Using On-Body Displays for Extending the Output of Wearable Devices

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ABSTRACT

In this work, we explore wearable on-body displays. These displays have the potential of extending the display space of smart watches to the user's body. Our research is motivated by wearable computing devices moving technology closer to the human. Today, smart watches offer functionalities similar to smart phones, yet at a smaller form factor. To cope with the limited display real-estate we propose to use on-body displays integrated with clothing to extend the available display space. We present a design space for on-body displays and explore users' location and visualization preferences. We also report on the design and implementation of a prototypical display system. We evaluated the prototype in a lab study with 16 participants, showing that on-body displays perform similar to current off-screen visualization techniques.

Author Keywords

On-Body Display; Wearable Computing; Focus + context; Smart Textiles.

ACM Classification Keywords

H.5.2. User Interfaces: Screen design

INTRODUCTION

Smart watches are gaining importance in our everyday life. Apart from retrieving the time, receiving notifications on emails, upcoming appointments, or news headlines have become commonplace. However, the limited display space hinders the adoption of more complex tasks, such as navigation, playing games, or visualizing physiological data. As a result, users often opt to switch to the smart phone in case the display is considered to be too small for the task at hand. While this is reasonable for some cases (e.g., information retrieval), tasks that are performed on the move could strongly benefit from the wearability of a smart watch.

At the same time, there is a current trend towards wearable on-body displays. Such displays evolved from huge physical prototypes [19] to textile-based displays [3] that can be easily integrated with clothes. This transition allows the display to be located on arbitrary positions of the human body, for example the forearm. It is worth to note, however, that such displays are currently limited in terms of resolution.

Figure 1. The wearable on-body display used in a t-shirt. The heart rate visualized on the chest (left) and a progress bar, weather information, and e-mail notification on the forearm (right).

We see an opportunity here for fusing wearable devices and on-body displays to create what has been previously coined *focus and context screens* [5]. In 2001, Baudisch et al. presented an approach that allowed the display space of a high-resolution LCD screen to be extended with a low-resolution projection while at the same time maintaining the context. Similarly, low-resolution on-body displays can extend the visual output capabilities of a high-resolution smart watch. In this way it does not only become possible to show additional, contextual information – for example, the location of a hotel a user is currently navigation to but whose position is currently off the smart watch screen – but also to first draw the attention towards the on-body display and then allow more fine-grained information to be accessed through the smart watch – for example, showing a heart rate curve on the on-body display and providing detailed physiological data as the user is out running.

In the remainder of this paper we first present a design space for on-body displays. We then report on the design and implementation of a prototype. In a lab study we show that the display is able to increase users' performance as they interact with the display.

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CONTRIBUTION STATEMENT

The contribution of this work is threefold. First, we present a design space for on-body displays. Second, we report on the results of a study exploring location preferences and potential visualizations. Third, we present the results of an in-depth evaluation of using an on-body display as a means to present off-screen points of interest for a navigational application.

BACKGROUND AND RELATED WORK

Our work draws from several strands of prior research, most notably, on-body display technologies, focus and context screens, and wearable display applications.

On-body Display Technologies

On-body displays can be realized using various technologies. To allow displays to be worn on the body, there is an inherent need to design them flexibly so as to fit the user's physiology.

Single (small-sized) displays can be easily attached to different parts of the human body. Examples for such displays are smartwatches or displays in the form of a brooch [8, 11]. Furthermore, larger displays that would have otherwise been difficult to attach to the body directly have been integrated with backpacks [1] and handbags [10].

Building larger on-body displays is challenging, since their form needs to fit the user's body shape. On one hand, displays can be explicitly manufactured so as to *fit a particular body part*. For example, von Zadow built a prototype of a display in the form of a sleeve [25]. On the other hand, a more flexible approach is to create displays consisting of a *matrix of smaller displays*. The small displays in such a matrix can consists of small but high-resolution displays themselves [22]. Or, in order to add further flexibility, they can consist of very small pixels (for example, single LEDs).

Furthermore, on-body displays can be directly *integrated with fabric*. Solutions include optical fibres to create *light-emitting fabric*[1]. Combining this technology with a controlling unit, Koncar used such fibers to create a display jacket [18]. Another approach is using electroluminescence which can be printed in a matrix design to realize a multifunction display or in custom shaped segments [21]. Besides the application on paper and other stiff material, it can also be printed onto fabrics [3] or woven into fabrics [15].

Finally, on-body displays can be realized using *projection*. Harrison et al. suggest using projections to augment the human skin with visual output [16]. Similarly, Freeman et al. projected cues on the user's hand to support learning gestures [12]. Following this idea, Olberding et al. presented applications and interaction possibilities for augmented skin, focusing on the forearm [22].

In our work we focus on fabric-based displays which can in the future be integrated into everyday clothing. However, due to technical limitations of current displays (e.g., resolution, color), we use low-resolution LED displays as a prototype, simulating fabric-based displays that could be integrated into clothing in the near future.

[1] http://www.lumigram.com/

Wearable Display Applications

Wearable and on-body displays have been used for a variety of applications. Meme Tags were among the first digital wearable public displays. Worn around the neck, they allowed 64 character messages (memes) to be shown to the public [8]. Since the meme tags did not have any input capabilities, messages were authored by means of a kiosk system that then pushed the messages to the tags. One year later, BubbleBadge was a wearable display in the form of a brooch [11]. Based on a GameBoy, it allowed notifications and quotes to be presented to the public. Ten years later, Alt et al. presented the concept of a contextual, mobile display integrated with the user's clothes which was capable of displaying information based on the users' context, such as location [1]. In this way it was possible to, for example, provide information about a nearby sight. SleeD was a wearable display designed as an interaction device for large interactive screens [25]. In particular, it allowed interaction to be personalized as multiple people interact with a display. Finally, Colley et al. presented a wearable display in the form of a handbag allowing users to observe the content of the bag [10].

While in previous work most applications where developed with a particular task in mind, the aim of our work is to provide a wearable display that is capable of supporting various tasks. Furthermore, we use it to enlarge the display real-estate of small high-resolution displays, such as smart watches.

Focus and Context Screens

Dealing with limited screen real-estate when it comes to displaying information has been at the focus of InfoVis research since its inception. We believe this so-called presentation problem to be an immanent challenge for the design of wearable displays. Prior approaches employed in desktop and mobile applications include zoomable user interfaces [7, 23] as well as overview and detail interfaces [17]. However, it is often important to maintain the context of a visualization. A popular solution to this is the use of Fisheye views [13]. However, this form of a visualization that maintains the context infers distortion which we believe to be a major challenge for small (wearable) displays, in particular if presenting text.

Hence, we employ the concept of focus and context screens introduced in 2001 [5]. At that time, the concept aimed to address a similar challenge as today's wearable displays: on one hand, small high-resolution displays were available (LCD screens) which could be complemented with large, but lower-resolution projections. Applying this concept to wearable displays seems reasonable, since as of today, both small high-resolution displays are available in the form of smart watches whereas display technology integrated with fabric is still low-resolution but can considerably extend the available display space and be used for contextual information.

DESIGN SPACE FOR ON-BODY DISPLAYS

In the following we present a design space for on-body display. The design space is centered around four main dimensions – user, context & application, interaction, and technology. This design space is useful for designers of applications for on-body displays.

User

On-body displays allow the content to be targeted towards the wearer or towards third persons. While we envision – similar to the smart phone – most applications to be targeted towards use by the wearer (for example, notifications or a navigation app), interesting use cases may be created by presenting information to others. As an example, at work, colleagues may be informed that the wearer is currently deeply engaged in a task, leading to that an inquiry is postponed. There may also be cases where content is targeted towards both the wearer and bystanders (i.e., joint use), for example a multi-player game where the on-body display serves as a shared game board. As a result, designers need to consider the following dimensions:

Observer People observing the display may be the wearer himself or third persons, such as passersby, or both. As a result, designers need to think where to place a display and whether there needs to be a mirror feature (i.e., wearers might want to see what is being displayed on their back).

Content Origin The displayed content can either be generated by the wearer or the observer. For many use cases, the wearer and the observer are the same person. However, for some use cases, the wearer could create content for the observer. One example would be visualizing physiological parameters of the wearer so that the observer could take them into account (e.g., stress level).

Context & Application

Wearable displays enable a myriad of applications that can be used in a variety of contexts, such as at home, at work, during commuting, or while being in a public space. Of particular interest for the designers of applications is whether or not on-body displays extend existing applications or are self-contained. In addition, privacy considerations may need to be taken into account, i.e., whether content should be only perceivable by the wearer or also by bystanders.

Application Purpose Apps for wearable displays may be manifold. Example include, but are not limited to *navigation*, *quantified self*, *notifications*, and *entertainment*.

Extension of Application In case where on-body displays are being used together with smart watches or phones, designers need to think about how existing applications can be extended, using the on-body display. *Direct* extension, for example, includes showing content that does not fit on the smart device screen, such as off-screen locations in a navigational task or additional information on a played music track. In contrast, *indirect* extension includes presenting notification (for example, for messages or calendar) or physiological data (for example, pulse).

Privacy Applications may be private, personal, or public. *Private* applications may provide access to sensitive data (e.g., the user's current account balance or a TAN the user is supposed to enter at an ATM). Such information should be shown in a way such that passersby cannot easily shoulder-surf it. In *personal* applications, for example, information that is relevant for people who know each other may be shown. For instance, two people may want to exchange an address. In this case, a display application should account for that information is visible to a close bystander while not being visible from afar. Finally, *public* applications show primarily content that is meant for a wider audience or for which it is uncritical if perceived by bystanders. Such information can include advertisements, current time, or news headlines.

Interaction

The third dimension concerns interaction with the wearable display: input modality, output, and flow of interaction.

Input Modality Different input modalities can be supported by an on-body display [20]. This may include *touch input* (e.g., directly on the display or on a connected mobile phone or smart watch), *gesture-based input* (e.g., gestures performed in front of the body, recognized through a camera integrated with the users' glasses), *gaze input* (e.g., using a camera / eye tracker integrated with glasses), or *speech* (e.g., using a microphone integrated into clothing).

Feedback Today, displays mainly provide visual feedback to users. Yet, there is also research on displays using other modalities such as *haptic*, *auditory*, or even *olfactory*.

Flow of Interaction Wearable focus and context displays enable two different ways of how interaction can flow. On one hand there may be a flow of the interaction *from the focus display to the context display*. This is the case if interaction starts at the smart device (e.g., entering a location a user wants to navigate to) and then extends to the context display (for example, showing information on the distance and direction of the nearest subway station). In other cases, interaction may flow *from the context display to the focus display*. The user might receive abstract information on heart rate on the context display while running but then at some point decide to look up additional, more specific information on time and distance covered.

Technology

Finally, the available / employed technology needs to be considered when creating on-body display applications.

Size We expect future on-body display to come in arbitrary sizes. While primarily being limited by the available garment surface, future research on-body displays may seek to extend the available space through projection (for example, on the part of the floor a user is standing on).

Shape On-body displays can be manufactured in many different shapes, matching the intended body location and/or screen real-estate required by the application.

Orientation Based on whom the content is being targeted to, the orientation of the display needs to be taken into account. Whereas for the wearer the display should be oriented in a way such that content can be optimally perceived, the direction from which third persons are approaching is often not clear and hence orientation would need to be flexible. In this case, application designers may also need to take into account that the user is moving and hence update the orientation dynamically.

Position on Body In case only parts of the body serve as a display, designers need to consider different aspects: who are the users, how many users need to be supported, how do they interact, and from where do they see the display.

Display Technology Current on-body displays need to make a trade-off between wearability [14] and spatial, temporal, and color resolution. While displays completely fabricated using garments have a low resolution, flexible OLEDs achieve similar performance as smart phone screens but with reduced flexibility and, thus, reduced wearability. Again the application for which such a display is used is important. Simple notification for a single purpose are easily realizable with garment based displays but more complex UIs would currently require flexible OLEDs.

Display Factors Finally, display properties may be chosen based on the intended use case. Properties may include *color depth*, *brightness*, and *resolution*.

APPARATUS

We created an on-body display prototype using two 8x8 multicolor LED matrices (cf., Figure 1) extending the display space of a smart watch. We deliberately chose a display with a low resolution since we strive to present content that is easily perceivable but not overloads the user with information. Furthermore, displays with this resolution are producible using garment based displays. Both LED displays are attached to an Arduino that is connected via Bluetooth to the smartwatch. The smartwatch used for the implementation is a Simvalley Mobile AW-414 smartwatch with a 240x240 pixels, 1.5” touch screen running Android. The content of the display is controlled via an Android application that defines the color of each LED and sends the values to the Arduino.

EXPLORING DISPLAY LOCATION AND VISUALIZATIONS

In a first study, we explored at which location potential users prefer on-body displays for either personal or public usage. In addition, we explored different visualizations for each of the application scenarios.

Participants and Procedure

We invited 16 participants (3 female, 13 male) between 20–31 years (*M*=23.6, SD=2.9) via university mailing lists. After participants arrived at the lab, we first introduced them to the purpose of the study. We showed them our physical prototype of an on-body display. To make the idea of an on-body display more tangible to participants, we presented 6 different application scenarios. These scenarios were developed through a review of available products in the filed of wearable computing and current smart watch applications. Each of them can utilize the on-body display as an additional context display.

Heart Rate Physiological measures are becoming more and more important and the number of wearable devices capable of measuring these is increasing. While the sensing part can be easily integrated into clothing, the communication of the measured information is mainly done via smart phones. Using an on-body display, this information is instantly accessible for the user.

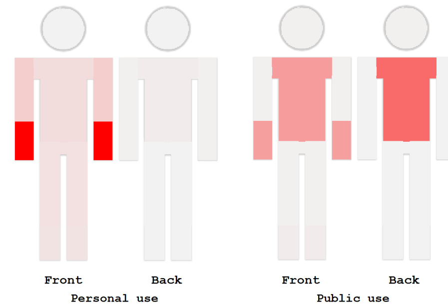

Figure 2. A heatmap of the location preferences of the participants in the first study when the display is showing content for the wearer (left) and public (right).

Step counter Fitness bracelets allow the steps made by the user to be measured. However, most of the time, output is limited due to the small device size. Exploiting a larger on-body display, users can easily keep track of their steps.

Message notifications The number of notifications being generated on mobile phones is steadily increasing. Utilizing on-body displays helps to quickly and unobtrusively notifying users of incoming messages.

Navigation Providing navigational cues to the user becomes more an more common due to navigational systems being available on smart phones. However, carrying the phone in the hand while walking can be cumbersome and, thus, an on-body display can help presenting necessary navigational information.

Calendar On-body displays allow proving instant access to the calendar by showing the next appointment, the time till it starts, or the location.

Weather As an example of simple, static information, we chose weather information.

The application scenarios were presented in counter-balanced order (Latin square). For each of the scenarios, participants were given two tasks. First, we wanted them to think about the perfect location of the display on the body given a particular task. Therefore, participants were asked to mark the position on a print-out of a human body (cf., Figure 2). In addition, we asked them to sketch a visualization for the output on the wearable display.

Results

Location Preferences

We identified 6 different options to place the display: forearm, upper arm, torso, head, legs, and feet. Overall participants preferred placing the display on the forearm when used by themselves (68.8%) and torso when used by others (67.8%). The main reason for this might be the display size which can be perceived from a greater distance on the torso compared to small displays on the forearm. While most participants naturally located the display on the front of the user for personal use, the front (57.0%) and back (43.0%) was evenly chosen for public usage. An overview of the chosen locations is depicted in Figure 2.

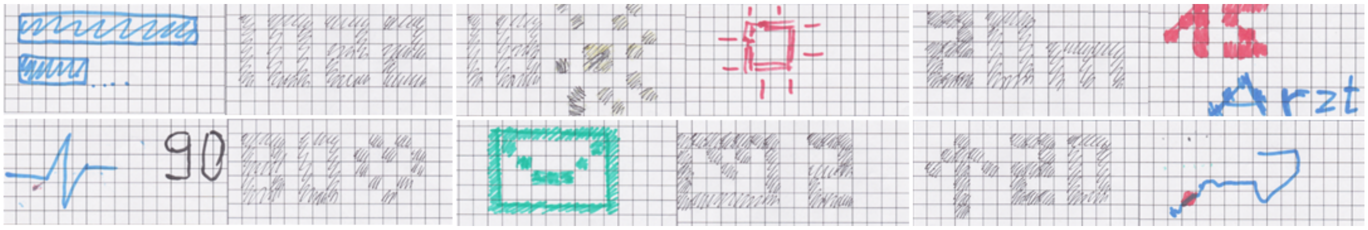

Figure 3. Two of the visualizations for each application scenario drawn by the participants in the first study. Top row: step count, weather, and calendar – bottom row: heart rate, notification, and navigation.

Participants also expressed the need for a mapping between content and location. For instance, two participant would display the heart rate next to the actual position of the heart at the torso. Similarly, placing measurements from fitness applications such as the number of steps made today directly at the feet or legs supports an easy and intuitive understanding of the information.

Visualizations

Participants envisioned various visualizations for the proposed use cases. Most visualizations are adopted from current visualizations known from smart phone applications to the requirements of the on-body display. For example, many participants depicted arrows for the navigational scenario or a mail icon for incoming email notifications. Examples of the drawn visualizations are shown in Figure 3.

USE CASE: NAVIGATION

As a next step, we decided to implement a particular application – a navigation app – and explore how it could be adapted to our wearable focus and context display. Both the focus display (smart watch) as well as the context display were placed next to each other. The map is shown on the smart watch. Presenting off-screen objects such as points of interest (POI) is a common challenge when designing navigational systems. Research explored different ways of visualizing this. Most prominently, Baudisch and Rosenholtz present *Halo* [6]. Halo surrounds off-screen objects with large enough rings to reach the border of the display view port. Thus, the user can infer the location of the off-screen object by estimating the center of the ring. Burigat et al. compared Halos to Arrows [9]. They show that arrows perform similar compared to Halos. Furthermore, their results suggest that Halos perform better the less off-screen objects are presented. We believe that on-body displays have the potential to present off-screen elements in a more natural way and communicate the distance and direction to an object simply by showing it accordingly on the display. In a user study, we compared all three visualizations with respect to the task completion time, errors, usability, and user preferences.

Prototype

We used our display prototype and created an Android navigational application based on Google Maps. The app is capable of displaying a map on the smart watch and the off-screen points of interest on the on-body display. We included in total 4 different maps with 10 different locations each. None of the location was known to the persons beforehand. As a baseline in our user study, we re-implemented two techniques: halos (following the explanation of Baudisch and Rosenholtz [6]

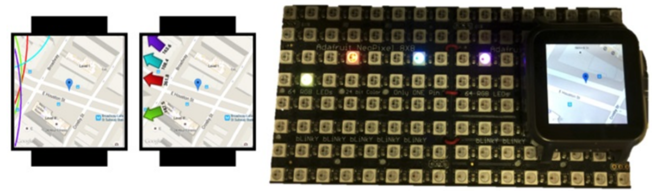

Figure 4. The three off-screen visualizations used in the user study: halos (left), arrows (center), and low resolution on-body display (right).

– Figure 4, left) and arrows (as used by Burigat et al. [9] – Figure 4, center). In addition to that we used our on-body display and presented colored dots at the location the points of interest are (cf., Figure 4, right). Thus, the spatial ratio between points in the real world and in the visualization stays the same, similar to the size of the halos.

Participants and Procedure

We invited sixteen participants (5 female, 11 male), aged 18–26 years (M=21.94, SD=2.05) to take part in the user study through University mailing lists. After participants arrived at the lab we explained them the purpose of the study. The main study consists of two tasks, namely, locate the closest POI and locate a specific POI. The zoom function was disabled for both tasks. For each task, we equipped the participant with a smart watch and the on-body display on the forearm. Then, they performed each task. After the participants performed both tasks they filled in a final questionnaire.

Locate the Closest POI

First, the participant should identify the closest point of interest on a map. As an example, we provided them the scenario of finding the closest restaurant. We presented the three off-screen visualization technique (i.e., halos, arrows, and on-body display) in Latin-squared order. Participants received one task as an example so familiarize with the technique. After understanding the visualization, participants should locate three times the closest POI for each technique. We measured task completion time and errors. After performing the task with each technique, participants filled in a System Usability Scale (SUS) questionnaire [4]. We also asked how easy participants could estimate the distance and direction to a target on two 5-Point Likert scales (1=simple; 5=complicated).

Locate a Specific POI

Second, participants should identify a certain item out of a group of items. This was introduced as a certain restaurant a table was booked at. In this task, we furthermore explored the influence of the display size of the on-body display on the task completion time and error rate. Thus, we used four

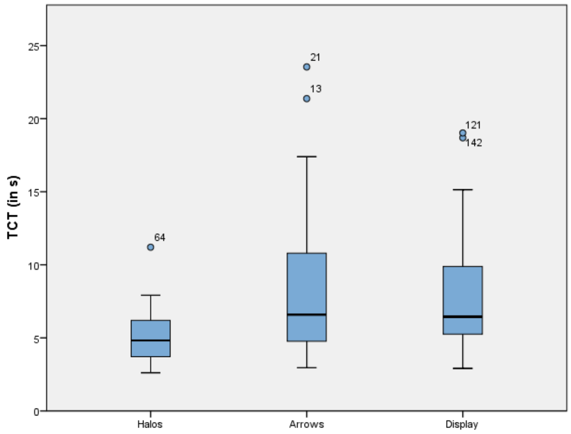

Figure 5. The task completion time of the three different visualization techniques for the locate the closest POI task.

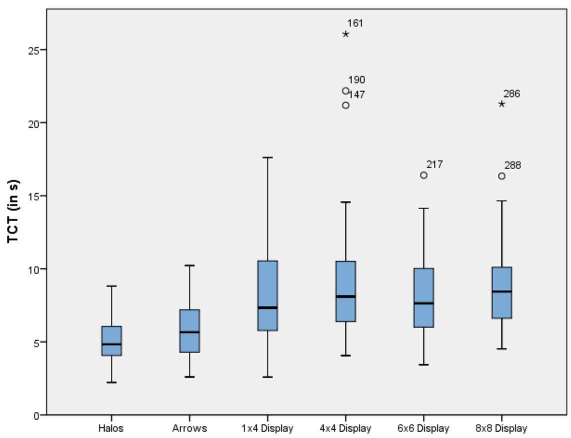

Figure 6. The task completion time of the three different visualization techniques and different display sizes for the locate a specific POI task.

different sizes: 1x4, 4x4, 6x6, and 8x8 pixel for visualizing the off-screen content. Again, each technique was used three times and each display size was used three times as well. We measured the task completion time and errors.

Results

Overall, we recorded 144 search tasks. We removed all data points in which participants did not select the correct POI (Halos 5, Arrow 8, Display 12). Overall, participants rated the usability of the on-body display (M=79, SD=13) and halos (M=79, SD=14) higher compared to arrows (M=78, SD=16) using the SUS. For locating the closest POI, participants using the halos (M=5.1s, SD=1.8) method located the POI faster compared to arrows (M=8.3s, SD=4.8) and on-body display (M=8.3s, SD=4.1). The result of a repeated measures analysis of variance shows a statistically significant difference between the task completion times, $F(2,28)$=8.096, p=.002. Bonferroni corrected post-hoc tests show participants performed statistically significantly faster using halos compared to arrows (p=.018) and on-body display ($p<$.001). The post-hoc tests did not show any statistically significant differences for arrows and on-body display (p=1.000). In contrast, the on-body display (M=1.69) outperformed halos (M=2.50) and arrows (M=2.75) with regard to ease of distance judging as stated by the participants.

For identifying a specific POI, participants performed best with halos (M=5.2s, SD=1.3), followed by using arrows (M=6.0s, SD=2.0) and on-body display (M=8.8s, SD=4.2). When comparing the different display sizes, the results show that participants perform best using 6x6 pixel displays (M=8.3s, SD=3.1) followed by 1x4 pixel displays (M=8.8s, SD=5.6) which both outperform 4x4 (M=9.3s, SD=4.6) and 8x8 (M=8.9s, SD=3.3) pixel displays. A repeated measures analysis of variance shows that these differences are statistically significant as well, $F(5,60)$=8.602, $p<$.001. The post-hoc tests reveal that halos perform statistically significant faster compared to the on-body display versions. All other comparisons did show any statistically significant differences. In contrast, using the Likert scale question, participants rated the arrows (M=1.19) best, followed by on-body display (M=1.50) and halos (M=2.31).

Discussion and Limitations

The presented results show that on-body displays are a valuable alternative to current off-screen visualization techniques. We used a display with a low number of pixels that could in the future be integrated into clothing. In particular in the user ratings, the display outperforms the halos and arrow methods.

Another benefit of the on-body display is that the off-screen visualization does not mask parts of the map. While this was not an issue in the study since the participants did not need to take care of streets or possible modes of transportation, this could further increase the usability in a real world application.

We acknowledge the following limitations of the study. Even though we believe fabric-based displays to offer many benefits, we used a non-fabric based display. The main reason for this is that no fabric-based displays are available yet that offer the required functionality. The current prototype only allows POIs to be visualized that are located in a single direction. Future work could explore POIs located in different directions. This would be feasible with our prototype since the focus display can be positioned at arbitrary locations.

CONCLUSION

In this paper, we explored the design space for on-body displays. We presented a prototype of an on-body display which we used in two user studies. First, we investigated users' location preferences and possible visualizations, taking the requirements of on-body displays into account. Second, we implemented a typical use case for on-body displays in which the display serves as a context display in combination with a smart watch serving as a focus display. The study results show that using such a combination can create a benefit for the user, e.g., when it comes to judging the distance of a POI.

For future work we plan to investigate how further application scenarios can benefit from on-body displays and we will focus on further related research questions [2]. For example, we are interested in the social acceptance of on-body displays and their ability to cope with privacy concerns. Furthermore, we consider the combination with other pervasive displays, such as mid-air displays [24], to be an interesting direction for future work.

REFERENCES

1. Florian Alt, Albrecht Schmidt, and Christoph Evers. 2009. Mobile Contextual Displays. In *Proceedings of the First International Workshop on Pervasive Advertising (PerAd'09)*. Nara, Japan.

2. Florian Alt, Stefan Schneegaß, Albrecht Schmidt, Jörg Müller, and Nemanja Memarovic. 2012. How to Evaluate Public Displays. In *Proceedings of the 2012 International Symposium on Pervasive Displays (PerDis '12)*. ACM, New York, NY, USA, Article 17, 6 pages. DOI: http://dx.doi.org/10.1145/2307798.2307815

3. Orkhan Amiraslanov, Jingyuan Cheng, Peter Chabrecek, and Paul Lukowicz. 2014. Electroluminescent based Flexible Screen for Interaction with Smart Objects and Environment. In *Workshop on Interacting with Smart Objects. Proc. IUI*, Vol. 14. 43–46.

4. Aaron Bangor, Philip Kortum, and James Miller. 2009. Determining what individual SUS scores mean: Adding an adjective rating scale. *Journal of usability studies* 4, 3 (2009), 114–123.

5. Patrick Baudisch, Nathaniel Good, and Paul Stewart. 2001. Focus Plus Context Screens: Combining Display Technology with Visualization Techniques. In *Proceedings of the 14th Annual ACM Symposium on User Interface Software and Technology (UIST '01)*. ACM, New York, NY, USA, 31–40. DOI: http://dx.doi.org/10.1145/502348.502354

6. Patrick Baudisch and Ruth Rosenholtz. 2003. Halo: A Technique for Visualizing Off-screen Objects. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '03)*. ACM, New York, NY, USA, 481–488. DOI: http://dx.doi.org/10.1145/642611.642695

7. Benjamin B Bederson, James D Hollan, Ken Perlin, Jonathan Meyer, David Bacon, and George Furnas. 1996. Pad++: A zoomable graphical sketchpad for exploring alternate interface physics. *Journal of Visual Languages & Computing* 7, 1 (1996), 3–32.

8. Richard Borovoy, Fred Martin, Sunil Vemuri, Mitchel Resnick, Brian Silverman, and Chris Hancock. 1998. Meme Tags and Community Mirrors: Moving from Conferences to Collaboration. In *Proceedings of the 1998 ACM Conference on Computer Supported Cooperative Work (CSCW '98)*. ACM, New York, NY, USA, 159–168. DOI: http://dx.doi.org/10.1145/289444.289490

9. Stefano Burigat, Luca Chittaro, and Silvia Gabrielli. 2006. Visualizing Locations of Off-screen Objects on Mobile Devices: A Comparative Evaluation of Three Approaches. In *Proceedings of the 8th Conference on Human-computer Interaction with Mobile Devices and Services (MobileHCI '06)*. ACM, New York, NY, USA, 239–246. DOI: http://dx.doi.org/10.1145/1152215.1152266

10. Ashley Colley, Minna Pakanen, Saara Koskinen, Kirsi Mikkonen, and Jonna Häkkilä. 2016. Smart Handbag As a Wearable Public Display - Exploring Concepts and User Perceptions. In *Proceedings of the 7th Augmented Human International Conference 2016 (AH '16)*. ACM, New York, NY, USA, Article 7, 8 pages. DOI: http://dx.doi.org/10.1145/2875194.2875212

11. Jennica Falk and Staffan Björk. 1999. The BubbleBadge: A Wearable Public Display. In *CHI '99 Extended Abstracts on Human Factors in Computing Systems (CHI EA '99)*. ACM, New York, NY, USA, 318–319. DOI: http://dx.doi.org/10.1145/632716.632909

12. Dustin Freeman, Hrvoje Benko, Meredith Ringel Morris, and Daniel Wigdor. 2009. ShadowGuides: Visualizations for In-situ Learning of Multi-touch and Whole-hand Gestures. In *Proceedings of the ACM International Conference on Interactive Tabletops and Surfaces (ITS '09)*. ACM, New York, NY, USA, 165–172. DOI: http://dx.doi.org/10.1145/1731903.1731935

13. G. W. Furnas. 1986. Generalized Fisheye Views. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '86)*. ACM, New York, NY, USA, 16–23. DOI: http://dx.doi.org/10.1145/22627.22342

14. F. Gemperle, C. Kasabach, J. Stivoric, M. Bauer, and R. Martin. 1998. Design for wearability. *Digest of Papers. Second International Symposium on Wearable Computers (Cat. No.98EX215)* (1998). DOI: http://dx.doi.org/10.1109/ISWC.1998.729537

15. Sabine Gimpel, Uwe Mohring, Hardy Muller, Andreas Neudeck, and Wolfgang Scheibner. 2004. Textile-Based Electronic Substrate Technology. *Journal of Industrial Textiles* 33, 3 (2004), 179–189. DOI: http://dx.doi.org/10.1177/1528083704039828

16. Chris Harrison, Desney Tan, and Dan Morris. 2010. Skinput: Appropriating the Body As an Input Surface. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '10)*. ACM, New York, NY, USA, 453–462. DOI: http://dx.doi.org/10.1145/1753326.1753394

17. Kasper Hornbæk, Benjamin B. Bederson, and Catherine Plaisant. 2002. Navigation Patterns and Usability of Zoomable User Interfaces with and Without an Overview. *ACM Trans. Comput.-Hum. Interact.* 9, 4 (Dec. 2002), 362–389. DOI: http://dx.doi.org/10.1145/586081.586086

18. V Koncar. 2005. Optical Fiber Fabric Displays. *Optics and Photonics News* 16, 4 (2005), 40–44.

19. Steven a Lewis, Gary D Havey, and Brian Hanzal. 1998. Handheld and bodyworn graphical displays. In *Second International Symposium on Wearable Computers*. 102–107. DOI: http://dx.doi.org/10.1109/ISWC.1998.729535

20. Jörg Müller, Florian Alt, Daniel Michelis, and Albrecht Schmidt. 2010. Requirements and Design Space for Interactive Public Displays. In *Proceedings of the 18th ACM International Conference on Multimedia (MM '10)*. ACM, New York, NY, USA, 1285–1294. DOI: http://dx.doi.org/10.1145/1873951.1874203

21. Simon Olberding, Michael Wessely, and Jürgen Steimle. 2014. PrintScreen: Fabricating Highly Customizable Thin-film Touch-Displays. *Proceedings of the 27th annual ACM symposium on User interface software and technology* (2014), 281–290. DOI: http://dx.doi.org/10.1145/2642918.2647413

22. Simon Olberding, Kian Peen Yeo, Suranga Nanayakkara, Jurgen Steimle, O Boost Processor, and Virtually a L L Recent. 2013. AugmentedForearm: Exploring the Design Space of a Display-enhanced Forearm. In *Proceedings of the 4th Augmented Human International Conference (AH '13)*. ACM, New York, NY, USA, 9–12. DOI: http://dx.doi.org/10.1145/2459236.2459239

23. Ken Perlin and David Fox. 1993. Pad: An Alternative Approach to the Computer Interface. In *Proceedings of the 20th Annual Conference on Computer Graphics and Interactive Techniques (SIGGRAPH '93)*. ACM, New York, NY, USA, 57–64. DOI: http://dx.doi.org/10.1145/166117.166125

24. Stefan Schneegass, Florian Alt, Jürgen Scheible, Albrecht Schmidt, and Heifeng Su. 2014. Midair Displays: Exploring the Concept of Free-Floating Public Displays. In *CHI '14 Extended Abstracts on Human Factors in Computing Systems*. ACM, New York, NY, USA. DOI: http://dx.doi.org/10.1145/2559206.2581190

25. Ulrich von Zadow, Wolfgang Büschel, Ricardo Langner, and Raimund Dachselt. 2014. SleeD: Using a Sleeve Display to Interact with Touch-sensitive Display Walls. In *Proceedings of the Ninth ACM International Conference on Interactive Tabletops and Surfaces (ITS '14)*. ACM, New York, NY, USA, 129–138. DOI: http://dx.doi.org/10.1145/2669485.2669507