Interaction in Motion with Mobile Projectors: Design Considerations

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ABSTRACT
Emerging research and growing use of mobile projectors reveal a need for better understanding of how to design interaction with such devices. This paper examines key aspects affecting the use of mobile projectors during motion. With the help of two prototypes we explore visibility issues of mobile projectors, in particular how surface colors and geometry affect the visibility of projected information. We then consider the choice of placement of information in the human field of view in the context of peripersonal and extrapersonal spaces. Finally, we raise the issue of body mount location and design implications of long-term use of this type of pervasive display. The paper presents two design explorations using projected displays to address projection on outdoor regular surfaces (snow) and projection on indoor irregular surfaces (indoor and outdoor), in the form of useable prototypes presenting map navigation. Use of the prototypes was explored in various contexts, leading to insights into the limitations and possibilities of such displays. These insights are presented in a set of design considerations intended to inform designers of future mobile projector applications.

Author Keywords
Interaction in Motion; Mobile Projector; Mobile Display; Snow Projection; Design Considerations

ACM Classification Keywords
H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

INTRODUCTION
As mobile devices are worn increasingly often, people change their movement patterns and behavior. Most mobile interfaces today use a "stop-to-interact" paradigm which requires the user to pay visual and mental attention to the device while standing still [20]. Although humans have evolved to move over long distances [5], a sedentary lifestyle seems to have become the norm with increasing use of technology [10]. Current mobile devices separate us from the physical environment. Instead, our environment could act both as a transportation medium and as an information carrier, so that the environment would become a responsive part of the information domain. It should not constrain and capture attention, imposing limitations on our behavior, but provide contextual information where it is needed, and leverage familiar tasks and expectations.

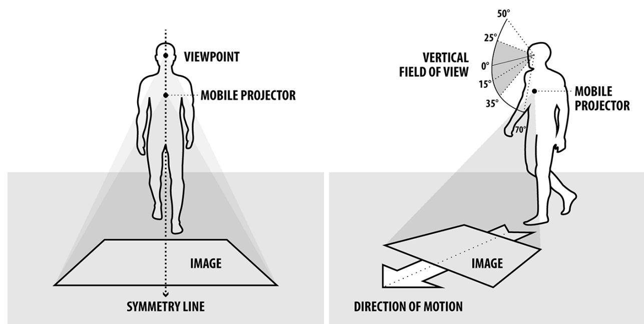

Figure 1. Projector mount location on human body symmetry line (left); Field of view and projection location in the direction of walking (right)

Projectors are becoming smaller and cheaper, enabling new ways of interacting with information on the go. Unlike displays for laptops or mobile phones, using projectors in mobile settings needs to account for different surfaces and the movement of the projector itself. The increased use and research on mobile projectors shows the need to better understand how we can make better use of such devices. While in motion using a mobile projector, users encounter surface colors, textures, and geometry of projection surfaces, all affecting perceived projection visibility. Designing novel interaction methods for mobile projections must take into account that this type of display requires the use of surfaces in the environment in order to be visible.

The exploratory research presented in this paper is based on two prototypes addressing complementary visibility issues: one projects on snow, and one is a portable geometry-aware projection system. The former prototype aims to explore factors that affect the projection on seemingly ideal white en-

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vironmental surfaces, as well as how motion while walking affects the projected image. The latter prototype implements a method adjusting the projected display to accommodate unsuitable surfaces by encouraging its user to move to other, more appropriate surfaces. The study of these prototypes has led us to insights into the limitations and possibilities of this technology. Our insights are presented as a set of design considerations intended to inform designers of future mobile applications.

RELATED WORK

In this work, we focus on mobile projectors and their relation to surfaces in the environment surrounding a user in motion. Next, we review works covering research on handheld and body-mounted mobile projectors, projection visibility factors, and human factors of interaction in motion.

Mobile projectors

Huber presented a research overview of "mobile projected user interfaces" [14]. Huber et al. [15] categorized applications and interaction concepts for pico projectors into four groups, based on whether both projector and the projection surface were fixed or mobile. Rukzio et. al identify concepts, interaction techniques, and applications for personal projectors for pervasive computing [30]. While a projector can be carried in a range of alternative ways, next, we discuss handheld and body-mounted projectors.

Handheld projectors

Handheld projectors were proposed as displays that would free users from having to share their attention between screen and environment by projecting directly onto the latter [2]. Cauchard et al. identify challenges affecting use of handheld pico-projectors on walls, desks, and floors, suggesting that these settings are unsuitable for many tasks [6]. MotionBeam is a mobile projector that couples the content to the movement of the projection [37]. ProjectorKit provides technical support for rapid prototyping of mobile projector interaction techniques [35]. Molyneaux et al. [22] developed a geometry-aware handheld projector that displays content accordingly, enabling multi-touch interaction on arbitrary surfaces.

Body-mounted projectors

Wear-Ur-World (WUW) is a wearable gestural information interface using a head-worn projector and everyday surfaces [21]. Interaction techniques have also been prototyped with simulated wrist-worn projectors and wall surfaces [4]. Ota et al. [25] explored alternative body locations for wearing multiple projectors while walking and standing for navigation and photo slide show applications, displaying information on floors. The Ambient Mobile Pervasive Display is a shoulder-mounted projector able to display on environmental surfaces, the floor, and the hand [38]. The system is capable of projecting on the user's hand and on the floor while the user is walking, supporting the vision of having a display anywhere.

Projection visibility

While surface reflectance, surface color, and surface geometry are characteristics of our physical environment, the occlusion, projection jitter, and keystone distortion also depend on how the mobile projector is operated in that environment.

Surface reflectance and surface color

Environmental surfaces have varying degrees of reflectance, color, and geometry, which affect the visibility of mobile projections. Systems were proposed to compensate for this, integrating a camera into the projector system. Nayar et. al proposed a method that allows projection onto arbitrary surfaces which have different colors and textures or surface markings, while still preserving image quality and mitigating surface imperfections [24]. More recently, Son and Ha [32], and Kim et al. [17] enhanced the projected image by analyzing the color and lighting conditions of the projection surface. In our first prototype, instead of transforming the projection to be visible on any surface, we aimed to experiment with the ideal projection surface of snow, which we considered had good visibility while allowing extensive mobility.

Surface geometry

An algorithm that can compensate inside the projection space both for surface color and geometry has been implemented using a physics-based model [12]. Bimber et al. [3] gave an overview of "real-time image correction techniques that enable projections onto non-optimized surfaces" for projector-camera systems. For uniformly colored planar surfaces, simple homographies can be used [27], while for non-planar surfaces of known geometry, perspective texture mapping is a suitable technique [29], and for cases of textured surfaces, pixel-by-pixel measurements and structured light approaches can be used [3].

Projection jitter

Raskar et. al addressed the jitter problems that affect handheld projection. Their projector position (location and orientation) was computed relative to the display surface and the location of four points of known coordinates recorded with a camera aimed at the projection [28]. Tajimi et. al identified two approaches for stabilizing the projection while walking: through mechanical means or through image processing to estimate the projector's spatial displacement [33]. They employed the latter approach and proposed a stabilization method for a hip-mounted projector. Konishi et. al developed a marker-based stabilization method for palm projection and tested it while walking and running in place [18]. Projectors have been used in motion without stabilization, with good visibility results for the task of map navigation using a bicycle-mounted projector [9].

Occlusion

Static projector research shows how to adapt projected content, dependent on depth discontinuities in the environment, by warping regular rectangular layouts into freeform, environmentally aware representations with the shape of bubbles [8]. This research is relevant for interactive tabletops in places like work or home. In these cases, tabletops would also have everyday physical objects placed on them, causing occlusion of information [16, 13, 11]. There are several approaches [16] to manage this, but the most relevant to our work would be the matrix-based method for finding visible areas and encouraging the movement of physical objects to a location that improves content visibility [11].

Keystone distortion

Ideally, a projector is oriented perpendicular to the surface projected upon. But most of the time, as shown in Figure 2, the projector has another angle to the ground because of its orientation and location. This results in what is called keystone distortion [27, 29].

Human factors of interaction in motion

We introduce visuo-spatial and temporal human factors relevant to interface design of interaction in motion.

Visuo-spatial factors

Humans have a 180° horizontal field of view (FOV), 124° of which is defined as "binocular vision" that is perceived by both eyes and therefore enables depth perception [34]. The remaining 56° is called "far peripheral vision" which is more useful in recognizing well known shapes, identifying similar form and movement patterns, and perceiving the background context of the object focused on. The center 50° of human FOV permits shape and symbol recognition, but when focused, the gaze angle is only 10°. Vertically, humans have a 60° FOV, that goes up to 125° with eye rotation.

The following action spaces for FOV, also shown in Figure 5 were identified: peripersonal (reaching and manipulation), ambient-extrapersonal (postural control and locomotion), focal-extrapersonal (visual scanning), and action-extrapersonal (navigation and orientation control) [7].

Temporal factors

Useful mobile projector applications could be developed that account for the user's motion, minimizing interruption rather than making them stop to interact. When designing such applications, we need to account for the capacity, attention, and effort required for interaction in motion. Under single task conditions, if one invests more effort and resources into one task, performance will increase [36]. Under dual task conditions, performance varies in favor of the task that requires most attention. Mobile devices have been empirically evaluated in motion for the dual task of walking and reading, and have shown that a treadmill yields less reliable subjective measures than on a defined walking path [1]. Cognitive load depends on walking speed [23], but increases significantly during walking while reading or selecting a target on the mobile phone [31]. An outdoor study has shown that young adults can modify their gait speed in order to maintain their typing speed [26]. When looking at prolonged use, a study on mobile phone text messaging has revealed that 83% of the participants reported having hand and neck pain, showing the impact mobile displays can have on humans [19].

To better understand some aspects of these human factors, we propose two distinct prototypical uses of interaction in motion. The first prototype addresses specific outdoor conditions; the second addresses projection visibility with ordinary realistic surfaces. Since our research is exploratory, these prototypes were tested using informal studies. As we chose not to measure performance data, we rather focused on exploring visibility aspects that we consider to be fundamental for the design of mobile projectors.

Figure 2. Map navigation with chest-mounted system projecting on: fresh snow (left) and frozen snow (right)

PROTOTYPE 1: SNOW PROJECTOR

The purpose of this prototype was to explore mobile projection in a situation where environmental surfaces support ideal visibility. Because the white color of snow reflects light well, we considered it ideal for use with mobile projection. We created a chest-mounted projector described below, that allows for handsfree map navigation. The assumption was that having an ideal surface for projection and the projector mounted on the body, we would focus and explore factors and changes influencing a prolonged walking task.

Apparatus and interfaces

The chest-mounted projector consisted of a 3D-printed holder, mobile phone, battery, projector, and strap. The smartphone was an LG Optimus 4X 4D (Android 4.0) with a 1280×720 resolution. The pico-projector was a PicoMax MX 60 connected to the smartphone via an MHL adapter and powered by a battery. The strap was shaped as a holster, with one strap going around the chest and the other over the left shoulder.

Informal study

We used the prototype on a hiking route during a snowy night. Although we expected projecting on snow would offer ideal visibility, we soon discovered different snow types have different visibility qualities. We tested two snow types: fresh fallen snow that was soft and melting, and hard frozen snow. We noticed that both snow types blurred the projection and lowered visibility, but the fresh one seemed to have slightly better visibility. Patches of ice and obstacles on the route deformed the projection and lowered visibility. We varied the projection location on the ground relative to the feet of the user. Although visibility improved when the projection was closer and smaller with less pronounced keystone distortion, it was preferable to have the projection further away, larger, and in the FOV while walking, rather than having to tilt the head and look down. While walking we noticed that the swings of our natural gait caused the projection to jitter, greatly affecting visibility. Reducing walking speed improves visibility, but is not desirable for the task of hiking. While walking, we tested whether attaching the projector to body parts such as hips or head would reduce jitter, but noticed no difference. Stabilization through mechanical or image processing solutions, as suggested by Tajimi et. al [33], is considered necessary for the task of walking.

The projection served both as a flashlight and as a map (Figure 2). We considered the flashlight functionality useful since we were able to adjust the orientation of the projector using our hand to light up the road 10–20m ahead or to the side. While hiking with the projected map, we identified a series of walking variations: walking and slowing down (WD), walking and stopping (WS), and walking and turning torso (WT). WD and WS appeared when we needed to take a turn at a crossroad. WD turned up on narrow paths that required more attention and balance. WS occurred when taking breaks to rest. WT occurred mostly because it was night and we could use the flashlight to make the sides of the path visible. Some walking variations were implicit, as they occur during normal hiking, but the context of having a chest-mounted projector changed and encouraged turning the torso, thus influencing walking and movement patterns. Turning the torso left and right to point in a direction was quite easy and intuitive and requires a body part that is usually not used as input. Sometimes, the hands were used to adjust the projector angle to point further away or closer to the feet. We noticed that it was easy to get used to having the information "sticking out" of the chest and extending a couple of meters away in the environment. Another observation was that when the strap was not completely centered on the chest, it was necessary to turn more with one part of the torso.

PROTOTYPE 2: GEOMETRY-AWARE PROJECTOR

To further investigate the relationship between body-projector movement and environment geometry, we developed a geometry-aware projector. This connects a handheld projector, a depth sensor, and a single-board computer, supporting flexible and easy manipulation of the projector. An image of a map was projected and transformed in real-time influenced by environmental surfaces. This section presents the hardware, libraries, and calibration method we developed as the basis for supporting our exploratory research of mobile projectors. The assumption was that in ordinary indoor and outdoor environments, ideal projection surfaces are rare, so we wanted to explore a great number of surfaces with various geometry and orientation, as well as offering the freedom to move the handheld projector.

Apparatus and interfaces

The handheld projector was a Brookstone HDMI Pocket Projector with a resolution of 854x480. The single-board computer was a Pandaboard ES[1] with a dual-core 1.2GHz CPU and 384 MHz GPU. The operating system was Ubuntu 12 with the LXDE desktop environment. The depth images, at a resolution of 640x480, were collected by an Asus Xtion Pro sensor connected and powered via USB from the computer. A battery and a step down converter powered the Pandaboard. For displaying graphics, we used OpenGL ES 2.0. For acquiring depth images, we used OpenNI[2]. Throughout the following text we will use the term "pixels" to specifically denote depth image pixels.

Calibration

The purpose of calibration is to identify the location of the projection in the depth image, achieved by projecting the depth image and setting an overlying rectangle to fit over the coordinates of the projection itself (Figure 3, left). In other words, the calibration involves matching the coordinates of the projection area (large rectangle) to the coordinates of the projection as seen from inside the depth image (small green rectangle). The left image in Figure 3 shows this task from the user's perspective. The user fits the large rectangle between points on the wall marked in red at the upper left and lower right corners. During the tests presented in the accompanying video, the green rectangle's top left corner was positioned at x=165, y=65, the width 300, and height 140. This was consistent in a range between 1.5 and 9m. The calibration seen in the video shows this scaling at 1.5 meter intervals, marked on the floor (Figure 3, right).

Figure 3. Matching the coordinates of the projection area (large rectangle) to the coordinates of the depth image (small green rectangle). From user's perspective, 3m away from the projection (left). At a distance of 6m from the user (right).

Grid cell processing

A simple way to process information from the depth image is to divide the image into grid cells and sum up the depth pixels inside that cell. Grid cells enable algorithms to perform fast computation on complex geometry. We also compute the average value of the depth image, representing average distance to the surfaces in front of sensor. Depending on this value, we can vary the grid size. With a large distance from the sensor, grid cell size could increase to acquire more detail. This would be determined by the needs of the application. In our case, we found that from tests in indoor and outdoor environments, a grid cell size of 51x51 (each cell has 12x9 pixels) is appropriate for detecting continuous surfaces.

Localizing continuous surfaces and transition regions

Based on the grid cell values obtained in the previous step which summed up pixels in each cell, we check the upper and left neighbors of each cell within a certain threshold. Continuous regions have an increasing or decreasing depth within a threshold that we determined empirically. This method resembles the edge detection algorithm because it finds discontinuities between neighboring cells, resulting in transition regions between two continuous surfaces. The last step of the algorithm is to connect transition cells if they are within a distance of two grid cells in any direction (up, down, left, right, or diagonal). This increases the transition region and makes it more stable.

[1] `http://www.pandaboard.org/`

[2] `https://github.com/OpenNI/OpenNI`

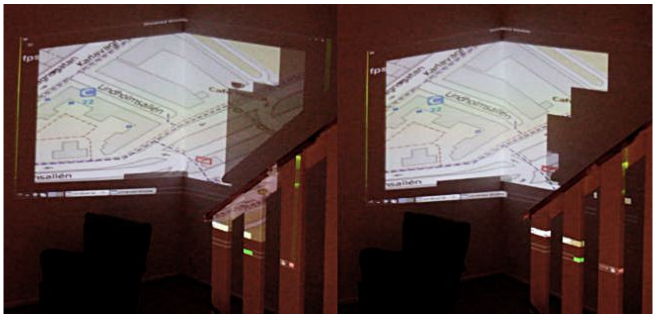

Figure 4. In the regions of the depth image with sudden changes (transition regions between planar surfaces), the following overlay modes are applied on the projected image: Grayscale (left); Black (right)

Transforming projection according to transition regions

Surface characteristics are important for the visibility of the projection. In this work, the system finds continuous surfaces for projection, and upon encountering a problematic surface transforms areas of the projected image by occluding or improving contrast. Based on the continuous regions we found in the previous steps, we overlay the transition region's grid cells onto the city map we want to project (Figure 4). The three overlay modes are the following: *Increasing Contrast* – enhances colours for map areas in the transition regions, *Grayscale* – covers areas of the map in the transition regions under dark shades of grey, and *Black* – completely occludes the contents of the map in the transition regions. The rationale behind having three modes was to explore what type of color, if any, would be appropriate over the transition regions with poor visibility. Suppose that during motion with the projector system, a surface with poor visibility is encountered. Because the user is in motion, correcting and recovering from the current state can be easily achieved by moving the projector back to the visible surface, or localizing a better surface along the direction of movement. In this way, correcting the position of the projector could be more efficient, as opposed to the user concentrating on an adjusted display on a surface with visibility issues. Transforming the color of the transition regions to grayscale would still permit the user to see parts of that information, while blacking out is a more dramatic change, prompting the user to return to the previous surface or to find a more appropriate one.

Informal study

This test was performed to explore how a handheld projector could be made geometry-aware. A user study was not performed at this stage since the goal was to explore different overlay modes and find out which mode, if any, would make sense in this setting. We tested ourselves the different overlay modes of the transition regions in indoor and outdoor environments, and found that increasing contrast in transition regions encourages the user to focus and understand information at different distances. Grayscale was considered a good option for indoor environments while in motion. Figure 4 shows how shadows are partially covered by grayscale and completely covered by blacking out the projected image. In transition regions like window frames or doors, loss of color created a transition to completely reflective surfaces like window glass, and also indicated to the user if a particular direction should be avoided. Blacking out the information completely was found to be useful in outdoor environments at longer distances and larger projection areas. At these distances, a small movement of the projector results in a great change in the projected image, since it quickly covers several meters. Hand gestures and movements are similar to using a flashlight and lighting up the environment; however, holding the projector for long periods soon becomes tiring.

DISCUSSION

Replacing flashlights and headlights with projectors displaying context sensitive information is an example that makes use of an already known setting, while adding information and supporting an existing task. Careful consideration of application design and context of use could result in novel systems that can become widespread. The two map-flashlight prototypes address and explore two main visibility issues of mobile projectors – surface color and surface geometry.

Prototype 1 showed how walking variations were influenced by the permanent information displayed in the FOV. It revealed that white snow is not enough to create the perfect surface for projection and that both fresh and frozen snow blur the projection. While hiking, the chest-mounted projector acted both as a flashlight lighting up the path, and as a map showing the route. Using torso movement as input is hands-free and intuitive. The implications of long-term use can be significant, as suggested in a study on psychophysiological patterns of mobile phone usage showing increased muscle discomfort [19]. We consider that mounting the projector on a symmetry line would balance and minimize torso turn movements (Figure 1, left). For the task of hiking, stabilization is considered necessary to compensate for jitter and improve visibility of projected information. Future work could include examining in more detail different types of snow and image processing methods for improving visibility of snow projections. This could enable new applications supporting tasks such as skiing, skating, or snowmobile driving.

Prototype 2 used depth information to enable geometry-aware interaction with content. Future applications using this system could guide the user to appropriate surfaces, recognizing and understanding geometry intended for interaction. Mobile projection research should take into account surfaces in the environment, projected imagery, and perception of the projected information. We also suggest the importance of coupling the movement of the projection to the environment's geometry, which provides natural feedback for the user. We suggest that enhancing visibility on problematic surfaces asks for and requires more effort from the user. Instead, the user should be guided by the system to move away from the transition regions and find more appropriate surfaces to project onto. Explicitly covering information upon encountering surfaces with poor visibility results in the user moving the projector to shine on more appropriate surfaces. This method is intuitive and since it is real-time and dynamic, it complements the dynamic task of locomotion.

There are two main components for interaction in motion using mobile projectors: locomotion and positioning of infor-

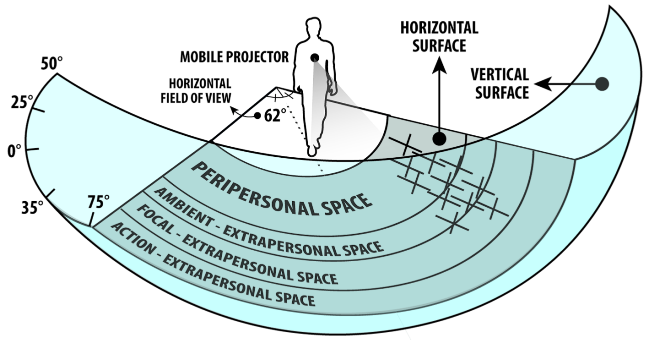

Figure 5. Action spaces (ambient, focal, action), based on [7]

mation. Locomotion is characterized by *speed* which affects cognitive load while walking [23]), and *direction*, which is inside the FOV (Figure 1, right). Therefore, the positioning of information should be on the same line as the direction of locomotion. The distance of the projection relative to the body is also an important factor. Larger distances relative to the body result in a larger projection area in the central FOV at a cost of less brightness. The lower the projection is in the vertical FOV, the smaller the projection area, but the greater the brightness, and the greater the head tilt required to bring the information from the peripheral to the central FOV.

The extrapersonal spaces change because of placement of the projection in the direction of walking (Figure 5). In this context, users have access to and can influence their extrapersonal space by using the body-mounted projector. The action-extrapersonal space is normally used for navigation purposes [7], so it makes sense to augment it with information supporting this task. On the other hand, the peripersonal space could be used to display more private information. From the point of view of prolonged use and human evolution, this type of mobile pervasive display enables the human to affect the physical space around him which is normally out of reach. It is as if human reach has extended into the collocated space and gained the ability to modify it instantly.

DESIGN CONSIDERATIONS

We identify a set of design considerations for interaction in motion with mobile projectors.

Body-mount on symmetry line Holding a projector for an extensive period of time causes fatigue. Mounting the device on the body would solve this problem, but should still support adjustment of projector orientation. Using the torso's movement as an input is intuitive, but mounting the projector on a symmetry line (Figure 1) would balance and minimize torso turn movements.

Peripersonal and extrapersonal space Humans have evolved to use peripersonal space for reaching and manipulation and action-extrapersonal space for navigation [7]. Peripersonal space could be used to display private information, while extrapersonal spaces could be employed to display information regarding navigation (Figure 5). This extends human reach into the collocated space and illustrates our new ability to modify it instantly.

New information spaces Environmental surfaces that have so far been ignored may take on new meaning to users, who will reconsider them as a space for interaction with a mobile projector. However, light intensity drops with distance affecting how suitable surfaces are for projection.

Localizing a suitable projection surface While in motion, localizing a suitable projection surface is based on the interaction between the projector movement, user perception, and the geometry-adapted image. Using a depth sensor with similar limits as the projector simplifies calibration and can detect and respond to surfaces unsuitable for projection, for example highly reflective or transparent (glass) surfaces, and detects uneven surfaces.

Context and design space Examples such as snow projection and bike-mounted projectors [9] are applications that reduce the design space. This approach could lead to novel and specialized applications.

Headlights and flashlights If projectors are used to replace flashlights and headlights, the application design makes use of an already known setting, adding context information while supporting an existing task. Map navigation is an example of such a task.

Projection jitter Wearing or holding a projector while walking requires stabilization (mechanical or digital through image processing). Supporting locomotion tasks enabled by wheels (driving a car, riding a bike), sliding mechanisms (skiing), or flying (quadcopters) would likely require no stabilization and lower the cost.

Dual task performance assessment For mobile projector applications, locomotion could be the primary task, and engaging with information could be the interfering task. This way, experiments can be set up to better understand the attention and effort required for interaction in motion.

Interaction in motion Most mobile interfaces use a "stop-to-interact" paradigm [20]. Designers could develop pervasive displays using mobile projector applications complementing people's movement, and minimizing interruption while they move.

SUMMARY AND OUTLOOK

Designing for interaction in motion with a mobile projector needs to take into account visibility aspects, such as surface reflectance, colors, and geometry. We tested map navigation with snow projection on a hiking route for the purpose of exploring projection visibility on an ideal surface in order to find factors and changes influencing a prolonged walking task. For everyday surfaces, we have developed and tested a geometry-aware projector to explore the relationship between body-projector movement and environment geometry. Based on these prototype tests in various environments and usage modes, we laid out a series of design considerations that could help in designing future interaction systems and techniques for mobile projectors. We hope that this work will help us better understand how to design pervasive displays that can support people in their tasks by projecting information, where they need it.

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