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Personal Projectors for Pervasive Computing

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Projectors are pervasive as infrastructure devices for large display, but are now also becoming available in small form factors that afford mobile personal use. This article analyzes "projectors on the move" and their interaction space with a survey of input and output concepts, underlying sensing challenges, and emerging applications.

Projectors are a flexible medium for large, scalable and transitory display. They are pervasive as presentation infrastructure, widely deployed for public viewing, and increasingly replacing large screens in the home. Beyond display, projectors facilitate augmentation of real-world objects with visual overlay, and in combination with camera systems give rise to new forms of user interface from interactive surfaces to "everywhere" interfaces [1]. Due to size, projectors have developed as infrastructure device, typically permanently installed, or set up ad hoc in a fixed position. However, miniaturization has now led to a first generation of devices, referred to as pico projectors, that are small enough to be used in truly mobile fashion – as handheld or wearable device, standalone or integrated with other personal devices. As a mobile personal device, pico projectors will be used in very different ways from projectors as we know them – just consider how different the use of handheld and wearable computers is from the use of PCs.

In this article, we survey current research on mobile personal projectors to understand how pico projector technology is embraced for pervasive computing. Our contribution is a comprehensive overview of developments from a conceptual perspective – analyzing personal projector concepts, structuring the input and output space for interaction with projectors, and discussing sensing challenges and emerging applications.

Personal Projector Concepts

The box overleaf provides an overview of current pico projector technologies and products. The adoption of these developments for mobile personal use has a variety of motivations that find expression in different device concepts. A general motivation is display portability: access to a display anywhere and anytime, with devices that fit in the pocket but are not limited to pocket size in their display. More specific motivations are to overcome screen limitations of personal devices that people already routinely carry; to facilitate shared viewing of content from personal devices; to provide hands-free displays for mobile work; and to enable new ways of interacting with physical environments. The device concepts that are emerging in response to these drivers can be grouped into four categories:

- **Peripheral.** Portable projectors can be viewed as notebook peripheral, and in the same manner pico projectors are now available as self-contained external display for personal devices. As a peripheral, they depend on a host device for application but can be flexibly used with different devices, such as handsets and digital cameras. Devices in this category include the Optoma Pico PK-101 and the Microvision SHOWWX Laser Pico Projector (Fig. 1a)

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Three different technologies have emerged that enable projection with very small form factor devices: Digital Light Processing (DLP), Laser pico projectors, and Holographic Laser Projection (HLP). DLP from Texas Instruments is based on emitting light onto a micro mirror matrix that is manipulated to control the reflection and intensity of projected pixels. DLP is the most mature of the three technologies and adopted in many of the early pico projector and projector phone products currently on the market. This includes for instance the Samsung W9600 / Galaxy Beam i8520, LG Expo, NTT DOCOMO Keitai F-04B, and the Optoma PK 102.

Laser pico projectors are based on a single laser beam that is steered across the projection surfaces to "paint the picture". This form of projection has the distinct advantage that the image is always in focus, and it is also more efficient as images are formed by steering light, as opposed to blocking light. First products include the SHOWWX from Microvision and the L1 from AAXA technologies. A different laser-based technology, HLP, is under development by Light Blue Optics. Here, the laser light is used to illuminate a micro display that is diffracted in order to generate the projected image.

The first products available on the market have a brightness of up to 30 ANSI-Lumens, battery lifetime of up to two hours, VGA/WVGA/SVGA resolution, and can easily project images up to a size of 100". The form factor is compact and some projector phones are barely larger than comparable smart phones.

- **Handset-integrated.** Mobile phones have become a central device for mobile information services but their screen size and resolution severely limits display of rich media including web content, maps, photos and video. This is a strong driver for integration of pico projectors as built-in component in handsets. First products in this space include the Epoq EGP-PP01, NTT DOCOMO's Fujitsu F-04B, Samsung's W9600 (Fig. 1b). Projectors are also becoming integrated with other handheld devices, and the COOLPIX S1100pj is an example of digital camera with built-in projector.
- **Wearable.** Pico projectors provide new opportunities for supporting mobile activity, as part of wearable system solutions. A principal consideration in this context is to mount projectors on the body such that users can use their hands for other tasks. A range of examples have been demonstrated in research, including projectors worn on the wrist [2], shoulder [3], head, or chest [4] (Fig. 1c).
- **Standalone.** Personal projectors are also investigated as "first class" devices in which projection is not an add-on but central to the interaction. Developments in this space are research driven and explore projector concepts through which users can interact with their environment in novel ways. This includes for instance projectors used in a torch-like fashion to explore the environment with a projected magic lens [5] (Fig. 1d).

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Figure 1. Personal projector concepts (from left to right): a. peripheral (Microvision SHOWWX), b. handset-integrated (Samsung W9600), c. wearable (figure courtesy of Pranav Mistry and his colleagues, photo by Sam Ogden) and d. standalone (figure courtesy of Stefan Rapp and his colleagues)

How personal projectors are conceived, whether as handset-integrated, wearable, or standalone device, raises distinct questions and challenges. Handsets, for instance, are associated with a very private viewing experience using the built-in screen, which is strongly contrasted by the public-facing display a built-in projector provides. In initial products, output is mirrored from the screen to the projector, which does not reflect their different properties and potential to complement each other. Wearable projectors, on the other hand, raise questions of placement on the body and appropriation for use in mobile tasks, including in difficult environments. How a projector is held, worn or integrated with another device has strong implications for interaction design and application – where projections can be displayed, how projections are controlled (by hand, body or head movement), and how users can interact with projectors and projected content.

Interaction with Personal Projectors

Projectors as we know them are predominantly used for passive display and controlled indirectly via host computers. Direct interaction with projectors or projected content has received limited attention, for instance with concepts for interaction at-a-distance [6] and steerable interfaces [1]. Personal projectors however open up a novel interaction space due to their mobile nature, and the different ways in which they can be carried, worn and manipulated. We structure this space on the basis of a survey of personal projector research which led us to identify four principal concepts for input and control, and four concepts for projected output.

Input and Control

We have identified four conceptually different approaches to interact with a personal projector system, as illustrated in Figure 2:

- **Input on the projector:** using controls on the device (e.g., keys, buttons, or touch-screen)
- **Movement of the projector**: sensing location, orientation and movement as input (e.g., gestures such as a flick of the projector to project the next image)
- **Direct interaction with the projection**: using the projected image like a touch-screen (e.g., to invoke projected controls, or to draw on the projection surface)
- **Manipulation of the projection surface**: changing position, orientation, shape and potentially other features of the projection surface as a way of providing input

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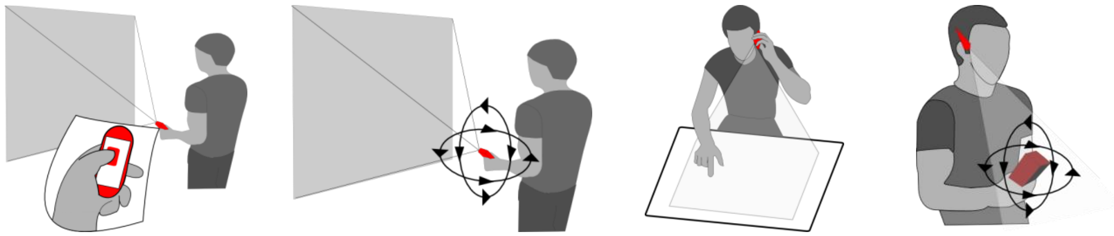

Figure 2. Concepts for interaction and control with a personal projector.

Input on the projector leverages common interfaces such as buttons (e.g., Epoq EGP-PP01), scroll wheel [5] or soft controls on a touch screen (e.g., Samsung W9600). Some research work has emphasized interface simplicity to enable users to provide input while maintaining a focus on the projection, for example via a two-button interface that is operated with the user's thumb [7]. Projector phones provide richer interfaces with touch screens or keypad-screen combinations that can be leveraged for projector interaction. A problem with these devices is that users will typically need to switch attention between projection (output) and handset (input), resulting in a higher task completion time, error rate and task load [8].

Movement of the projector is an implicit control for selection of the projection area. If the movement is tracked then it can also be used as input. This is used for instance in systems that reveal content depending on the location and orientation of projector [2,5,7]. In the case of handheld projectors, movement can also be used be employed for gestural input. Tilting the projector up or down, and left or right can be used, for instance, to pan an image, map or webpage [2]. Such gestures are intuitive and allow the user to keep their focus on the projected image as opposed to the input device, but they can be challenging to implement for use beyond environments instrumented with a motion tracker.

Direct interaction with projected content was extensively explored with steerable projectors [1] and has since also been demonstrated with wearable camera-projector systems [3,4,9,10]. Karitsuka and Sato were first to present a shoulder-worn system that included an IR light module to illuminate a notepad fitted with retro-reflective markers [10]. This enabled camera tracking of the relative position and pose of the pad, for distortion-free projection. In addition, interaction on the pad was tracked, facilitated by IR light emitting finger caps worn by the user, and enabling selection of controls as well as drawing on the projection. The Brainy Hand system takes this concept further, envisioning earpiece-integration of the camera-projector system, for interactive projection into the user's hand [9] (Fig. 3). The Wear Ur World (better known as SixthSense) system in contrast expands on interaction with projections by supporting in-the-air hand gestures in addition to touch on the projected surface [4]. The system is worn either as a pendant or a head-mounted device that employs color markers to track fingers. It has been proposed for many scenarios ranging from augmented reality projection onto objects held by the user to projection onto walls in the user's environment. A variety of direct interaction

Figure 3. Projector-camera unit in form of a headset (figure courtesy of Emi Tamaki and her colleagues).

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methods have also been considered in a prototype designed for military use [3]. Amongst others it has been considered to project onto the floor, and to use a laser pointer, telescopic stick with light emitting tip, or the user's boots (with reflective marker) for pointer input.

Manipulating location and pose of a handheld projection surface provides implicit input for pre-warping of projections in systems such as Karitsuka and Sato's [10]. However there is potential to use surface manipulation as more explicit input: for example, a handheld surface might be bent inward or outward to zoom in or out of a projected image, and tilted for panning.

Output and Presentation

Also in terms of output, we observe four distinct ways of using personal projectors for presentation, illustrated in Figure 4:

- **Anywhere display:** utilization of arbitrary surfaces as display.
- **Spotlight**: using the projector to reveal part of a larger virtual information space.
- **Augmented Reality (AR):** augmentation of real world objects with projected information and interfaces.
- **Multi-projector interaction**: multi-user interaction and collaborative use of personal projectors.

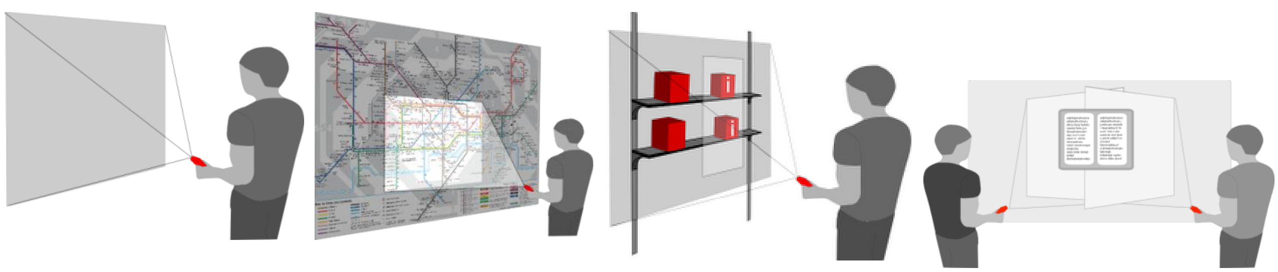

Figure 4. Output concepts of personal projectors.

To **display anywhere** is the simplest of these four presentation concepts, as it does not require tracking of the projection with respect to a virtual space, real objects, or other projections. However it requires adaptation to surfaces that are selected for presentation, in particular pre-warping of the image for distortion-free projection. In some application domains, such as military operations, it can be critical that display is also possible on less ideal surfaces that may be curved or textured, and content may have to be adapted accordingly [3]. It has also been proposed to use two pico projectors in tandem for anywhere display, with one as output and the other for projection of virtual keyboard for input [11].

Spotlight interaction involves movement of the projector to reveal information that forms part of larger virtual space and has been explored with a variety of projector systems [2,5]. This technique enables exploration of large and high resolution virtual information layers which might for instance be mapped onto a large wall. For instance, moving a projector closer to the projection can be employed to semantically zoom into an information space [5]. Selections in such a space can be performed by simulating a mouse cursor with a cross-hair in the centre of the projection, and a button press on the projector.

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Augmentation of real world objects with mobile and wearable systems has been widely studied in the field, with a host of scenarios from mobile tourism to maintenance work. The advantage of handheld and wearable projectors over previously used systems such as HMDs is that they facilitate AR display directly on the objects of interest [12,13,14]. A prerequisite is registration of the object by the projector system. This can be based on objects broadcasting information about their location and shape [14], external location and information systems [7], or visual identification by the system itself [12]. Handheld AR projection can also serve for control, for instance by projecting tracks for robots to follow [15], and for mixed reality experiences, for instance by projecting content that interact with hand drawings of the user [12].

Multi-projector interactions become possible when a group of users use their personal device in a collaborative manner. The View & Share system enables a group of users to share a personal projection, for example enabling interaction with the projection via another user's device [16]. Other work has demonstrated use of multiple projections side by side to create a larger shared display [7]. In the same work it has been suggested to combine multi-user projections also in other ways, for instance projection of a large image with one projector, and spotlight projection within this image to create a focus & context display, for instance for interaction with maps. A key challenge for these techniques is accurate relative tracking of projections.

Sensing and Tracking

All but the most basic uses of personal projectors (i.e., as a display that is manually aligned to a surface) requires tracking of system components and their relative spatial arrangement, to underpin projector control, interaction and output. There are four entities that can be tracked in principle:

- The projector
- The projected content
- The projection surface
- The user's hands and fingers

Tracking of the projector itself is relevant in particular when it is handheld or wrist-worn as opposed to fixed rigidly on the body, as this provides freedom of movement for projection onto different objects around the user, spotlight scanning of virtual or physical spaces, and gestural input. Accurate tracking of the projector position and pose requires extrinsic sensing, for example with a camera infrastructure that tracks visual markers on the device [7], infrared reflective markers [2], or active light emitting markers [17]. Intrinsic sensing can be used to track the orientation and relative movement of the device, using accelerometers [2,3,12,15], alone or in combination with a gyroscope [5,13,14], or magnetic compass [5].

Tracking of projected images is employed primarily for the purpose of detecting and removing distortions. To this end, a camera is integrated with the projector unit, tracking reference laser points to determine the relative orientation of the projection plane with respect to the projector [13,14]. A further purpose for tracking of the projected content can be to support multi-projector interaction, for example to associate different projections with different users [17] and to combine projections [7,15].

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Most personal projector systems are independent of the **projection surface**, however some are proposed for surfaces that the user can move and manipulate. In these cases, surface tracking needs to be incorporated. A common approach is to place markers on the surface, such as passive markers (visible [13] or infrared [10]) that can be tracked by projector-mounted camera, or photosensing tags that enable surfaces to detect their arrangement with respect to a projector [14]. Alternatively, surface position and orientation can be derived from tracking and analysis of the projected image [12]. There is also a larger body of work on analysis of the projected image to derive other surface properties such as texture for the purpose of adapting the projection [17].

Systems that support input on the projection, with either direct touch on the surface, or gestures at-a-distance, require tracking of the input device: typically the **user's hands and fingers**, but in some cases sticks, pens, or the user's feet. Tracking is generally performed with a projector-mounted camera, and supported by markers, for instance passive markers [3,4,7,17] or active infrared light emitting markers [3,10]. There are also marker-less approaches using image processing to separate out the user's hand in a scene, and to track pointing and potentially other gestures [1,9].

Survey of the Interaction Space

To understand trends and challenges in interaction with personal projectors we have classified research literature on the topic according to type of device, and input, output and tracking concepts. For the purposes of this overview article, we have selected 16 works that, in our view, capture the most significant developments, and classified them as shown in Table 1.

		Mobile projector		**Wearable projector**		
		Handset	Standalone	Wrist	Shoulder/front	Head
Input	Input on the projector	[8,12,16,17]	[7,13,14]	[2]		
	Movement of the projector	[12]	[5,7,13,14,15]	[2]		
	On the projected image	[11,12,17]	[7]		[3,4,10,18]	[4,9]
	Manipulation of surface				[10,18]	
Output	Anywhere Display	[8,11,16,17]	[13,14,15]	[2]	[3,4,10,18]	[4,9]
	Spotlight		[5,7]	[2]		
	Augmented reality (AR)	[12]	[13,14]			
	Multi-projector interaction	[16,17]	[7]			
Sensing	Tracking of projector	[12,15,17]	[5,7,13,14]	[2]	[3]	
	Tracking of projected content	[17]	[7,13,14,15]			
	Tracking of projection surface	[12,17]	[13,14]		[10,18]	
	Tracking of users' hands	[17]	[7,15]		[3,4,10,18]	[4,9]

Table 1. Classification of research literature by device type and interaction and tracking concepts.

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Application of Personal Projectors

Cao identified three main application areas: personal information processing, interaction with the physical world, and interpersonal information exchange [19]. Others have suggested projected desktop applications, projected augmented reality, and selection of physical regions of interest as application classes [13]. From our own survey and research, we propose four areas to be particularly significant: games and entertainment; augmented reality; data visualization and manipulation; and group collaboration.

Games and Entertainment

Personal projectors facilitate entirely new mobile interaction experiences with strong potential for playful use, especially by teenagers and young adults. Youth culture has played a major role in adoption of mobile technologies such as camera phones, and comparable cultural impacts can be expected from projector integration into handsets, with application stores providing a ready vehicle for creative development. Among the features that render projector phones intriguing for game development is the availability of a private display alongside a public-facing projection. Published research has also presented concepts for playful projector interaction with real world props and user drawings [12], and for games that build on interaction with multiple projectors, for instance a collaborative puzzle and a treasure hunt where some targets can only be uncovered when projections overlap [7].

Augmented Reality

Personal projectors have application potential for AR interaction with the physical world although this requires registration of projected content with real world entities and hence more elaborate tracking technology. RFIG Lamps are an early exploration of how physical objects can be detected, tracked, and augmented with mobile projectors [14]. The general concept is to project a visual information overlay, such as task guidance in maintenance scenarios, or travel directions on paper maps [12]. Typical scenarios discussed in the literature include logistics in warehouses, but it has also been proposed to use handheld AR projection for control applications such as robot navigation, and for mixed reality game experiences [12, 14, 15] (Fig. 5).

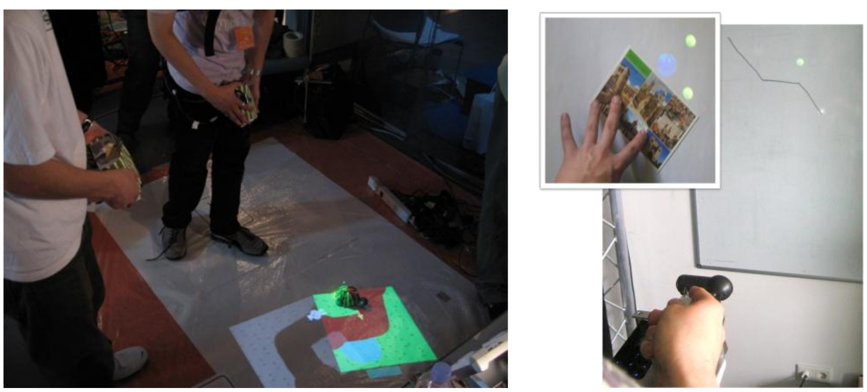

Figure 5. Examples for augmented reality concepts (from left to right): VisiCon (figure courtesy of Kazuhiro Hosoi and his colleagues) and LittleProjectedPlanet (figure courtesy of Johannes Schöning and his colleagues).

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Data Visualization and Manipulation

Mobile projectors enable anywhere display of visual data, and moreover facilitate new ways of exploring large data visualizations using spatial metaphors such as demonstrated in spotlight interaction. Applications that have been demonstrated range from display of standard desktops including use of the projector as mouse pointer [13] to visualization and analysis of stock information [2]. A range of input methods are studied for interaction with visualizations, but gestural input on the projection or directed toward the projection is generally viewed as most intuitive.

Group Collaboration

Personal projectors facilitate social sharing of information from a personal device without dependence on display infrastructure in the environment. This alone is significant for support of mobile collaborative practices, but mobile projections might also be appropriated as ad-hoc single display groupware on which multiple users can interact simultaneously (e.g., using their mobile phones for input [16]). A further dimension for social interaction opens up with collaborative use of multiple personal projectors. The applications explored by Hosoi et al. [15] and Cao et al. [7] exemplify the potential of combining projections for very practical aspects (larger display, document exchange) as well as for collaborative problem solving (e.g., collaborative visual analysis).

A User-centered Research Agenda

From a technical point of view, personal projectors still need to shrink and become brighter and more energy efficient before these systems will be adopted more widely in practice. Likewise, significant technical advances are required in sensing and tracking technology for mobile projection “in the wild”, such as methods for projectors to determine the geometry of their environment, and to visually register with unprepared real world objects. However, in addition to advancing technology we argue for a user-centered research agenda, to understand interaction with projectors, and usability and social factors of their application.

Understanding interaction and usability

Our survey shows that there is a wide range of interaction concepts and techniques that are being considered for mobile personal projectors. However, there has only been limited research into understanding interaction and usability aspects of personal projectors. Empirical studies have been undertaken with experimental projector phone configurations, providing insight into task performance and qualitative aspects of displaying interfaces on the handset screen versus projector [8], as well as user preferences for sharing of media [16]. A formative study has been reported on the usability of wearable projectors in difficult environments [3]. As the technology matures, further work will be required to gain a principled understanding of the usability of different interaction concepts and modalities, and their utility for different applications and contexts.

Personal projector interfaces have thus far been explored with bespoke developments, or interface concepts as known from the desktop [10,13,14]. We propose that abstractions and widgets tailored to mobile projection will be required for more effective interface and application development. This might, for instance, include notions such as “floating window” and “flashlight” as proposed by Cao [19].

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Social Acceptance, Visual Pollution and Privacy

Overuse of mobile projectors can ultimately lead to overwhelming visual clutter in the environment [20]. Research will need to establish practices that avoid the distracting effect of such projections as well as problems of invading the personal spaces of other people in the vicinity. A first formative study has indicated that personal projections in public spaces such as pubs, clubs or train station gain strong attention and are socially accepted but this might change as the technology becomes more commonplace and intrusive on bystanders [21].

Personal projectors also raise new privacy challenges, as they extend inherently private devices in a very public-facing manner. Mobile phones in particular are highly personal and rarely passed to others as this invokes privacy issues. It is safe to assume that projector integration in handsets will not replace but add to a built-in private screen. Guidelines and interface frameworks will need to be developed that ensure a privacy-aware design of interfaces and information displays across the private screen and public-facing projector, including easy-to-use safeguards against unintended projection of sensitive information. In related work on symbiotic use of private and public displays it has for instance been proposed to blur sensitive information on the large display while using the personal device to explore detail [22]. Related concerns have also been explored in work on multi-projector collaborative use, considering for instance visual indication of ownership, access, and visibility of content [7].

Conclusion

We believe that pico projectors are on the brink of wider adoption, in particular in high-end mobile handsets. The “anywhere display” capability they bring to small devices has compelling use cases in everyday life, for viewing and sharing of media at larger than pocket size. Component costs, limited quality (brightness), and energy demands still present barriers for widespread use, but these are increasingly overcome by advances in enabling technology.

With advances in sensing and tracking, personal projectors will be able support rich and innovative forms of interaction. Ultimately, they have the potential to transform the way we are displaying and consuming information, wherever we are. In this survey we have analyzed interaction with personal projectors, and mapped out input, output and sensing concepts for both handheld and wearable systems. The survey provides insight into the complexity of the design space. As the technology matures, it will therefore be important to advance understanding of the human and social factors of personal projectors.

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