Light-In-Light-Out (Li-Lo) Displays: Harvesting and Manipulating Light to Provide Novel Forms of Communication

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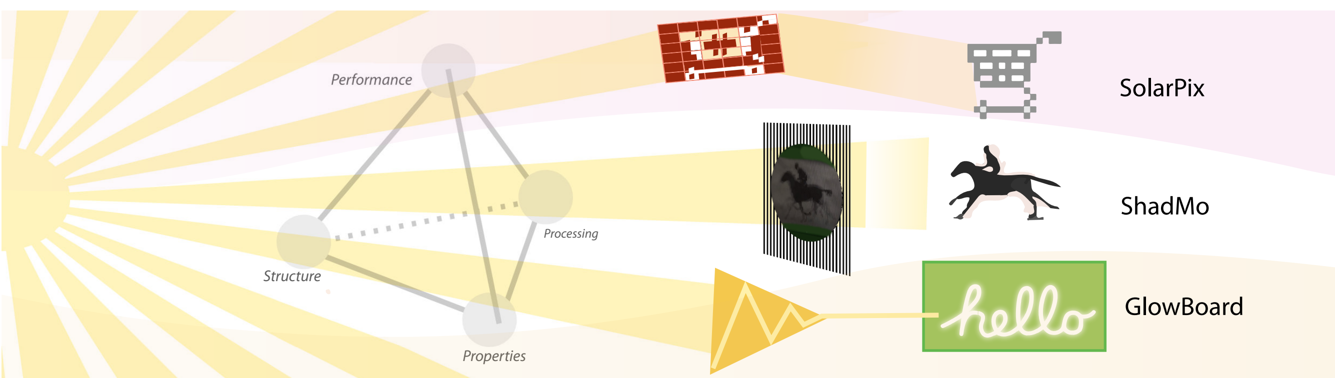

Figure 1: Artist's representation of the Li-Lo concept. Light from the sun or indoor light (left) interacts with material qualities (centre left) to reflect (centre right, top), occlude (centre right, middle) or focus a drawing light beam (centre right, bottom), for SolarPix, ShadMo and GlowBoard, respectively (right) with all the digital and physical actions sustainably powered.

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ABSTRACT

Many of us daily encounter shadow and reflected light patterns alongside macro-level changes in ambient light levels. These are caused by elements—opaque objects, glass, mirrors, even clouds—in our environment interfacing with sunlight or artificial indoor lighting. Inspired by these phenomena, we explored ways of creating digitally-supported displays that use light, shade and reflection for output and harness the energy they need to operate from the sun or indoor ambient light. Through a set of design workshops we developed exemplar devices: SolarPix, ShadMo and GlowBoard. We detail their function and implementation, as well as evidencing their technical viability. The designs were informed by material understandings from the Global North and Global South and demonstrated in a cross-cultural workshop run in parallel in India and South Africa where community co-designers reflected on their uses and value given lived experience of their communication practices and unreliable energy networks.

CCS CONCEPTS

• **Hardware** → **Wireless devices**; • **Human-centered computing** → **Displays and imagers**;

KEYWORDS

Sustainability, ambient devices / internet of things, public displays.

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1 INTRODUCTION

Can you remember a time when you or a fellow school student used the bright reflection from the glass of a wristwatch to playfully "draw" on the classroom walls? Perhaps you've stood entranced as you watch the shadows of clouds move across a distant mountain as the winds of a coming storm pick up. Or, maybe you've been fortunate enough to visit buildings that have used light, shadow and reflection to complement the built environment, such as the ways the tessellated roof of the British Museum's Great Court casts changing patterns varying with the sunlight outside.[1]

We are working towards interactive displays that draw on such experiences, using the light available to the device to produce a reflection, image or shadow that might be used in meaningful inter-person or inter-group settings. At the same time, mindful of the need to think carefully about the sustainability of innovations, and following previous examples (e.g., [25, 47]), the same light sources are used to provide all of the power required to activate the display and its communications with a wireless network.

In this paper we describe three exemplar prototypes developed through a process of material-centred design that begins and is driven through interrogations of photovoltaic (PV) and optical manipulators (such as mirrors). Each device takes in light to power the display and also manipulates the light in one of three ways: SolarPix reflects light via mirrors; ShadMo occludes light, forming animated shadows; and, GlowBoard focuses a beam of light, resonant of the wristwatch-reflected pinpoint of light to form short-lived images on a phosphorescent surface. The prototypes are illustrated in Fig. 1 and described in more detail below.

While self-powered interfaces are attractive to many in the "Global North" for climate emergency reasons, in many places in the "Global South" they have the added benefit of being able to operate without grid power. In these locations, on-grid energy sources can be unreliable or economically challenging; meanwhile, sunlight is often more readily apparent. Prior research has also shown the ingenuity and diversity of people in such regions to innovate novel communication practices that work-around resource limitations such as power, technological literacy or device sophistication (e.g., [8, 34]). Mindful of these two design drivers, then—lack of on-grid power availability and communication practices—in this work we also asked two groups in India and South Africa to work synchronously to react and elaborate on the prototypes.

2 BACKGROUND

Our work draws on and extends the literature relating to light-based user experiences; subtle and intimate communication in HCI; material driven design; and, Human Computer Interaction for Development (HCI4D). We survey the key works here and in Section 3.3 detail how the three exemplar prototypes created relate to these.

2.1 Light-based user experiences

There has been a great deal of interest in using light—and its manipulations—as a medium to provide novel displays and interactions; furthermore, as a recent systematic review of tangible interaction with light suggests, this is an area of increasing significance [41]. All of this work, aims, as does ours, to embed the digital more directly into the physical world, drawing inspiration from the Tangible Bits programme of work and especially its call to consider optical—light, shadow, reflection—perspectives [32].

2.1.1 Artificial light and projection. In light of the developments in LED technology, Lucero and colleagues [43] called for an evolution in how lighting could be integral to digitally-mediated interfaces and experiences. Commercially, we have seen expressions of this sort of thinking in highly successful products such as Philips Hue and Nanoleaf. To explore the possibilities, research studies have explored how people might interact with digitally-connected lighting for both "utility" reasons (e.g., in office settings [65]) and to afford expressive, creative and gaming experiences (e.g., [59]).

One focus seen in the literature is to use artificial light—via positioning,intensity, colours and dynamics—to communicate in ambient, abstract ways, with examples including encouraging moments of physical activity while working [21, 55], to support navigation tasks by adding lighting to a steering wheel [46] and to combine with wearable devices to increase awareness of personal stress [69] and focus levels [64]. Many of these proposals involve stand-alone objects but others have been conceived as being integrated into household appliances such as lamps (e.g., [13]) or to be used in conjunction with digital devices (e.g., Sparkle [50] supplements a tablet interface to indicate the location of off-screen points of interest).

In contrast to these ambient light displays, a number of projection based systems—using large scale projectors or handheld mobile pico-projectors—have been used to provide more figurative or explicit displays and interactions. For example, PicoTales [56]

[1]https://blog.britishmuseum.org/everything-you-ever-wanted-to-know-about-the-great-court

enables users to collaboratively create video animations by tracking mobile device movements as images are projected; LightBeam creates interactive surfaces on everyday objects by projecting visual interfaces [31]; and, PICOntrol provides light-based hand-held controls for operating physical devices in an environment [58].

2.1.2 Recruiting natural and ambient light via material design. There has been less of an emphasis in prior work on the use of either natural (i.e., day-) light or light emitted from other objects in the environment (e.g., a standard desk lamp). The fields of computational architecture and human-building interaction have, though, provided notable examples including Rekimoto's Squama architectural features that provide a range of communication possibilities including "programmable shadows" [54], turning wall panels opaque to cast shadows on objects in the environment. Meanwhile, WindowWall conceives of changes to glass transparency to occlude window areas, selectively blocking external light and enabling messages to be presented in the glass itself [3]. In contrast to these occlusion approaches, Shutters [15] displays symbolic and literal content by permitting some light to pass through the fabric deformable display, thereby casting message shadows on a nearby surface.

At a smaller scale, the Water Lamp uses shadows and reflections of digitally actuated water ripples to present ambient information [17]; the Candle Shadow Display deploys a rotatable candleholder to cast simple emoticons [39]; and, in another prototype, shadows are cast by activating different patterns of an electrochromatic display to enhance storytelling for children [33].

2.1.3 Shadows, reflections and light channelling. We have already outlined some examples of shadow output via ambient light. Others have considered the use of shadows as a form of input. For example, tracking users' shadows has also been explored to: add new interaction techniques to home appliances [14]; detect hover gestures on multi-touch tabletop displays [19]; and, to provide tactile feedback to a user regarding their position on a large screen display by their position through shadows cast onto the display [29, 61]. Then, there are approaches that combine shadows for input and output: for instance, in Colley et al. [16] plant shadows are captured, distorted and projected back to provide passive notifications; and, projecting previously captured pedestrian shadows has been proposed as a way to demonstrate the shared nature of public spaces, allowing for the capture of a memory pool of an individual's physical expression.[2]

In contrast to the breadth of work on shadows, there are far fewer examples in the literature on the use of reflections and other forms of light-chanelling for explicit, visible interactions [41]; although the opportunities have been long highlighted (e.g., [17, 32]). The use of reflected light has been proposed though to enable the tracking of objects but without the user being aware of the interaction mechanism: for instance, in Wang et al. [66] the authors propose distorting and reflecting sunlight using coatings on vehicles, with the resulting light patterns decoded by sensors situated in the environment; and, in Echtler et al. [19] non-visible IR shadows are used to enhance multi-touch surface interfaces.

There are also examples from the maker and artistic communities of objects that channel or reflect light to create displays. These include a 3D-printed mirror array that uses a similar principle to our SolarPix device[3]; and, Daniel Rozin has an oeuvre of inspiring mechanical displays where a person's "reflection" is created by actuating a pixel grid made from a variety of materials from pine to pom-poms (e.g., [57]).

2.2 Subtle and intimate communication in HCI

While much digital communication—intimate or otherwise—is increasingly direct, fast-paced, there is an enduring research interest in more subtle, slower, lower-bandwidth interactions to maintain and enhance connections between people. Examples include the use of both user-initiated messages and those automatically generated by a system. Kaye et al. [38], then, explored the value of single-bit communication between long-distance couples where a partner can click a button on their task-bar and a corresponding circle on their loved-one's bar illuminates and fades over time; CouplesVibe [4], on the other-hand, illustrates the use of automatically generated haptic patterns on a mobile phone to give a partner a sense of their loved-one's location. During the pandemic, of course, the loss of in-person connection has heightened the relevance of this sort of research: Gaver et al. present a range of COVID-19-inspired prototypes—YoYo machines—to facilitate lightweight and playful ways to remain in touch when kept apart [63].

The desire to be in touch is clearly global, and studies have shown the creative appropriation of existing technologies and prototypes proposals beyond the Global North. In South Africa, for example, users were seen to deploy missed call "beeps" and free "callback" ten-character messages to avoid mobile call costs whilst still communicating intimacy [6]. The MXShare system in the rural Eastern Cape of South Africa afforded asynchronous social networking [7]. Meanwhile the PV-Pix [53] prototypes are examples of novel systems for inter-group intimate communication, co-created with informal settlement families in India. These self-powered low-resolution deformable physical displays were seen to afford a wide range of simple but expressive messages in deployments [53].

2.3 Material driven design

Fernaeus and Sundström [20] speak of a need for a "turn to the material", recognising the limitations of conventional user-centered design in taking full advantage of user experience opportunities physical materials may afford. They suggest that in doing so, systems with a strong physical-digital integration should be developed in ways designers have done for many decades before with non-digitally-infused physical objects, in what Shon calls a "reflective conversation" with materials [62]. With the advances in material science, Karana et al. argue for a methodology—Material Driven Design—that progresses through stages from an understanding of the material to potential visions of experiences such properties might platform to user studies of products that embody these visions [37]. While that perspective was illustrated via non-digitally-infused materials, they also show that the approach can be effectively deployed with the forms of system and smart-materials that we are interested in here (e.g., [5, 23]).

[2]https://jonathanchomko.com/shadowing

[3]https://github.com/bencbartlett/3D-printed-mirror-array

2.4 HCI4D

Human Computer Interaction for Development has grown in significance due to the work of pioneers such as the late Gary Marsden in Cape Town [35]. Much of this work has focused, rightly, on investigating ways to ensure digital devices and services work for communities with resource opportunities and constraints, cultural expectations and experiences that often differ significantly from those in the Global North. Large numbers of these studies have considered how to enable non-textual communication and service access through mobile devices, the pervasive technology in these regions (e.g., [2, 36]). There has been, however, interest in the use of publicly-situated displays and other devices for these purposes (e.g., [22, 49]).

Global South communities and contexts, though, have also provided important design and innovation insights that have significance for the rest of the world. Recognising this, there have been calls to enrich and diversify human computer interaction by working with such communities to envision and explore potential digital futures (e.g., [34, 68]).

3 PROTOTYPE DESIGN PROCESS

Our team—of material scientists and interaction designers—is focused primarily on a equal reflective dialogue involving state-of-the-art PV and optical materials and interaction design practices and insights, with both the material science and design thinking being challenged and reshaped by this engagement. In other work, one of the issues surfaced by research teams working at the interface of design and material science relates to a misalignment of traditional user-centred and material science processes. Both the timescales and drivers of the processes differ: user-centred design typically iterates quickly to move from lower- to higher-fidelity prototypes to understand potential novel form factors, interfaces or interactions, without slowing the process through "detailed" technical implementation; meanwhile, research engineers and chemists are focused on creating a viable proof of concept through production and manufacturing processes that are much longer [52]. This can lead to interaction design researchers elaborating concepts that material scientists then find hard to instantiate in an expeditious way. This has the potential for a frustrating monologue between the disciplines where interaction design researchers do all the talking while the material scientists attempt to satisfy the constraint-free ambitions they are presented with.

Material Driven Design (as outlined in Section 2.3) in contrast begins the design journey through a detailed technical and experiential understanding of the materials at hand before moving iteratively through to prototypes. The approach we took has clear resonances with this method; however, we extend the understanding of the practice in four ways:

- The specific materials we started with were not necessarily intended to be the basis of the resulting prototype concepts.
- We did not distinguish between the roles of technical specialist, "designer" and "user"; rather this was a co-creative process where technical and interaction experts worked alongside each other and non-experts to envision and design possibilities in a dialogue-labs style approach [44];
- We specifically included "sustainability" as a key element, responding to the call highlighted in an extensive survey of Tangible User Interfaces [28];
- We recruited both Global South and Global North perspectives.

Before embarking on workshops, Swansea University's Ethical Review Board considered and approved the studies.

3.1 Phase I: Interrogating materials at hand

This phase began with the research team (authors of this paper) identifying a palette of PV and optical materials that could initiate the design journey over a series of sessions where the engineering and chemist researchers presented alternative materials to the design and HCI team members. Inspired by and using the design space presented by Meena et al. [47], the final palette of materials included flexible and rigid PV materials. These materials were also produced in a range of sizes and shapes (e.g., square and hexagonal) and in renderings to demonstrate opaque, coloured and patterned possibilities. The patterned examples included a demonstrator to show how a simple moiré animation could be made by combining two PV printed surfaces: the top one consisting of vertical lines of PV and the bottom the animation surface.[4]

3.1.1 Material-centred design workshop. We recruited nine Swansea University researchers (6M, 3F) for a half-day workshop. These participants were chemists, electrical engineers, material scientists and three interaction designers. After a brief welcome, members of the research team introduced the key purpose of the day: to produce a range of interactive digital systems and services which were powered by the PV materials at hand, and where the PV forms themselves played a key role in the interaction, being then types of computational material [1].

The non-HCI experts were placed into three groups (of three people) and one HCI researcher from our team joined each group. Members of the research team moved between groups observing and facilitating. Using an approach based on the dialogue-labs methodology [44], each of these groups spent fifteen minutes in every zone in the workshop room. Zone 1 focused on illustrating a range of flexible and rigid materials; Zone 2 on patterned and coloured PV material; and, Zone 3 on previously published PV demonstrators. At each Zone, the groups could manipulate physical examples, watch a related video (e.g., in Zone 3 the video showed a state-of-the-art demonstrator operating in self-powered mode) and make use of printed illustrations (e.g., in Zone 1 these included images of architectural uses of different forms of glass). Participants were free to discuss, sketch and "prototype" potential interactive uses of the materials.

After participants had visited all Zones, we brought everyone together to listen to and debate the ideas generated. This process led to agreement on the two most interesting and viable concepts. The first built on the moiré animation illustrations, but instead of simply using the PV materials to animate a graphic within the computational material, participants saw great value in casting shadowed animations with such a device on to a range of surfaces (e.g., a nearby wall, floor or table) and at various sizes and distortions

[4]See: https://www.instructables.com/2D-Moire-Slit-Animation

depending on the light source, distance from the device to the surface and any distortions of light angles that might be deployed.

The second favoured concept was a set of fridge magnet style objects fabricated from a form of PV called Dye-Sensitised Solar Cells (DSSC), each having a letter or a symbol etched on to it. As these magnets are arranged together to create a message, the power harvested by the DSSCs would drive on-board microprocessors to digitise and transmit the message to a local wireless network. This digital copy could then be viewed by others on their phones or other devices. In form factor and function this idea resonates with those of Sifteo Cubes [48] and PickCells [24].

Over the following three weeks, we met six times to design-around the two concepts. In particular we thought about how to use light to communicate the messages formed by the fridge magnet tiles. To do this, we explored the possibility of using LiFi with the tiles emitting light to transmit their identifiers and ordering.[5] As with all elements of the concepts, this light-pulsing would be powered by the energy harvested by the tiles themselves.

Through these sessions we also began to define the notion of Light-In Light-Out interactive displays that is the focus of the rest of this paper. These displays would take light in and through some form of processing give out light during their operation, with all of the processing and output being enabled by the energy harvested from the light input.

3.2 Phase II: Non-expert perspectives on the material designs

With the two concepts elaborated within the over-arching Li-Lo principle, we ran two workshops with non-experts, again following the dialogue-labs ideation method. Both workshops had five participants (workshop 1: 3M, 2F; workshop 2: 2M, 3F) who were undergraduate students from Swansea University. The need to run two workshops and the small size in both was a function of local COVID-19 restrictions at the time of the study. At the start of the workshop we explained our interest in Li-Lo interactions and briefly described how the two prototypes participants would be considering had been shaped in Phase I. After this introduction, we formed two groups (of three and two people, respectively) and guided them to two different areas in the room: one area contained prototypes relating to the moiré shadow animation; the other to the fridge magnet-style tiles (see Fig. 2).

The moiré area included example animations; concept demonstrators showing how these might be formed of material that could harvest energy to power the mechanisms needed to move the surfaces to create the animations; and, lights, mirrors and lenses to provoke potential manipulations of the light sources and shadows. The magnet tile area included wipe-clean hexagons for participants to write or draw on, along with the original DSSC hexagon examples from the earlier workshop to demonstrate how the concept could be fabricated. In both areas, participants were asked to consider interactive uses of the materials, as well as refinements or alternative concept designs. Participants were asked to consider both indoor and outdoor contexts.

Both groups were accompanied by at least one researcher and other members of our team moved between the areas observing.

[5]See: https://purelifi.com/lifi-technology

Figure 2: Prototype materials in the user-centred design sessions. Left: the moiré area, with demonstrator prototypes, lamps, lenses and small mirrors used to interact with and create experimental light manipulations. Right: the magnet area, with wipe-clean plastic hexagons used to explore how tiles could work and be used together.

After an hour-long discussion, groups were swapped; i.e., the group exploring the moiré concepts was requested to move to the magnet tile table and vice versa. After two hours, participants were regrouped to reflect on the ideas generated in the workshop. All the ideas were presented back to the group and built upon as a collective surfacing shared key themes and brainstorming using flipcharts. This part of the session was recorded for later reference.

3.2.1 Findings. The moiré area generated a good number of use-cases, ranging from forming shadows on the ground to give passers-by directions, to educational and fun uses (e.g., attaching the moiré device to a ceiling lampshade such that a range of animal "flashcards" could be shadowed onto a child's bedroom wall at night). However, more significantly, the participants were more engaged in refining the materials and how they operated. Their suggestions fell into three categories:

- Adjusting the size or shape of the animation shadow to provide additional meaning: e.g., at a lifeguard post, a wave shadow could be made larger or smaller via lenses to correspond with the wave forecast for surfers and swimmers.
- Adjusting the speed of the animation: e.g., creating a shadow of a person walking and increasing the speed of the movement to reflect the number of steps recorded by the family's fitness watches during the day.
- Mechanisms to provide interchangeable animations: while we explained that our ambition was to provide dynamic updates to the animation, we did not specify how. Participants provided a range of interesting possibilities including: having a circle of moiré images that could be rotated to change the animation (cf. [26]); having a cartridge of moiré "slides" that could be moved forward and backwards above the striped surface with the required slide being pulled down to from the cartridge to create the desired shadow; and, the use of

System	Light manipulation(s)	Related work	Novel aspects
SolarPix	Reflection	[3, 15, 17, 39, 54]	Self-powered, reflection vs. shadow output, pictograms
		DIY Maker Mirror[3]	Self-powered, interactive and actuated, pictograms
		Rozin Mirror Art [57]	Self-powered, reflection vs deformation output
GlowBoard	Projection, channelling & capture	[56]	Self-powered, phosphorescence, natural light channelling
ShadMo	Oclusion	[3, 15, 39, 54]	Self-powered, high-resolution and animated shadows

Table 1: Each prototype illustrates a distinct manipulation of light and extends previously reported systems (more details in Section 2).

coloured inks that could—somehow—be injected into a mesh of tube structures in the glass to change the animation layer.

The discussions in respect to the moiré concepts also surfaced the potential value of using the mirrors or lenses without the moiré surfaces to reflect or channel light as a means of developing interesting ways of communicating.

In the magnet zone, participants provided a series of interactions with the tiles that went beyond the example case of fridge magnet-style arrangements to send text or symbolic messages to family members:

- Food and eating: magnets to represent commonly-bought food items, tiled together on the fridge to create a shopping list during the week or tiled together to show what is left in the fridge/larder for a system to suggest interesting meals.
- Security and safety: children take a tile from the fridge when they leave the house and place it on the class "register" when they arrive at school, leading to a confirmatory message being sent to a parent's phone (the tangible token being seen as being more hack-proof than a GPS digital tag system); and, tiles to be arranged in a pattern and order on a door or next to a device to unlock/lock it (i.e., a tangible form of "swipe" unlock).
- Fun and games: tiles hidden in an outside area (charging in the sunlight) and players have to find them and connect them together, with clues to the next tile being generated as the pattern forms; and, for indoor contexts, game designers could envisage tile-based games where the physical tiling is communicated to a mobile device to provide additional digital layers of game-play.

In contrast to the moiré zone, participants did not discuss any additional light-based manipulations. This is not surprising as light was not used to form or manipulate displays presented to the user but simply to harvest energy and to perform LiFi communication.

3.3 Phase III: Generating exemplar forms of a material-centred design space

Inspired by the material-focused adaptions provided by our non-expert participants, we refined the Li-Lo principle and specified a series of prototypes to exemplify it over a series of design sessions.

The refined Li-Lo principle defines this new class of displays as ones which:

- harvest energy to provide any power they require to present content and communicate with an external network; and,
- obscure, reflect, channel or retain light to create a visible, meaningful light based output.

While both the moiré and the magnet concepts satisfied the first criterion, the magnet concept did not use light as part of the output. During these design sessions, then, the moiré concept was further elaborated and additional emphasis was put onto considerations of how to exploit the non-experts' suggestions for magnifying, bending, interchanging patterns and so on using both PV and other materials at hand.

At this stage we also introduced a further materially-focused design driver: the material contexts and practices seen in Dharavi, a vast informal slum in Mumbai. Our motivation here was to consider ways of accommodating people who lived in such settings where self-powered devices might be particularly attractive due to both infrastructure issues (i.e., power availability) and economic factors (e.g., disincentive to use power except on essential devices due to financial concerns). Further, we acknowledge the value of diversifying design by taking account of perspectives hitherto overlooked (e.g., [11, 51]). To bring in these perspectives at this stage we combined the expertise of one of our team (and an author) based in Mumbai who had access to Dharavi during the work with the experience of four of the other authors who have worked extensively in this context, and also drew on the results of previously published studies that gave insights into resource-constraints, physical settings and communication practices in informal settlements in India (e.g., [53]), South Africa and Kenya (e.g., [67]).

From these design sessions, the three prototypes we present in the rest of this paper emerged: SolarPix, GlowBoard and ShadMo. We detail each below at a conceptual, implementation and technical evaluation level, showing in each case how the Dharavi perspective was considered. The design sessions were similar to the ones reported in the material design work in [12]: in that project, the design team moved towards working prototypes through many iterations with inputs from designers and engineers.

In selecting and elaborating the prototypes, the key criteria used were: a prototype should demonstrate one or more significant manipulations of light (and be distinct in this sense from the other prototypes); and, differentiate itself from previously published work. The ways each of the three prototypes fulfils both of these criteria is summarised in Table 1.

All three prototypes enable both direct and subtle communication depending on the patterns and sequences sent to the display. In considering alternative prototypes we did want to differentiate between public and private settings, however: SolarPix is envisaged,

System	Feature	Design genesis
SolarPix	Reflections	Phase II Moire Area (Mirror discussions)
	Pictograms	Phase II Moire Area (Slide carousel discussions)
	Form-factor and Light Provision	Phase IV Dharavi Alley Ways
GlowBoard	Light Writing	Phase II Moire Area (Mirror discussions)
	Phosphorescence	Phase II Moire (Bedroom nightlight scenario)
	Phosphorescence	Phase III Dharavi (Typical dwelling ambient light)
	Light channels	Phase III Bottle Lights in Slum Settings[7]
ShadMo	Animation	Phase I Palette of Material
	Shadowing	Phase I Zone 2
	Animation Speed	Phase II Moire area
	Shape/ Size of animation	Phase II Moire Area
	Information through Shadows	Phase III Shadow art in India[8] [42]

Table 2: Design genesis: how the design phases shaped the LiLo prototypes.

then, as a public display (e.g., alleyway-based) while GlowBoard and ShadMo are more suited to private contexts (such as communication between homes of relatives or friends).

4 DEVICE DESCRIPTIONS

The different design phases described earlier contributed to a range of features in each prototype. These origins are summarised in Table 2 and further described, below.

4.1 SolarPix

SolarPix is a light-based community display system that uses a low-resolution array of mirrors to selectively reflect sunlight onto a display surface to form a simple pixellated pattern. PV material harvests energy to drive the mirror array as well as to receive the encoding of the pattern wirelessly (i.e., which mirrors to flip upwards and thereby not reflect the sun onto the display surface). Figure 3 (centre) shows the design of SolarPix along with an example reflected pixel pattern. The grid can be used to encode meaningful patterns or textual characters with the higher the number of mirrors, the greater the resolution (cf. [53, 59]). Users are able to draw their own custom pictograms directly onto the surface of individual pixel mirrors to convey an even richer set of messages (see Fig. 3, right). Here we drew pictograms using easily erasable whiteboard marker pens. This element of the design draws on the non-expert participants' slide-projector schemes surfaced in Phase III of the material-design process.

Dharavi's residences, workshops, stores and businesses have been developed in a densely packed way, meaning that there are many miles of dark and narrow alleyways in which people have to navigate. Some of the alleyways in Dharavi are only wide enough for one person to pass and they are problematic for the residents as they are prone to flooding in Monsoon season or overcrowding during festivals. The buildings on each size of these alleyways are typically only one two storeys high and the roofs usually consist of gently sloping corrugated iron. Usually no other structures or facilities are placed on the roof tops. In this context, then, we might make use of the space on roofs and walls of low rise structures to bring light and communication to people in the poorly lit alleyways. SolarPix would enable residents to (i) receive additional natural light (cf. the giant mirrors that have been used to light up valleys[6]); and (ii) allow the community to share simple graphical messages with one another.

4.1.1 Technical implementation and evaluation. An array of 16 servo-motor actuated mirrors are mounted on an acrylic backplane. Each servo-motor is individually addressable and driven via a microcontroller and custom electronics. When a user sends a message wirelessly to the display, the hinged mirrors are actuated by the servo-motor arm swinging forward.

SolarPix is designed to be self-powered and harvest all of the energy it needs to function from sunlight. The mirror array is pointed toward the sun and light reflected to a display surface (wall, floor, etc.). Mirrors that have been activated reflect sunlight away from the display surface onto a single solar panel, where light energy is harvested to power the SolarPix device.

With any self-powered digital device, a key question is how often can it be activated. Assuming an outdoor deployment and using data we have on the average light levels in Dharavi over an extended period, we calculate that over 32,000 mirror actuations per hour would be possible – more than enough to dynamically update the messages sent by users.

Turning now to the quality rather than the quantity of images displayed, the way the light is reflected and the pixellated image fidelity primarily depends on both the mirror arrays and the light source. We evaluated SolarPix with two light sources: initially, a lamp light source was used to test the array in the laboratory. This yields excellent results in terms of image fidelity. Next we evaluated the performance of SolarPix in direct sunlight (e.g., see Fig. 3). In this case, we found that the performance is very much limited by how flat the backplane is. At close proximity to the display surface, pixel fidelity is good, but as the distance between SolarPix device and the display surface is increased, the image fidelity deteriorates due to backplane bending and warpage.

[6] https://www.theatlantic.com/photo/2013/10/using-giant-mirrors-to-light-up-dark-valleys/100613

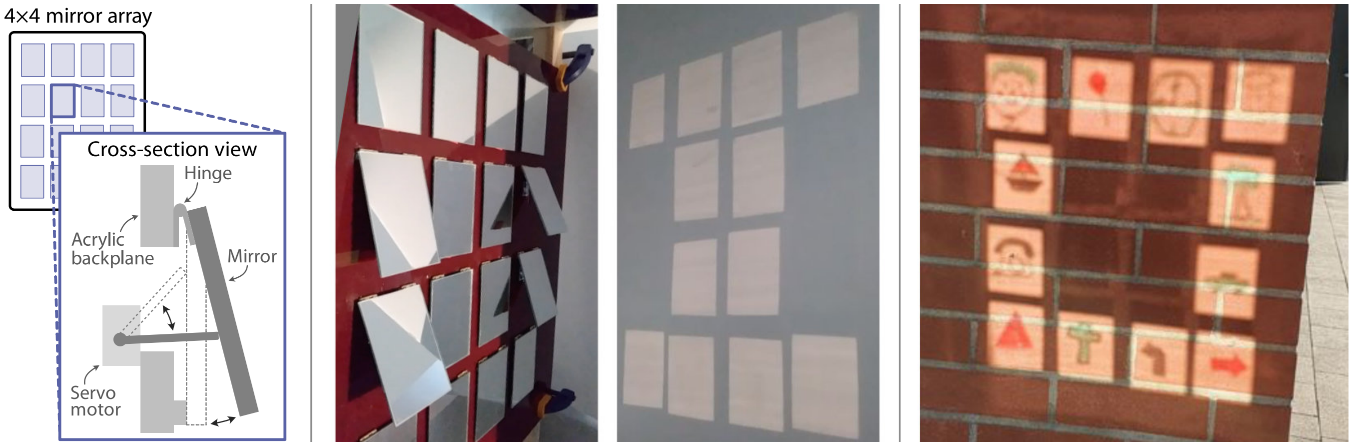

Figure 3: (a) SolarPix in operation. Left: a 4×4 array of mirrors is individually actuated to direct light either to a nearby surface (two rightmost images) or to a solar panel mounted above (the dark area just visible at the top of the centre left image). Centre: SolarPix provides light output by reflecting light 'pixels' in meaningful patterns. For example, the 'I' shape shown here is created by actuating four of the 16 mirrors to direct light away from the projection surface. Right: the device's pixel mirrors can themselves be augmented with pictograms to add a further layer of output and meaning by combining both light patterns and sketched icons.

4.2 GlowBoard

Many of Dharavi's busy and overcrowded slum residences are multi-functional – serving as places of work during the day, living rooms in the evening and sleeping areas at night. With very little natural light entering the rear of the dwellings, there is an opportunity to create communication devices that are well suited to environments with little or no light. GlowBoard encourages people to explore their artistic side by creating glowing symbols, letters, numbers and shapes to directly communicate short lived messages with friends, family and neighbours. The darkness of the dwellings is an effective context for the phosphorescent material that captures and emits the patterns.

4.2.1 Technical implementation and evaluation. GlowBoard uses UV light, which can either be sunlight that is piped in from outside [7] or produced by an artificial light source that is powered by harvested sunlight. The UV light is then traced over a phosphorescent surface within the dwelling to leave short-lived glowing messages (see Fig. 4).

The present iteration of GlowBoard uses an x–y mirror galvanometer to steer a beam of light (in this case from a UV laser) to allow the user to draw short-lived (typically 1–10 minutes, depending on ambient light) patterns and simple messages on a phosphorescent board. The same message is automatically drawn on a duplicate board in another location. A user writes a simple message on the phosphorescent board via the touchpad positioned below the phosphorescent board. Coordinates are processed by the microcontroller, which in turn drives the x–y mirror galvanometer's servo-motors. At the same time, the x–y coordinates are sent, wirelessly, to the receiver's duplicate unit in a nearby house when the user has finished writing their message. As with all the prototypes,

[7] Inspired by: https://www.thehindu.com/sci-tech/energy-and-environment/a-bottle-full-of-light/article2960029.ece

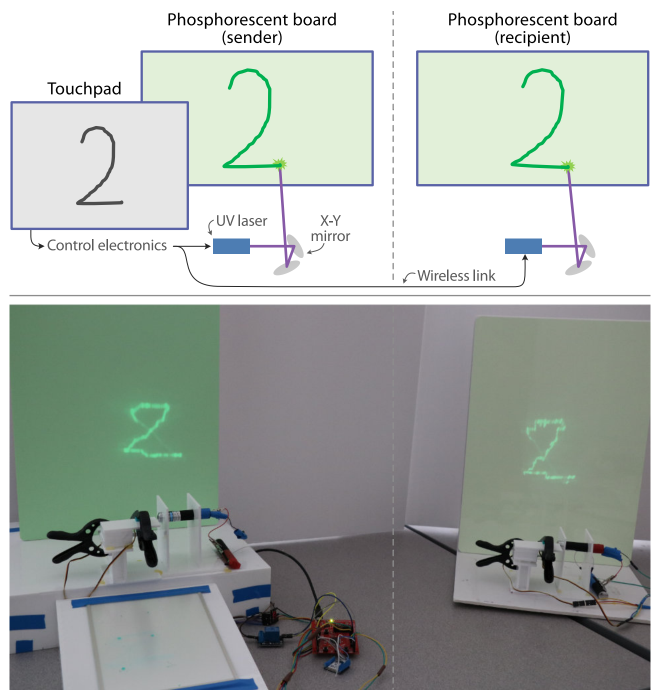

Figure 4: GlowBoard in operation. Top: the sender writes their message on a local touchpad, as shown in the schematic diagram. The sketch appears simultaneously on the local phosphorescent board (left); and, the recipient's unit (right). Bottom: the prototype GlowBoard system in use. Input from the touchpad (lower left) is presented as light output on both the local (left) and remote (right) phosphorescent boards using a UV laser beam steering X–Y mirror galvanometer mechanism.

all of the energy required for its operation is harvested sustainably via PV materials.

4.3 ShadMo

Architects, artists and performers have all previously used shadows to either change a person's experience of a place or to entertain. There is a long and rich history of shadow puppetry in India [42]. In one such installation, an artist has created street art shadows that moves as the sun arcs across the sky.[8] The artist installed a street-long awning, holding stencilled phrases that project shadows forming a tapestry of words on the ground. The author claims that "shadow-casting artwork adds an interesting layer to the streetscape and offers an approach filled with possibilities for other public spaces". ShadMo resonates with this idea and creates self-powered animated shadow patterns to convey simple messages with both sunlight and artificial indoor lighting.

4.3.1 Technical implementation and evaluation. ShadMo is designed to be used with either bright indoor lighting (e.g., light from a table lamp) or direct sunlight, i.e., any light source that is bright enough and can create a single shadow. The shadow patterns are created with two components: a stripe pattern and a user customisable design pattern. The stripe pattern is fabricated as a functioning part of the solar energy harvesting plate (DSSC), while the design pattern is mounted on a linear bearing system and driven by a linear servo-motor along the x-axis (see Fig. 5). Currently the design pattern can be changed—to enable user-customisation—via clip-on plates incorporated in the design. The speed of the animation is easily varied by increasing or decreasing the speed of the servo-motor as suggested by our non-expert participants in Phase III of the design process to add additional meaning to the message.

With indoor lighting the size and shape of the shadow can be adjusted by changing the distance between the light source and the device. It is possible, then, to cast large shadows onto a nearby wall or floor with even the small form-factor used in the current device. In sunlight we have used lenses and mirrors to achieve similar shadow size/shape adaptions.

For operation in direct sunlight, we note that Mumbai averages about seven hours of sunlight per day throughout the year. With the current design, we can store this solar energy and operate ShadMo for maximum of 34 minutes in any 24 hour period when ShadMo is exposed to direct sunlight. When it comes to operation with indoor lighting under a bright lamp, ShadMo harvests up to 8 mW. The lamp will need to be on for 12 hours a day for ShadMo to harvest enough energy to operate for five minutes. Of course, in both cases, ShadMo activity time can be extended with additional solar cells or modules.

5 RESPONSES TO THE PROTOTYPES – THE VIEW FROM DHARAVI AND LANGA

As we have seen, the prototypes emerged through a material-centred design process: experts in material science and HCI were asked first to interrogate a range of PV and light-based materials. Non-experts further built on the concepts also using a material-focus and then these were further elaborated by our team adding an additional design lens that drew in material considerations relative to informal settings in the Global South.

As a next step, we used these prototypes as provocations and starting-points for further co-design with communities in two slum contexts: Dharavi in Mumbai and people who live in the townships of Langa and Khayelitsha, in Cape Town. In Dharavi, six female and three male participants who are all residents with an age ranging from 19 to 60 met at one of the participants' homes. In Langa, another set of five female and five male participants, ages ranging from 24 to 47, from the above mentioned townships met at the co-located researcher's home. Our motivation for the workshop was two-fold: to understand any value or uses these co-designers could envisage for the prototypes or alternates; and, importantly, to further enrich the designs for anywhere use through the unique and valuable experiences these "future makers" bring [51].

Ethical and responsible innovation is core to all the work our team is involved in: having worked in the area of HCI4D for many years, we were mindful of ways to enhance equity, inclusivity and diversity in the work, adhering and going beyond suggestions made by others.[9] The community facilitators and the team undertook careful consideration of ethical issues before the plans were submitted to—and endorsed by—Swansea University's Ethics Approval Board.

5.1 Method

Prior to the COVID-19 pandemic, our team mainly carried out participatory design work in person using methods common to those seen in other work with what Galleguillos and Coşkun have recently described as "less privileged participants" [40]. Due to the pandemic, though, we were not able to visit these locations as a whole team or to transport the prototypes from our labs. Instead our participants and local researchers who were able to meet in person were linked together and with the remote team via Zoom. The workshop ran over a 3.5hr period (starting at 10am in South Africa and 1:30pm in India).

While the pandemic disrupted a fully in-person methodology, forcing us to be remote with limited local access to our community co-designers, we took advantage of the situation to do something we had not considered before: to bring two communities together at the same time, to share their experiences and to provide us all with a diverse and stimulating set of perspectives.

The value of recruiting cross-cultural perspectives has been demonstrated previously in regard to learning (e.g., asynchronous sharing of participatory video between students in India and others in Nepal [30]); digital design activities (e.g., gathering and comparing stories on work practices in India, Portugal and the UK [45]; and, comparing insights from parallel but independent mobile design workshops in Kenya, South Africa and India [34]). Clearly, remote methods have been used in the past to link design teams with participants (e.g., [60]) but, in surveying the literature we could not find work describing real-time participatory design across regions, linking two distinct participant groups, in the form described below.

5.1.1 Workshop segments. The workshop had five segments, with three involving all the participants, the co-located researchers and

[8] https://dirt.asla.org/2019/02/11/shadows-cast-artwork-onto-an-indian-street

[9] Minimum ethical standards in ICTD/ICT4D research: https://eprints.whiterose.ac.uk/140066

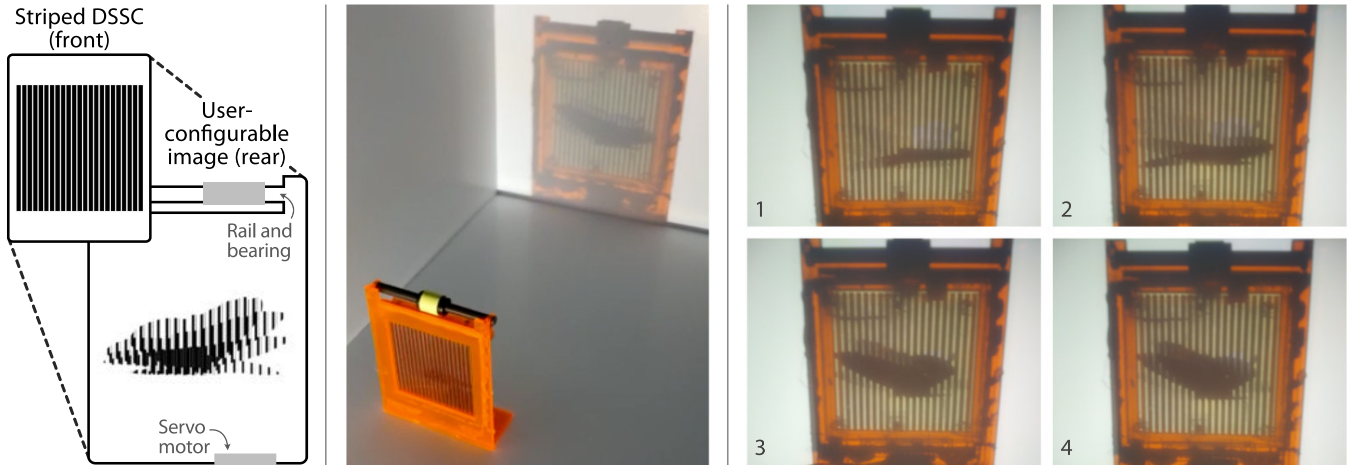

Figure 5: Left: ShadMo uses moiré effects to create dynamic shadow messaging output. The system consists of a striped DSSC and user-configurable moiré-patterned image. A servo motor moves the user's image along a horizontal bearing, creating an animation effect. Centre and right: close-up images of our prototype in use: as light hits the front panel (lower centre), the motor activates and causes the projected image to animate (sequence 1–4, far right), and the butterfly gently flaps its wings.

those remote in one main Zoom-room and two consisting of separate breakout rooms holding: i) the co-designers in Dharavi, the co-located researcher and two remote researchers; and, ii) co-designers gathered in Langa, the co-located researcher and two remote researchers.

- Segment I (everyone together): Welcomes and introductions. In these plenary sessions our locally-based researchers translated between Hindi, English and isiXhosa.
- Segment II (two breakout rooms): Overview of the sessions, and ethical consent individually given. Discussion of the part that light (internal and external) plays in participants' experience. Explanation of the work to use light for new digital/physical communications (and hence the reason we asked participants about light). Discussion of how the pandemic had affected their communications over the previous year. Segment II was designed as a way to both to frame the later discussions and to enable participants to open up by discussing topics they were familiar with, rather than starting with our prototypes.
- Segment III (everyone together): Sharing of key points from Segment II.
- Segment IV (two breakout rooms): SolarPix, ShadMo and GlowBoard demonstrated and explained to the participants using animations and video of the working prototypes (see Fig. 6). After each explanation, the groups were asked to:
  1. give their initial comments/questions,
  2. work in pairs to draw a message they would see as useful in that context on a printed copy of the display surface (see rows (d) and (e) in Fig. 6),
  3. discuss their images; and,
  4. discuss wider uses, issues and limitations.

  After each demonstration, participants were asked to comment or ask any questions they had; suggest where they might place the device and for what purpose; and, to provide any suggestions for changes.
- Segment V (everyone together): The Langa gathered participants were asked to share three key reactions they had to the prototypes; Dharavi residents responded comparing their views. Then, there was a discussion on which prototypes to progress and the relevance to global use.

5.1.2 Analysis. During the workshop the researchers (local and remote) made textual notes to record participants' questions, insights and suggestions. Segments III and V where all participants were together were used to highlight, share and compare the most significant aspects discussed in the individual breakout rooms. After the workshop, two of the researchers (one from the Langa breakout room and the other from the Dharavi breakout room) worked through the full set of notes to surface key themes. These independent analyses were then integrated to further refine the findings presented below.

5.2 Findings

5.2.1 Segment II – Light in life and communication during COVID-19. Light or the lack of it has a strong impact on community members in both locations, impacting practically, emotionally and spiritually. The availability of light and its changes over time was said to dictate the pattern and rhythm of the day. In Dharavi, for example, our participants spoke of the morning sun salutation yoga ritual and their afternoon walks. The Cape Town participants described how the lack of light (at night) had a profound effect on their sense of security – walking in the dark in their townships was avoided, and if found in this situation mobile phone flashlights were not used as this would make them even more vulnerable. Cape Town participants showed a keen awareness of the financial implications of using electricity for lighting, cooking and refrigeration, noting that they sometimes had to make choices and tradeoffs about what to turn on. These participants were regularly confronted with power

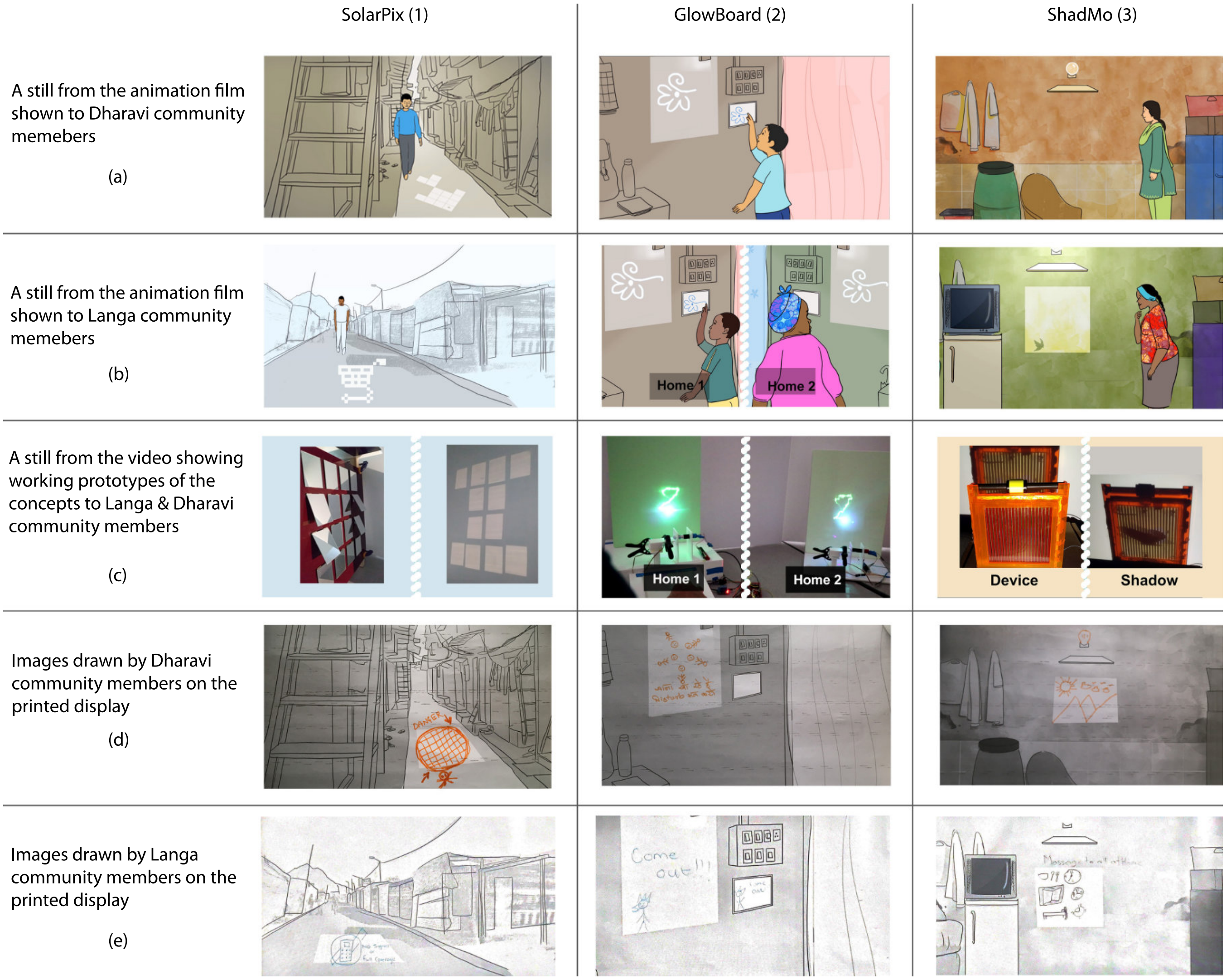

Figure 6: Frames from video demonstrators for each prototype (Rows a–c) and example images sketched by Dharavi (row d) and Langa-based (row e) participants. The simulated display outputs in rows a-b were drawn with the help of community members prior to the workshop. For SolarPix: (a) symbolises a popular fish market that can be reached via the alleyway; (b) is based on the logo of the main supermarket in Langa.

outages via a practice of "load shedding". Some of the participants had solar panels for heating water or electricity generation that could mitigate these situations.

Turning now to the discussions in regard to COVID-19's impact on their communication practices, both Cape Town and Dharavi participants noted the negative effects, with the loss they felt of physical togetherness and connection: *"Physical expressions of hugging, holding hands, being proximate when meeting a friend are now gone"* (Dharavi participant). Both groups increased their use of mobile messaging, and the Cape Town group highlighted the positive side-effect of the pandemic in their learning of new platforms (like Zoom on a phone) which they thought might be helpful in future job applications. The increased effort to keep in touch via digital means meant that both groups felt that some of their non-family relationships *"[...] had been fractured"* (Langa participant) while, conversely, there was extra effort to reach out and stay in contact with more distant family members. The Dharavi participants noted the problems the reliance on mobile phones brought for some of their family and friends who either did not have their own device or had not learnt to use one before the pandemic.

5.2.2 Segment III – Sharing and comparing experiences. The importance of light for safety and security noted in Cape Town was not seen as a key issue in Dharavi. These participants also did not relate to the electricity resource availability problems surfaced in the Cape Town workshop, with participants noting that the grid supply was quite reliable.

The shared deeper emotional and spiritual significance of light was illustrated through a range of comments that included: *"I'm morbid and moody in the dark of winter"* (Cape Town); *"In the morning light I feel good and fresh"* (Dharavi). The Cape Town participants heard about the specific light-based yoga rituals and responded by describing how some of them used candles in their own spiritual practices.

Participants explained to each other the overall negative impact of the pandemic on their sense of connection with others in their community.

In reflecting on this group discussion and those in the breakout rooms, then, it seemed clear that light might provide a potentially powerful basis for interfaces and interactions. Further, in considering the communication discussions, both groups highlighted a desire to connect to others in ways that go beyond what is currently possible on the mobile devices they owned or shared, addressing the needs expressed for more tangible connections and to accommodate those unable to use a mobile device.

5.2.3 Segment IV – Views on the three prototypes. **SolarPix:** Participants elaborated on the basic navigation scenarios presented in the animation, suggesting the value of SolarPix reflections that showed the way to health providers or the police. They also suggested the use of the display to provide community messages and in the case of Dharavi residences as a way of further adorning the alleyways they lived in along with patterns and images during the numerous yearly festivals.

The Cape Town participants warned against projecting the reflection on the floor as *"[...] walking with one's head down looks like you are not confident and makes you more of a target to be robbed"*. A different form of security concern was raised by Dharavi participants. In Dharavi there are many narrow dark lanes and, *"There are open holes on some of the lanes [...] People put a tree branch to show there is a hole [...] If it is not notified, people can go inside and many people have died like this. During flood it is more dangerous"*. To help with these dangers, participants suggested the SolarPix could project a pattern near the start of a pathway to show the condition of the pathway (e.g., how many slabs were currently missing) and the extent of the flooding. One participant further suggested that the images could be made to shimmer or blink to grab attention in these safety-critical situations.

While the Dharavi participants focused on displays within alleyways (a key feature of their environment), the Langa workshop participants suggested that central communal spaces such as a wall near the bus, train or police station were seen as good places to project on to. One Cape Town participant suggested using large mirrors to project big displays onto Table Mountain, a huge natural landmark visible from many suburbs in the region.

Participants in Langa also asked about how this public messaging could be used by sight-impaired members of their friends and family.

GlowBoard: Participants in both of the breakout rooms asked what this sort of method enabled that they could do with their mobile phones. They went on to answer their own question in part by noting that: the people they were communicating with had to be present at the display at the same time they wanted to communicate, leading to suggestions of games and emotional connections that could be made synchronously; there had to be sunlight in both locations for the messaging to work; they could express things such as textual scripts not supported on their mobile (Dharavi) and in freer ways (e.g., by sketching out a blown kiss, Langa); and, gossip more as the message would quickly fade (Langa).

ShadMo: Both groups struggled to see the value of this form of display. The Dharavi participants mainly saw it as a way of providing artful decoration in their homes (e.g., the shadow showing a cultural symbol of their home region or giving them *"a feel of the outside world when stuck in doors during lockdown"*). Cape Town participants suggested its use in allowing a parent away at work to signal to their family members activities such as time for homework or bedtime. These participants also suggested ways of altering the speed of the animation to add meaning to the message: for example, one idea discussed was to show family members at home how well a working parent's day was going (the faster the better), while a heart image that was animated to show its beat to emphasise the sender's love was also proposed.

5.2.4 Segment V – Sharing and Comparing Responses. The Langa group began the discussion by asking why researchers like us were developing these forms of devices when there is mobile phone technology: as one of the participants noted, *"these seem primitive compared to the phone!"*. Dharavi participants responded that in their context these devices might be more attractive as often not all of their family have access to a mobile and not all older family members want to use one. The Langa group also recognised that all of these ideas were more public and communal in their use and could be better than everyone with their *"heads buried in their phones"*.

Asked which of the prototypes they felt they would like to see developed further, both groups were enthusiastic about SolarPix (all participants in Dharavi and nine of the ten in Langa); ShadMo was not considered useful in the form presented to the participants (four Dharavi participants wanted to see it progressed; no-one in Langa); and, GlowBoard was seen as valuable in Dharavi (all participants) but not in Langa (one person would like to see it progressed). With the GlowBoard design a key problem for the Langa participants was the short-lived nature of the glowing message as they envisaged mainly asynchronous messaging; in contrast, the Dharavi co-designers spoke of a collaborative use of the devices, for playing games or learning between households. For the ShadMo concept, a key issue was the desire by participants to change the animation dynamically via their phones (the video demonstrator we used showed only our proof of concept with a physically fixed butterfly animation).

5.3 Incorporating our co-designers' suggestions

Given the enthusiasm shown by both groups for SolarPix, we explored how to accommodate two of the interesting adaptions suggested. Firstly, in order to enable a way of bringing attention to the projected critical images (a Dharavi suggestion), we could implement a scheme that allows for the activation of micro vibrations on each of the pixel mirrors.

Secondly, Langa participants pointed out that SolarPix excludes visually impaired people. A possible solution—inspired by the artist

Colourusso's SoundBoxes[10]—is to incorporate an audible element to SolarPix, for example by creating earcons [10] for different mirror—and hence pattern—configurations. Alternatively, if SolarPix is being used to dynamically present a series of characters to spell out a message letter by letter, a simple initial implementation might audiolise these.

5.4 Beyond the exemplar prototypes

The workshop elicited comments and insights in regards to the LiLo concept that motivate and can shape future material-driven design activities. Light is a valuable resource and elicits powerful "sensorial, interpretative, affective, and performative" [37] responses. While HCI has considered some aspects of its possibilities, given emerging lighting technologies, and materials that can capture, store and manipulate it, light is a material (albeit ephemeral [18]) worth pursuing. This is a particularly timely moment for such considerations given the climate emergency and the self-powered, sustainability focus, of Li-Lo-like devices.

Li-Lo devices depend on light both for power to operate and to display outputs. With changing light patterns daily and monthly, the times and ways these devices can be used will also vary. Designers can exploit this constraint as a spur for ways to enable new connections and interactions (e.g., as noted by comments with regards to GlowBoard).

The recent global pandemic has resurfaced practical and experiential reasons to design beyond the mobile phone—and indeed conventional digital display—to enhance connectedness between individuals and groups. Dharavi workshop participants, for instance, highlighted the problems during the pandemic for those without mobiles; and, all participants grieved the loss of togetherness. While a current commercial response is the situated home displays such as Facebook's Portal and Google's Home Hub, given the material properties of light noted earlier there are yet unexplored, subtler, intimate, reflective and sustainable opportunities.

Finally, the comment made in the Langa group about "researchers like us" proposing technology "primitive compared to the phone" is worth reflecting upon. We do not feel the statement was mainly about any overwhelming sense of a "them and us" given the members of the research team who were local or nationals of either India or South Africa and the framing of the workshop as a co-design effort. Rather, the emphasis was placed on a perceived lack of sophistication in the devices. Designers—including us—wherever the target communities are in the world need to embark on any non-mobile phone design activity fully aware of how the mobile paradigm might dominate participants' views (e.g., [53]) and employ techniques that give participants permission to think beyond their current reality (e.g., [9, 34]).

6 CONCLUSIONS AND FUTURE WORK

This paper has presented the results of a material-centred design process. We were initially motivated by a desire to see if a sustained, intensive engagement with the properties and structures of photovoltaic optical materials and the environments they might be embedded within could lead to innovative digital prototypes that were able to use the same materials to harvest all the energy

Figure 7: SolarPix and Dharavi alleyway: low-fidelity prototype (left, mounted on the wall between the grille and central doorway) and example display output (right, an 'X' projected on the grey paving stone).

they required to function. By detailing the properties of a new class of sustainable interface—Li-Lo Displays—and the example prototypes we hope we have provided evidence of the value of such approaches. Taking the findings of the final co-design workshop we plan to adapt the prototypes and, when the pandemic eases, deploy them in situ, returning to the communities in Cape Town and India. As a first step toward this, we constructed a low-fi prototype of SolarPix to help identify potential deployment locations in Dharavi (see Fig. 7).

All three of the prototypes presented here harvest all of the energy they require to operate. While this is clearly positive from a sustainability point of view, the amount of energy available does mean that the forms of display and degree of interaction are of course much more limited than those available on a fully-functioning mobile phone. Rather than see this as negative, though, we argue that this design constraint will stimulate exciting new ways for people to communicate and connect (cf. [27, 47]). Interestingly, there is an increasing uptake of consumer mobiles and tablets (e.g., the LightPhone[11] and the reMarkable tablet[12]) that trade power consumption with features to make a virtue of a calmer, more reflective use of digital technology.

Grid-free interactive devices are particularly suited to regions—mainly in the Global South—where energy supply can be interrupted or overly costly. Recruiting material understandings of two specific places—in India and South Africa—enriched our design process, providing insights that not only spoke to those contexts but challenged the orthodoxy of wire-free, non-self powered, interactive devices designed very much with the Global North in mind. The comment by one Langa participant that saw some of our prototypes as "primitive" compared to mobile phones is, we feel, a provocation to ensure that the growing drive to find less always-on, perhaps more mindful uses of mobile and other technologies is informed not simply by those in the Global North but the exciting diversity in the rest of the world.

[10]https://www.craigcolorusso.com

[11]https://www.thelightphone.com

[12]https://remarkable.com

The pandemic impinged on our work, of course, but did lead to us doing something we would not otherwise have considered – connecting two communities in informal settlements 8.000 km apart to share cultural and practical experiences and co-design together. Our method of using animations and videos to stimulate the discussions in a standard Zoom setting was somewhat effective, but there is lots of interesting work to be done to further enable such settings to accommodate greater levels of engagement and forms of design (such as physical prototyping).

ACKNOWLEDGMENTS

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