possible further air pollution visualization technique. The adoption of open-source methodologies and the creation of open-source documentation would also allow the impact of the project to be sustained beyond the timescale and budget constraints of the individual projects. The development of new devices and techniques for visualizing air pollution data through different artistic tools will enable interested members of the public to create their own artistic aesthetic representations of their environment. The showcasing of these images can become a powerful advocacy tool to promote collective action, motivating community members to get involved in activist work and instigating transformational change in their localities.

Methods

Light painting equipment

An Alphasense OPC-N2 optical particle counter was used to conduct the PM measurements[45]. It was polled at one-second intervals by a Raspberry Pi 0 W which translated that real-time signal data into instructions for a LED array driven at high frequency by an Arduino-compatible microcontroller. The sensor, microcontrollers and LEDs were all powered by a single USB mobile battery charger pack and designed to be worn on the artist's wrist. The fading in and out of the LEDs was controlled by a handheld trigger button. The LED

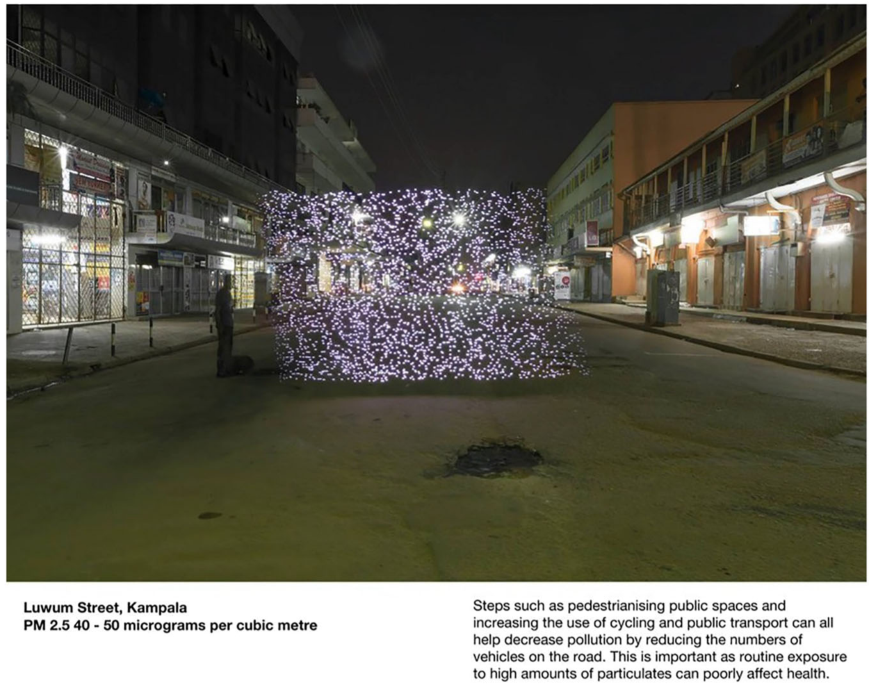

Fig. 6 | Light painting poster in Kampala, Uganda. Example awareness raising light painting poster used for the UN Habitat—Kampala Capital City Authority (KCCA) "Kampala Placemaking Campaign". The image was photographed and contextualized, then printed and displayed on site in Luwum Street, the location of the placemaking campaign.

array comprised a long thin strip of LEDs attached by Velcro to an adapted retractable boom pole intended for film and TV work. The number display of the PM reading and working controls were initially handled by an e-ink display/button unit though this was later adapted for wireless display/control by Wi-Fi connected smartphone. The design was intended to be both accurate scientifically whilst highly portable for ease of travel.

Light painting methodology

A camera (Nikon D5200) and tripod would be set up at a relevant photo location decided in collaboration with environmental scientists or other relevant stakeholders. The purpose of a location was to help tell the story of the causes, effects, differences in and possible ameliorations of particulate air pollution. After framing up the image the artist would wait until light levels allowed for a long exposure photograph to be taken without oversaturation of the camera. This would either take place during a seven-minute period at dawn or dusk or in an appropriately street lit area at night. Setting the camera for exposure priority was first given to the length of exposure (10 s–30 s), then aperture was set to give appropriate depth of field with visual subjects wholly in focus then finally setting ISO as low as possible within this. Once the equipment was in place and ready a series of photographs would be taken with the artist slowly walking with the sensor and LED array in front of the camera, calling out to an assistant when to release the shutter. After shutter release, the artist would hand trigger a fade-in using the trigger button and count out loud the passing seconds to ensure a fade-out was triggered before the camera's shutter closing. This process would be repeated until the artist was satisfied a suitably aesthetic photograph had been taken or the light had changed sufficiently to halt the process. During and after the photography a number of readings from the equipment were noted to give a range description of the PM at that brief point in time, along with the location functioned as the photograph's title. Minimal post-processing in Lightroom was used to ensure balanced color and exposure. Any unwanted stray light traces from the LED present on the pi zero would be removed with the heal tool.

Postcard technique for real-time data collection and analysis

Sentiments regarding air pollution from students of the Addis Ababa Institute of Technology were captured using a postcard data collection approach[46]. Postcards were filled out in English or Aramaic. Students' responses were extracted and translated from Aramaic to English. Deductive thematic analysis[47] was undertaken on these responses, using the COM-B behavior change wheel framework[37] to understand individuals' 'capability', 'opportunity' and 'motivation' of being able to change their behavior to reduce air pollution. Data management and coding was undertaken in NVivo, with the responses being assigned initial codes, and then categorized into the final themes. A robustness check and discussion confirmed the interpretation.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

Data are provided in the format of photographs (see figures), as this project is an art science collaboration study. Given the contextual conditions related to the lighting required for the use of the light painting technique, data from this study are not reproducible.

Code availability

Code for the light painting photo technique is contained in an open GitHub repository at https://github.com/robin-price/pollution-painter.

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Author contributions

F.D.P. and R.P. conceived and design the experiment, performed the experiment, analyzed the data, contributed to materials and analysis tools, wrote the paper; K.E.W. and C.L. analyzed the data, contributed to materials and analysis tools and wrote the paper; M.S.A., W.R.A., S.E.B., D.D., Z.G., S.M.G., R.H., M.K., A.K., Ch.L., S.K.M., B.N., K.N., A.S., B.T.W., G.N.T., F.W.

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Competing interests
The authors declare no competing interests.

Ethics information
The study was reviewed and approved by the University of Birmingham Ethical Committee (ERN_17-0994B).

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