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LONG PAPER

Interaction on-the-go: a fine-grained exploration on wearable PROCAM interfaces and gestures in mobile situations

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Abstract Wearable projector and camera (PROCAM) interfaces, which provide a natural, intuitive and spatial experience, have been studied for many years. However, existing hand input research into such systems revolved around investigations into stable settings such as sitting or standing, not fully satisfying interaction requirements in sophisticated real life, especially when people are moving. Besides, increasingly more mobile phone users use their phones while walking. As a mobile computing device, the wearable PROCAM system should allow for the fact that mobility could influence usability and user experience. This paper proposes a wearable PROCAM system, with which the user can interact by inputting with finger gestures like the hover gesture and the pinch gesture on projected surfaces. A lab-based evaluation was organized, which mainly compared two gestures (the pinch gesture and the hover gesture) in three situations (sitting, standing and walking) to find out: (1) How and to what degree does mobility influence different gesture inputs? Are there any significant differences between gesture inputs in different settings? (2) What reasons cause these differences? (3) What do people think about the configuration in such systems and to what extent does the manual focus impact such interactions? From qualitative and quantitative points of view, the main findings imply that mobility impacts gesture interactions in varying degrees. The pinch gesture undergoes less influence than the hover gesture in mobile settings. Both gestures were impacted more in walking state than in sitting and standing states by all four negative factors (lack of coordination, jittering hand effect, tired forearms and extra attention paid). Manual focus influenced mobile projection interaction. Based on the findings, implications are discussed for the design of a mobile projection interface with gestures.

Keywords Mobile computing · Augmented reality · Projection interaction · Gesture · Evaluation

1 Introduction

With miniaturization of devices and the advent of mobile sensors, computing is no longer limited to desktop models but shifts to ubiquitous models. Under these circumstances, increased requirements for research into interaction in mobile settings and scenarios cannot be ignored. Research into vision-based hand–gesture interaction has attracted increasing interest and become prevalent in recent years, as computer vision technologies have the potential to provide a natural, unencumbered and non-contact solution for human–computer interaction (HCI). In addition, projector miniaturization has led to the emergence of mobile devices

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with embedded projectors or palm-size pico-projectors. Projector components are starting to be embedded into household digital cameras or mobile phones. Besides its role as an auxiliary accessory, the pico-projector as an independent device has the ability to connect with other devices and to project high-quality images. Moreover, pico-projectors are small enough to be worn on the body, held in the hand or put in the pocket, which is ideal for mobility and content sharing. Based on the development of these two technologies, wearable projector and camera (PROCAM) interactions attract researchers' attention and have been studied for many years now.

A sophisticated mobile environment expects dedicated design of interfaces on technical issues including input and output techniques, as well as on practical issues involving human factors. However, existing work revolved more around investigation into stable settings such as sitting or standing, which cannot fully figure out the requirements of mobile interaction in sophisticated real life, especially when people are moving. Furthermore, an increasing number of users interact with their phones while walking or moving. As a mobile computing device, the wearable PROCAM system should take into account the situation where mobility influences usability and user experience. Concerning input, mobility results in the effect of jittering hand and tired arm [37, 38] and amplifies the aforementioned effects to varying degrees with gestures, which would degrade user experience. Besides offering unambiguous feedback, a reliable gesture is also required to solve the fat finger problem [27]. Concerning output, miniaturized displays play an important role in the field of wearable computing as a feedback supporter. Researchers working on mobile interaction expect displays to be light, easy to wear, able to display multimedia information and simultaneously support a presentation size as large as possible. As one of the wearable output visual displays, the pico-projector meets most of the aforementioned requirements, such as breaking the small screen limitation. It also has the advantages of augmenting directly on the physical surface and offering more interactive approaches. However, the floating property and manual focus of the pico-projector cause new issues to arise during mobile interaction. Also, existing wearable projector research revolved more around exploring interaction in a stable state such as standing, which is unable to satisfy interaction requirements when users are walking or moving.

With the aim of exploring and solving the aforementioned mobility issues, the authors first propose a wearable projector system with configurations as follows: a webcam for tracking finger motion, a pico-projector for supporting presentation of information and interactive items and a wearable tablet-like laptop used only for calculating and computing. The PROCAM device unit is stabilized next to the ear aside the head: Its projected image can then move as the head moves, following closely the eye movement. In the current stage, the hover and pinch gestures are proposed. The former supports pointing interaction on the graphic user interface (GUI), while the latter supports interactions such as pointing action, drag–drop action and painting. The reference-cell of the projected interface to avoid the fat finger problem is also designed. A lab-based evaluation is organized, focusing on the following questions: (1) How and to what degree does mobility influence different gesture inputs? Are there any significant differences between gesture inputs in different settings? (2) What are the reasons behind these differences? (3) What do people think about the configuration in such systems and to what extent does the manual focus influence such interaction? The study results imply that mobility impacts gesture interactions at different levels. The pinch gesture undergoes less influence than the hover gesture in mobile settings. Both gestures were impacted more in the walking state than in the sitting and standing states by all four negative factors (lack of coordination, jittering hand effect, tired forearms and extra attention paid). Participants were impacted mainly by tired forearms with both gestures in standing state. In the sitting situation, neither gesture was impacted noticeably by the four factors. Compared with pointing of the pinch gesture, the drag–drop action is stable in three states. While the ear side position is a convenient place, more effort should be put into improving stability and reducing the weight of the device unit. Although 50 % of participants thought that manual focus influenced interaction, all of them were satisfied with the projected interface. Finally, implications are discussed for the design of the mobile projected interface with gestures and pave the way on how to design and evaluate this novel interface.

The rest of the paper is organized as follows: Design and implementation are discussed in Sects. 2 and 3, respectively. The user study focusing on mobility issues is presented in Sect. 4, and the results in Sect. 5. The results and implications for design are discussed in Sect. 6. Related work is presented in Sect. 7, and conclusions in Sect. 8.

2 Design of interaction techniques

This paper proposes a wearable PROCAM system via which the user navigates using the pinch gesture and the hover gesture on the projected interface. In this section, the design of gestures as well as the reference-cells of the projected interface eliminating the fat finger problem for this system will be described.

2.1 Gestures as input

Use of one index finger to simulate the "pointing" action on the GUI is common practice in the gesture interaction system. The hover gesture is proposed, based on letting the user's finger hover briefly on interactive items. The user needs to remain in this position for a certain period of time to verify the selection. The button is thus considered as selected. The selection signal is generated via a time span. The user usually has the feeling of physical "pointing" when working with a WIMP system using a mouse. When interacting with a wearable interface based on computer vision technologies, sometimes the user obtains neither the feeling of touch or contact nor the feeling of haptic feedback. Since the hover gesture relies on dwell time, it is hard for it to provide a clear quick physical feedback, especially when the user interacts with the surface beyond an arm-length distance. In addition, it is complicated for the hover gesture to support actions other than pointing.

In order to break the hover gesture limitation, the pinch gesture in the wearable projector system is proposed, explained using a four-state input model [4] (see Fig. 1). The first state (state 0) is so-called out of range. In this state, fingers are beyond the reach of the webcam's vision, and finger movement has no effect on the system. As the fingers enter the webcam region, the system starts to track, and the tracking symbol is the cursor corresponding to the center point of two fingers. State 2 has two states, which are dependent on the widget types. For example, selecting an object, with a dragging property that is true (IsDrag = 1), will cause the selected object to be dragged, whereas selecting an object which cannot be dragged, meaning that this object is pointed.

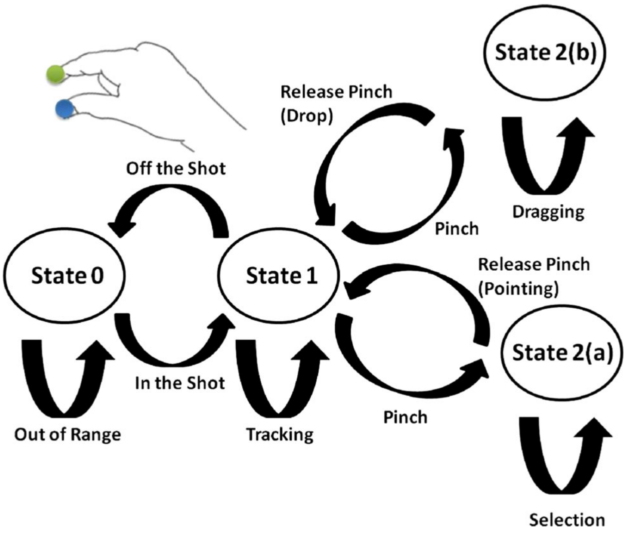


Fig. 1 The four-state model of pinch gesture

The standard pinch gesture is the posture when the index finger and thumb are parallel with the projected interface. The line between the tip of the index finger and thumb can be freely vertical, horizontal or at a certain angle. Besides the pointing action, the pinch gesture can support navigation with dragging, inking, pull-down menus, etc. Therefore, compared with the hover gesture, pinch gesture can perform more tasks.

2.2 Reference-cell for projected interface as output

Fat finger problems [27] exist extensively in the direct-touch finger input, thus impacting validation and other input actions. One approach is the offset cursor technique by Potter et al. [23]. Another solution is the Shift technique by Vogel and Baudisch [29], which offsets the area beneath the finger. Other techniques include the complex offsetting cursor technique [1], the touch cursor technique [31] and the dual finger midpoint [6].

In order to avoid the fat finger problem when using finger gestures, the reference-cell is defined as the basis of the projected interface layout. The reference-cell is a standard square of 20.0 mm × 20.0 mm (for hover gesture) or 40.0 mm × 40.0 mm (for pinch gesture). The projected interface is organized by the interactive items (such as buttons) running across one or more reference-cells. According to hand anthropometric data [24], the mean ± SD of the distal interphalangeal (DIP) width is 17.0 mm ± 1.9 mm. Thus, as illustrated in Fig. 2, 20.0 mm is defined as the length of the hover gesture reference-cell (one finger), and double DIP width, namely 40.0 mm, is defined as the length of the pinch gesture reference-cell (the pinch gesture employs two fingers to complete the pinch and the release-pinch actions).

3 Configuration, implementation and application

3.1 Configuration

Configuration consists of a wearable PROCAM device unit and a laptop for calculating. The unit contains a Logitech

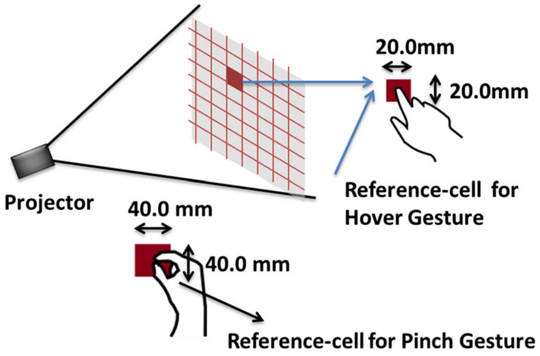


Fig. 2 The reference-cells for the hover and pinch gestures

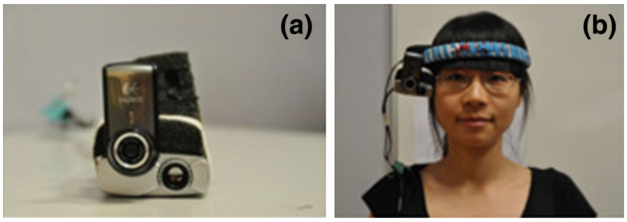


Fig. 3 Configuration: **a** PROCAM unit, **b** head-worn device next to the ear

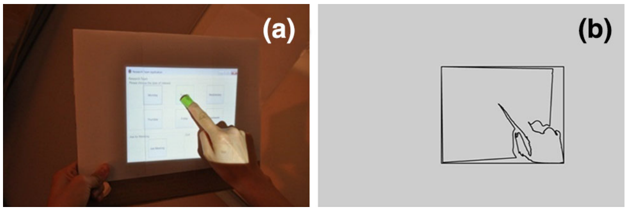


Fig. 4 **a** Original projected image, **b** preprocessed image and *contour* of *lightest* area

640 × 480 RGB image webcam and a pico-projector weighing 117g on manual focus mode. The user needs to adjust the focus manually to sharpen the projected image. The pico-projector has a resolution of 640 × 480 pixels, and a projection size (diagonal) of 127 cm maximum and 15 cm minimum. The laptop is a Dell Latitude XT2 with a rotatable multitouch screen. The user carries it on his/her back and uses it merely for calculating rather than displaying. The webcam and pico-projector are combined as a whole unit (see Fig. 3a) and placed next to the user's right ear by a plastic head band (see Fig. 3b). Thus, the camera sees what the user sees as the user turns his/her head, and the projector displays digital information precisely in the user's field of vision. This position reduces the possibility of image distortion and the inconvenience of moving down the head, compared with the chest position [36]. In this work, more miniaturization and stability of the device unit is required in the walking situation. The webcam and pico-projector device unit used ensures good performance in terms of stability, size and weight. This prototype could also satisfy interaction requirements in mobile settings.

3.2 Implementation

This part discusses calibration of camera and projector, tracking and recognition of finger gestures, and the cursor position in detail.

Even if the camera and projector are combined, disunity between camera and projector coordinates exists. We extract the lightest area in the camera vision field (see Fig. 4a), which is exactly the projection area, and preprocess this area as the real camera vision field in each frame. The projection contour is illustrated in Fig. 4b. In this way, calibration can be achieved automatically instead of using the traditional one-time four-point identification method. After coordinate unification, the user can be provided with either an offset cursor or a non-offset cursor position. In this paper, since interaction occurs on a nearer surface, a non-offset position is set, on which the user will focus on his/her finger gestures and not on the cursor symbol.

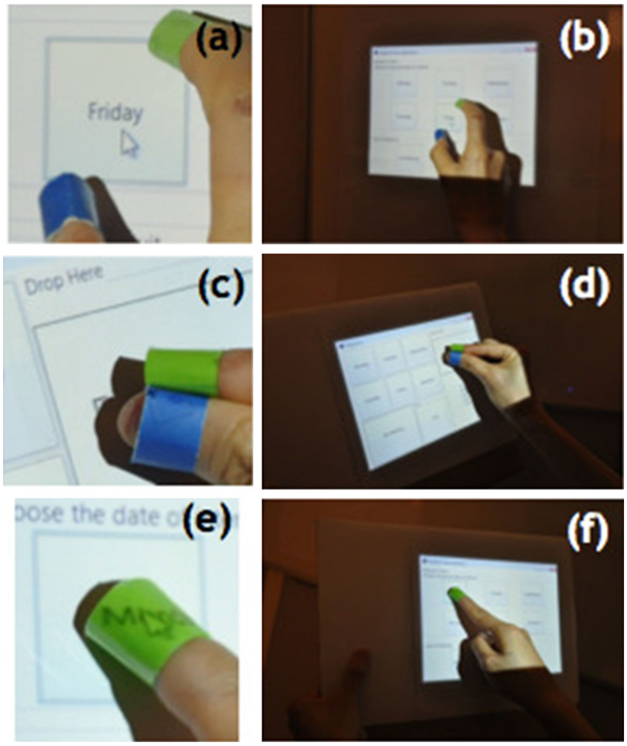


Fig. 5 **a** Cursor position of pinch gesture, **b** pinch gesture, **c** drop area, **d** drop action, **e** cursor position of hover gesture and **f** hover gesture (color figure online)

The vision-based method is used to track fingers. First, the unique color (green) marker is fixed on the tip of the index finger, or two markers with different colors (green and blue) are fixed on the index finger and the thumb. Then, the Camshift algorithm [3] is used and improved to track multiple colors in real time. While recording the color marker trace, the pointing action (hover gesture and pinch gesture) and drag–drop action (pinch gesture) are recognized if the trace meets the predefined condition.

For the pinch gesture, the cursor position is set in the middle of the line between two tips (with the green tip above and the blue one below) (see Fig. 5a). Since the reference-cell for the pinch gesture has enough space to enclose two tips of the index finger and the thumb, the user only needs to pinch within the button area (with the green tip above and the blue one below) (see Fig. 5b). For the drag–drop action, the user drags and drops within the target area as shown in Fig. 5c, d (with the green tip above and the blue one below). For the hover gesture, the cursor position is set above the tip of the index finger (green) (see Fig. 5e, f).

3.3 Application

With the wearable projector system, the user can project menus, schedules, Web sites, videos and other information on a planar large surface such as the wall while standing or on the table while sitting. When walking, the user can project the interface on a small personal projection surface such as a sheet of paper or cardboard held in his/her hand, or even a part of the human body. A number of different example applications that ran on this system were built. Among these interactive applications, a team member appointment application (TMAA) was created, which helped users engage in appointment activities with team members. Imagine the following scenario: Vivien and John are research members in the research laboratory, working on the same floor. One day, Vivien wants to discuss project progression with John. But when she knocks on John's door, she finds that he is out of the office. So Vivien returns to her office. On her way, she suddenly wants to make an appointment with John. While walking, she projects the interface on her notebook held in her hand and interacts with the system to check John's schedule, find an appropriate time and send a date request. After obtaining feedback from the system, she returns to her office and continues her work.

In the user study, tasks based on TMAA were created and participants were asked to perform these tasks. In the tasks, participants were instructed to check two different research members' schedules and ask for an appointment with two members as accurately and quickly as possible.

4 User study

To obtain a more profound understanding of such a system with finger gesture input and projection output in stationary and mobile states, a structured evaluation was organized, involving two gestures (pinch gesture and hover gesture) and three settings (sitting, standing and walking). Three main research questions were explored as follows:

1. How and to what extent does mobility influence different gesture inputs? Are there any significant differences between gesture inputs in different settings?
2. What are the reasons for these differences?
3. What do people think about the configuration in such systems and to what extent does the manual focus impact such interaction?

To answer these questions, task completion time, interaction time, action time, error rates, ease of learning, ease of use, satisfaction, preference and comments were recorded. Task completion time is the time between the user starting and stopping the task, which contains the time of the user's correct and incorrect operations. Operation refers to one action such as one pointing or one drag. Interaction time is the time of correct operations. Interaction time divided by the number of operation times equals action time. Mean action time refers to the average value of each action (such as pointing or drag–drop actions). Through observation, it was found that the reasons for errors while carrying out the tasks are mainly due to users' locomotion and misunderstandings on tasks. These two errors were counted by observation and system logs in each case per participant. The error rate was calculated as the error occurrence number divided by all operations/trials of 12 participants in each case. Besides, a qualitative method was also followed to obtain users' preference between two gestures and between two pinch gesture actions (drag–drop and pointing), ease of learning and use, satisfaction with the projected interface and ear side configuration, and participants' comments.

In this evaluation, it has to be stressed that by discussing the pinch gesture and the hover gesture, the authors refer to the pinch gesture with pointing action and the hover gesture with pointing action. Similarly, when discussing the drag–drop action and the pointing action, it is implied that these two actions are performed by pinch gesture.

4.1 Participants

In total 12 participants were recruited. Respondents were asked to specify their age, gender and experience in HCI and mobile phones. Of all participants, nine were male and three female. Participants were aged between 24 and 31 with an average age of 27.6 (SD = 2.15). All were right-handed. All participants had experience in using mobile devices, though only one of them had no experience in multitouch smart mobile device systems such as the iOS and Android OS. Regarding HCI experience, five said that they had neither taken HCI courses nor read books on this subject. The other seven had either taken HCI introduction courses or read relative books.

4.2 Procedures

A within-subjects design was employed, in which all participants perform six cases as shown in Fig. 6. The order of performance of six cases was counterbalanced with a 6 × 6 balanced Latin square [7].

In Cases A and D, participants were asked to sit freely in front of a table, which could provide a support for their elbows and alleviate tiredness of their hands and arms. In Cases B and E, participants were instructed to stand freely to simulate the stationary state without any support for their forearms. In Cases C and F, participants were asked to

Input techniques	Three settings		
	Sitting	Standing	Walking
Pinch gesture	Case A	Case B	Case C
Hover gesture	Case D	Case E	Case F

Fig. 6 The six cases with two gestures in three scenarios

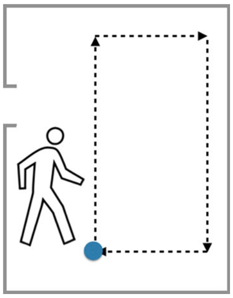
walk at a normal pace to simulate a true mobile environment. In all cases, participants held an identical light white cardboard in the non-dominant hand to project the interface and used the dominant hand to interact utilization gestures. The motivation is to reduce the systematic errors caused by different projected surfaces.

The experiment was conducted in a reserved room indoors without setting up an obstacle. To simulate normal walking state, a walking path was selected as shown in Fig. 7. Participants were asked to keep walking at a fixed pace in their usual way without stopping and to walk casually at a normal walking speed. If participants forgot to walk during interaction, they were asked to continue. A strict speed of walking for participants to follow was not specified since walking pace is not a dependent variable in the experiment. Mobility conditions only include sitting, standing and walking. Two programs were provided for the evaluation: the toy program and the true program. Both are based on TMAA. The toy program was a game program and made for participants to learn and practice, sharing the same interaction methods as the true program. The goal of introducing the toy program was to help participants familiarize themselves with interaction techniques and interfaces. The true program was employed to set tasks for participants.

The evaluation began with an explanation of the protocol in text form. The questionnaire attached to the protocol contained two parts: The first part covered basic individual data and background information on their familiarity with mobile devices and HCI, to be answered before the test; the second part provided questions in Likert scale form [14] and in an open-answer way, to be completed during and after the test. The participant then ran the toy program and stopped when he/she felt that he/she was able to carry out the following true tasks. Next, the participant was assigned the tasks and started the true program. The participant was asked to check one researcher's schedule and to request an appointment with this researcher as accurately and quickly as possible. Before, during and after the test, the participant filled in the questionnaire several times to share subjective opinions. In each case, the participant had to run the toy program first, and then use the true program. All participants completed six cases.

The system only records automatically the performance log with true tasks in six cases. For the pointing action, each participant performed one task pointing with each gesture seven times. This produced 42 trials per participant (two input techniques × one task × three settings × seven pointing trials = 42 trials). For the drag–drop action, each participant performed 12 trials (one input technique × one task × three settings × four drag–drop trials = 12 trials). Thus, each participant performed 54 trials in total. The summary number was 648 trials (12 subjects × 54 trials = 648 trials). These data were used to analyze the error rates.

Fig. 7 The walking path



5 Results

This section presents the quantitative and qualitative results, including interaction time, action time, error rates, ease of learning, ease of use, preference, satisfaction and comments. Shapiro–Wilk tests of observed values (interaction time and action time data) and visual inspections of their histograms, normal *Q*–*Q* plots and box plots, showed that data were not normally distributed for all conditions (gesture conditions: pinch gesture and hover gesture, situation conditions: sitting, standing and walking). Data concerning ease of learning and use were approximately normally distributed, though Likert scores were ordinal data. A within-group design was adopted, where each participant tested all hand gesture and mobility situation conditions. Therefore, the Wilcoxon signed-rank test [35] was used to analyze data, which is a nonparametric version of a paired *t* test on non-normal distributions, working on data collected using a within-group design.

5.1 Interaction time

All participants performed tasks successfully. As stated above, task completion time was recorded and interaction time calculated based on task completion time. Interaction time contains correction operations without errors. As shown in Fig. 8, the clustered boxplot of mean interaction time was plotted with hover pointing and pinch pointing in the three states. In all three states, interaction time with pinch gesture is less than that with hover gesture with users performing the same task and using the same interface

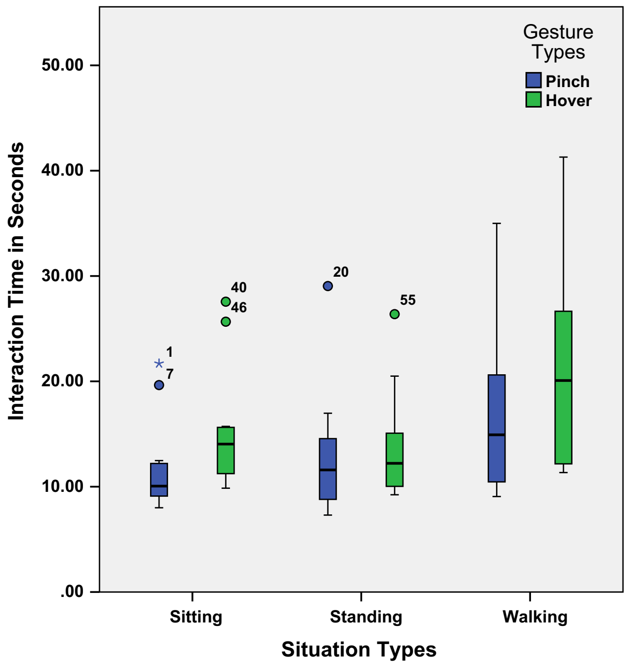


Fig. 8 Interaction time for two gestures in three scenarios

layout. With the pinch gesture, the mean interaction time in sitting (11.83 s, SD = 4.34 s) and standing (12.98 s, SD = 5.92 s) is both shorter than in walking (16.42 s, SD = 7.44 s). With the hover gesture, time has the same tendency as the pinch gesture (sitting: 15.31 s, SD = 5.68 s; standing: 13.80 s, SD = 5.18 s; walking: 21.34 s, SD = 9.91 s).

Overall, no significant differences were found in the result of the Wilcoxon signed-rank test (see Table 1) between the pinch gesture (median = 11.59 s) and the hover gesture (median = 14.32 s) in sitting ($z = -1.65$,[1] $r = -0.34$, $p > 0.05$), standing ($z = -0.94$[1], $r = -0.19$, $p > 0.05$) and walking ($z = -1.18$[1], $r = -0.24$, $p > 0.05$).

With the pinch gesture (see the first column in Table 2), there are also no statistically significant differences between sitting and standing ($z = -0.39$[1], $r = -0.08$, $p > 0.05$), or between standing and walking ($z = -1.33$[1], $r = -0.27$, $p > 0.05$). However, there is a difference between sitting and walking ($z = -2.20$[1], $r = -0.45$, $p < 0.05$).

With the hover gesture (see the second column in Table 2), no significant differences exist between sitting and standing ($z = -0.63$,[2] $r = -0.13$, $p > 0.05$), or between sitting and walking ($z = -1.49$[1], $r = -0.30$, $p > 0.05$). However, there is a difference between standing and walking ($z = -2.12$[1], $r = -0.43$, $p < 0.05$).

Table 1 Differences in situations between pinch gesture and hover gesture

Conditions	Sitting	Standing	Walking
Pinch–hover	$p > 0.05$	$p > 0.05$	$p > 0.05$

Table 2 Differences in gestures between sitting, standing and walking

Conditions	Pinch	Hover	Overall
Sitting–standing	$p > 0.05$	$p > 0.05$	$p > 0.05$
Sitting–walking	$p < 0.05$	$p > 0.05$	$p < 0.05$
Standing–walking	$p > 0.05$	$p < 0.05$	$p < 0.05$

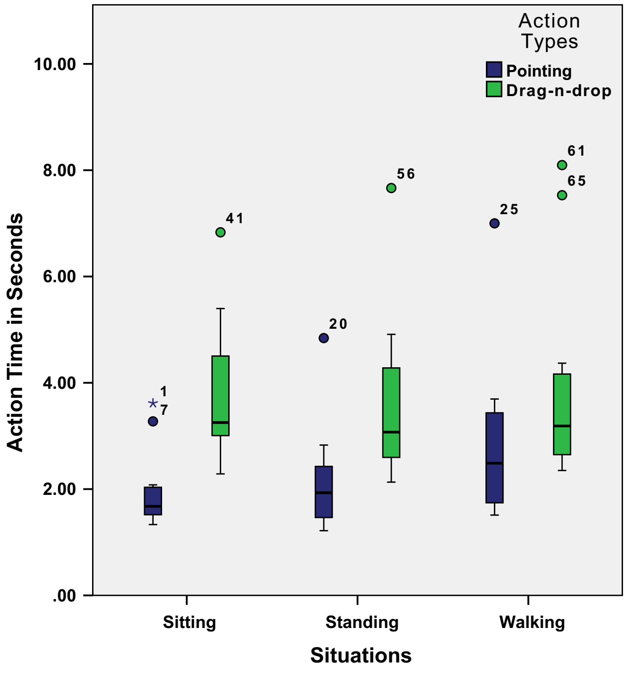


Fig. 9 Action time of the pointing and the drag–drop actions with pinch gesture in three scenarios

Results (see the third column in Table 2) also revealed significant differences between sitting (median =11.98 s) and walking ($z = -2.49$[1], $r = -0.36$, $p < 0.05$), between walking (median = 16.25 s) and standing ($z = -2.54$[1], $r = -0.37$, $p < 0.05$), but no difference between standing (median = 11.59 s) and sitting ($z = -0.14$[2], $r = -0.02$, $p > 0.05$).

5.2 Action time

To know how mobility impacts different actions in a fine-grained way, action time with pointing action and drag–drop action of pinch gesture were compared. Figure 9

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[1] Based on negative ranks.

[2] Based on positive ranks.

shows mean action time with pinch pointing action and pinch drag–drop action. Action time of drag–drop action is almost the same in sitting (3.81 s, SD = 1.31 s), standing (3.56 s, SD = 1.56 s) and walking (3.94 s, SD = 1.92 s). It was also found that action time of drag–drop action is longer than that of pointing action in sitting (1.97 s, SD = 0.72 s), standing (2.16 s, SD = 0.99 s) and walking (2.83 s, SD = 1.52 s).

The Wilcoxon signed-rank test showed that there are statistically significant differences ($z = -4.67^1$, $r = -0.55$, $p < 0.01$) between the pinch pointing action (median = 1.88 s) and the pinch drag–drop action (median = 3.35 s) in sitting (median = 3.18 s), standing (median = 2.46 s) and walking (median = 3.06 s).

To go one step further, it showed that (see Table 3) there are no statistically significant differences between sitting and standing($z = -0.94^2$, $r = -0.19$, $p > 0.05$), between sitting and walking ($z = -0.16^1$, $r = -0.03$, $p > 0.05$) and between standing and walking ($z = -0.79^1$, $r = -0.16$, $p > 0.05$) with drag–drop action.

5.3 Error rates

As shown in Fig. 10, in three scenarios, error rates with the pinch gesture are the same as or less than those with the hover gesture. For the pinch gesture, the lowest error rate occurs under the standing situation (error rate is 0 %). For the hover gesture, the lowest error rate occurs in the sitting and standing situations. A relatively high error exists in the walking state for both gestures. In the walking scenario, the error rate with the hover gesture is nearly twice as high as the pinch gesture (hover gesture 19.23 %, pinch gesture 11.58 %).

Moreover, error reasons were recorded via observation and subjective comments from the questionnaire. In Case A, only one participant made errors. These errors were all made due to an incorrect drop release action. In Case B, only one participant made errors, ascribable to the incorrect posture of the pinch gesture. In Case C, three participants made errors due to locomotion reasons. In Case D, all errors were made by one participant as he forgot the task. In Case E, one-third of the errors were made because the user forgot part of the tasks. The remaining errors were made because the absence of instant feedback caused the user to hover longer to obtain visual change. In this way, the user could easily point interactive items falsely in the subwindow while the windows were switching. In Case F, all pointing mistakes were made because the participants expressed that the projected window floated and waved excessively during walking.

Furthermore, error rates with drag–drop action were noted and compared with error rates for pointing action. As illustrated in Fig. 11, it was found that participants made fewer mistakes with drag–drop action than with pointing action in three situations using pinch gesture. The error rate in the walking situation (4.00 %) is slightly less than that in the sitting situation (5.88 %) with drag–drop action. For error reasons with drag–drop action, it was found that in the sitting situation, errors were made due to the user forgetting the task, forgetting dragging or forgetting dropping. In the standing situation, no errors existed. In the walking situation, errors occurred due to the user forgetting dragging.

Table 3 Differences in actions between sitting, standing and walking

Conditions	Pointing—drag-and-drop
Sitting–standing	$p > 0.05$
Sitting–walking	$p > 0.05$
Standing–walking	$p > 0.05$

Fig. 10 Error rates of two gestures in three scenarios

Fig. 11 Error rates of two actions in three scenarios

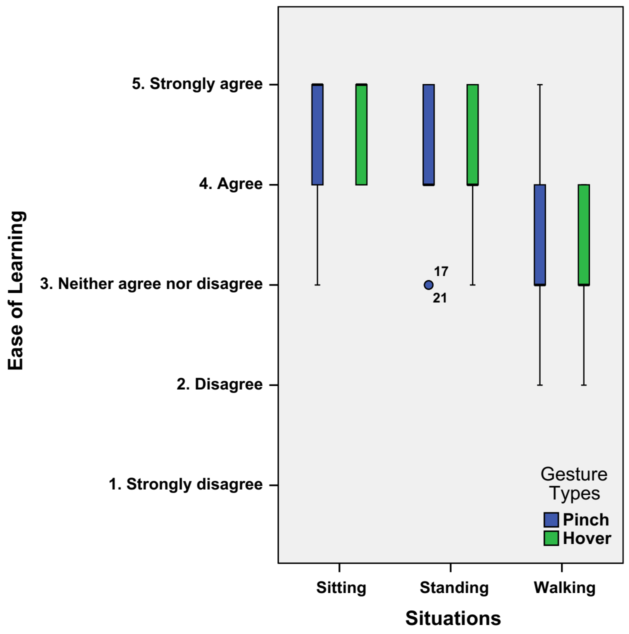

Fig. 12 Ease of learning in three scenarios

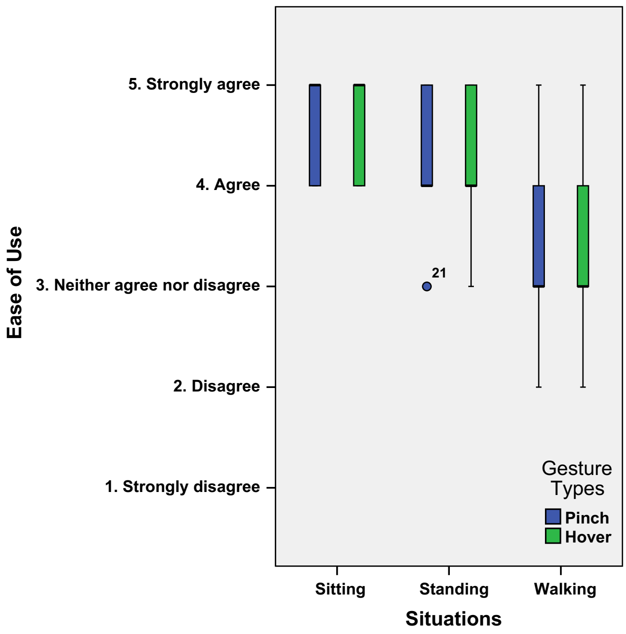

Fig. 13 Ease of use in three scenarios

5.4 Ease of use and learning

Participants were asked to answer questions relating to ease of learning and use. To obtain subjective opinions technically, they were asked to respond to the Likert questionnaire items [14] concerning ease of learning and use, respectively, for pinch gesture and hover gesture in three scenarios. They gave scores for six cases. Five levels (1—strongly disagree, 2—disagree, 3—neither agree nor disagree, 4—agree, 5—strongly agree) were used to describe ease of learning and use. Regarding ease of learning, results (see Fig. 12) showed that all participants thought it was easy to learn with the pinch gesture (median = 4) and the hover gesture (median = 4) overall. Participants also expressed that it was easy to learn when sitting (median = 5), standing (median = 4) and walking (median = 3).

After learning, ease-of-use scores are higher than ease of learning scores. Results (see Fig. 13) showed that all participants thought it was easy to use this system with the pinch gesture (median = 4) and the hover gesture (median = 4) overall. Participants also reported that this system was easy to use when sitting (median = 5), standing (median = 4) and walking (median = 3). As shown in Figs. 12 and 13, it is obvious that the walking scenario is more difficult for users to handle than the sitting and standing scenarios.

In addition to asking participants to give the scores for the six cases, it was also important to know the reasons behind the scores. Four pairs of factors which could impact the interaction were listed: coordination/incoordination between hand and device unit, stable/jittering hand, non-tired/tired forearms and non-extra/extra attention paid. After users responded to the five-point scale questions, they were asked to tick off on the positive polar lists including “coordination between hand and unit,” “stable hand,” “non-tired forearms” and “non-extra attention paid,” the factors which made them feel good about interacting. Also, participants were asked to tick off on the negative polar lists including “incoordination between hand and unit,” “jittering hand,” “tired forearms” and “extra attention paid,” the factors which made them feel difficult to interact. They did not have to tick off if they felt neutral. Taking the “stable/jittering hand” pair as an example, neutral means that participants thought that neither “stable hand” nor “jittering hand” impacted their interactions. In short, four pairs were labeled and classified as positive, negative and neutral groups. Based on the questionnaire, data were collected to calculate the percentage of participants selecting each factor for six cases as shown in Fig. 14. Taking the pinch pointing action for sitting (Case A) as an example, nine participants reported that it was easy to coordinate the position of the projected interface, device and hands. No jittering hand effect due to table support was reported by seven participants, while five participants reported no tired arms effect. Seven participants said they did not need to pay extra attention to interaction.

Figure 15 used the same data set as Fig. 14 though emphasized to what extent each case was impacted by negative groups of factors. As shown in Fig. 15, in Case C (pinch gesture in walking situation) and Case F (hover gesture in walking situation) more than 50 % participants

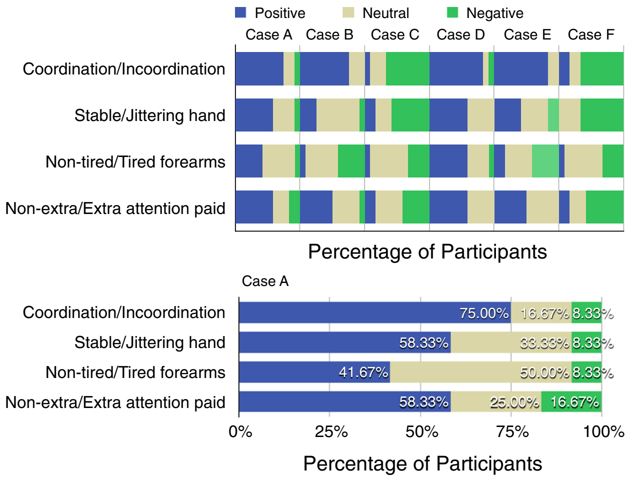

Fig. 14 The reasons behind the scores

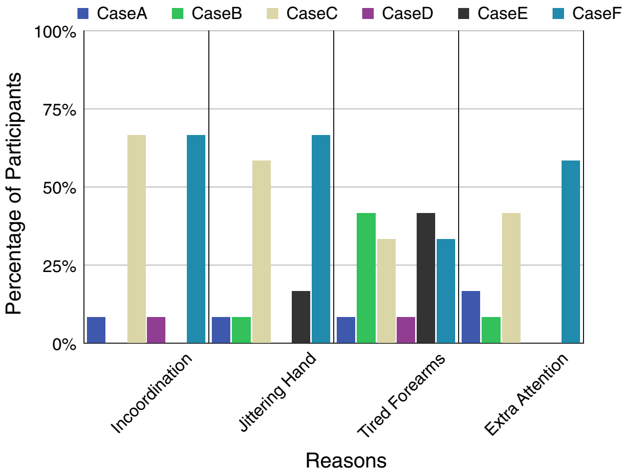

Fig. 15 Percentage of participants impacted by incoordination, jittering hand, tired forearms and extra attention

were impacted obviously by lack of coordination and jittering hand. Both the pinch and the hover gestures in walking state were impacted more than in sitting and standing states by all four negative factors. In Case B (pinch gesture in the standing situation) and Case E (hover gesture in the standing situation), participants were impacted mainly by tired forearms. In the sitting situation, neither gesture was obviously impacted by four factors.

Participants were also asked to evaluate ease of learning on two input techniques without considering situations and to give reasons and comments. The average Likert score of ease of learning for the pinch gesture and the hover gesture is 4.33 (SD = 0.89) and 4.25 (SD = 0.75), respectively. For the pinch gesture, seven participants reported an easy pinch action and six participants reported an easy release-pinch action. Also, five participants stated that it was not tiring to pinch and only one said the opposite. Among them, the person who gave two as the score reported a tired finger and the difficulty of dragging and dropping. For the hover gesture, seven participants said it was easy to control hover time, while four participants said the opposite. Also, six participants reported that their arm was not tired. Moreover, four participants commented that they should pay more attention to slipping their fingers while four people expressed opposite opinions. In addition, five participants said that a touch experience was possible when using the hover gesture.

The average score for ease of learning the drag–drop action is 4.25 (SD = 0.97), while that for using with drag–drop is 4.42 (SD = 0.90). Based on the questionnaire, 10 participants reported it was easy to drag, and nine participants thought that it was easy to drop. The low scores are mainly due to the difficulty of dropping, reported by three participants, and to the difficulty of dragging, reported by one participant.

5.5 User satisfaction and preference

After the experiments, participants were asked to give their subjective preferences and satisfactions. To study the projected interface, they were asked to provide a score on satisfaction of the projected interface and to select the satisfied reasons listed as well as to record any unlisted reasons. The average score of the projected interface is 4.33 (SD = 0.49). Based on the listed reasons in the questionnaire, it was found that half of the participants thought the manual focus could impact interaction, while the other half thought there was no impact. As regards configuration, the mean satisfaction score is 3.83 (SD = 0.58). As regards advantages, more than half of the participants reported the convenience of the view. With respect to disadvantages, more than half stated that the heavy weight involved would lead to discomfort if they wore it for a long time, while the locomotion of the head would impact interaction.

Most participants (67 %) expressed a preference for the pinch gesture; they gave the pinch input twice as many votes as the hover input (33 %). Most participants preferred the pinch gesture because it contains clear feedback and has a low possibility of false pointing with no need to wait, whereas the hover gesture provides no feedback. The remainder preferred the hover gesture because it is simpler to interact with one finger by hovering.

For the drag–drop action and pointing via pinch gesture, 11 participants preferred the pointing interaction to the drag–drop action. Most participants reported that it was uncomfortable to drag the interactive item to a long distant target area in the walking state, even though they had the ability to drag and drop correctly.

6 Discussions and implications for design

This section discusses the three main questions mentioned above in the first paragraph of the Sect. 4 by analyzing the results and findings. Implications for design are also discussed.

How and to what extent does mobility influence different inputs? Both the pinch gesture and the hover gesture are impacted by the walking scenario; however, the pinch gesture is affected less than the hover gesture. The Wilcoxon signed-rank test results on interaction time with the pinch gesture showed that there is difference between sitting and walking. The same test on interaction time with the hover gesture showed that there is difference between standing and walking. Results also revealed significant differences between sitting and walking and between standing and walking, with this novel input and output modality. In addition, error rates in three scenarios with the pinch gesture are lower than with the hover gesture. However, both gestures are still impacted by locomotion. Interaction time with the pinch gesture and hover gesture is ranked in an ascendant way as sitting, standing and walking. Also, the same tendency was observed on error rates. Furthermore, concerning users' comments, incoordination, jittering hand effect, tired forearms and extra attention were reported more in the walking situation than in the sitting and standing situations. Moreover, are there any significant differences between inputs in different settings? The results of the Wilcoxon signed-rank test indicated that there are no significant differences between the pinch gesture and the hover gesture when sitting, standing or walking with regard to interaction time. Participants were more successful at performing tasks and gave more positive ratings on ease of learning and use, satisfaction and preference for the pinch gesture than for the hover gesture.

What are the reasons behind these differences? Major factors that impacted interaction were identified. These factors impacted gestures in three situations at different levels. In short, both gestures in walking state were impacted more than in sitting and standing states by all four negative factors (incoordination, jittering hand effect, tired forearms and extra attention paid). Participants were mainly impacted by tired forearms with both gestures in standing state. In the sitting situation, neither gesture was impacted noticeably by the four factors.

What do people think about the configuration in this system? And to what extent does the manual focus impact such interaction? The ear side position is a convenient place, but more effort should be put into improving stability and reducing the weight of the device unit. Although 50 % of participants thought that the manual focus influenced interaction, all of them were satisfied with the projected interface and this wearable configuration. In the following, the implications for designing such a mobile system will be discussed.

6.1 Adopt gestures and actions according to tasks and situations

This study illustrated the advantages and limitations of the pinch gesture and the hover gesture in all three scenarios. The pinch gesture is discussed first. This gesture was less impacted by mobility, as stated above. In particular, the drag–drop action was not noticeably affected by mobility. The action time of the drag–drop action is almost the same. Also, analysis of the Wilcoxon signed-rank test on action time showed that there are no statistically significant differences between sitting and standing, between sitting and walking and between standing and walking with the drag–drop interaction action. The drag–drop action is more stable for interacting compared to the pointing action when the user is walking. Error rates for the drag–drop action were all low in all three scenarios. Second, the pinch gesture provides a clear feedback, a low possibility of false pointing and no load for waiting; when the user releases the pinch, he knows he makes a selection or an action. Third, the pinch gesture caused fewer errors, and more people preferred the pinch gesture to the hover gesture. Nevertheless, the limitation of the pinch gesture is still present. When making a wrong pinch gesture, the user will fail to pinch, release the pinch, or drag or drop. Also, the size of the reference-cell for the pinch gesture is larger than that of the hover gesture, which will limit the number of selected items on a page. The hover gesture is discussed next. First, the hover gesture does not need any articulated movements; it is simpler. Second, the small size of the reference-cell could allow more interactive items in the interface. Third, the hover gesture provokes the feeling of the touch screen for some participants. However, the limitation is obvious; namely, the user still needs to wait a short time to hover, and this gesture is impacted more by mobility.

The pinch and hover gestures are the example gestures for this wearable PROCAM system. The gesture set could be enlarged, and more gestures could be included in this system. However, the study findings suggest that participants responded better to some aspects in different situations of one gesture than another gesture. Also, they interacted better to some aspects in different situations of one action than another action. In short, gesture interactions and more fine-grained actions are impacted by mobility at different levels and by different factors. Therefore, it is important to assign appropriate gestures and actions to different tasks based on mobile situations, thereby enhancing the advantages and avoiding the disadvantages of gestures and actions.

6.2 Design for tired arms when standing

Results showed that participants were mainly impacted by tired forearms with both gestures in standing state. Usually, when people stand freely, they have no support for their forearms. Long time interaction would cause the tired forearms effect. An alternative solution is to redesign the tasks that can be performed in a short time and fit the ubiquitous situation. In addition, multimodel interaction can be considered such as introducing speech interaction to assist visual interaction, according to the context.

6.3 Design for moving interaction

Both gestures in walking state were impacted more than in sitting and standing states by all four negative factors (lack of coordination, jittering hand effect, tired forearms and extra attention paid). To compensate the mobility effect and decrease user's workload, future designs should consider providing an adaptive or scalable interface [36] based on context mobility. For example, when the system detects the mobile situation, the interface can alter the interactive item size or layout automatically to compensate the locomotion effect.

7 Related work

This section briefly summarizes the research work impacting the design of the wearable system and inspiring work on user studies. First, recent vision-based gesture research is discussed. Then, the related work on mobile projection interaction is reviewed. Finally, the authors focus on users' behavior when interacting with their mobile devices while moving, together with related evaluation results, techniques and methods.

7.1 Vision-based gesture input

Research into vision-based hand–gesture interaction has attracted increasing interest and become prevalent in recent years. Since human hands have characteristics such as a uniformly colored surface, proximity of limbs and a concave shape, it is difficult to recognize and interpret the motion of bare hands with a single recognition method outside the laboratory environment. Furthermore, the main issues encountered in the design of hand pose estimation systems include the high-dimensional problem, self-occlusions, uncontrolled environments and rapid hand motion [5]. Thus, research into computer vision-based hand tracking has gained support from colored stickers or markers, or colored gloves to detect hand gestures. Recognition of colored gloves or marked hands simplifies and facilitates image processing. For example, SixSense [18] proposes marked fingers' gestures as input and uses a webcam to track and recognize these gestures. It focuses on gestures including those supported by multitouch systems, freehand gestures and iconic gestures. Another vision-based tracking method consists in directly recognizing bare hand gestures through a depth camera. OmniTouch [8] allows the user to wear the depth camera and pico-projector on his/her shoulder to support interactive multitouch applications. Besides computer vision recognition technologies, two gesture solutions for selection are used in wearable PROCAM systems: the surface-contacted gesture and the contactless gesture (i.e., mid-air gestures). OmniTouch uses the surface-contacted gesture, however is limited when the environment has to be sterile [30]. SixSense uses the contactless hover gesture to select interactive items. However, the hover gesture relies on dwell time, which only supports the pointing action and cannot provide a clear quick physical feedback itself. As an easy-to-use gesture, the pinch gesture is used commonly in other mobile systems though not in a wearable projector system. It can support multiple navigations and tasks such as basic selection, zoom-in, rotate. TAFFI [32] and Pinch Watch [15] also contributed to consider this gesture for the work presented.

7.2 Projection interaction

In recent years, miniaturization of projectors has led to the emergence of mobile devices with embedded projector or palm-size pico-projectors. Projector components are starting to be embedded into household digital cameras or mobile phones. Besides its role as an auxiliary accessory, the pico-projector as an independent device has the ability to connect with other devices and to project high-quality images. Moreover, pico-projectors are small enough to be worn on the body, held in the hand or put into the pocket, which is ideal for mobility and content sharing. Four conceptually distinct approaches for interacting with the pico-projector system have been identified [25] and discussed: input on the pico-projector, movement of the pico-projector, direct interaction with projection and manipulation of the projection surface. The present study focuses mainly on direct interaction with projection in a mobile environment on everyday surfaces.

Kurata et al. [12] present the BOWL ProCam that proposes interaction techniques effectively employing both nearby projection surfaces such as the user's hands and far projection surfaces such as a tabletop and a wall. AnatOnMe [20] projects medical imagery on the patient's injured body to facilitate exchange of medical information. This augmentation is achieved by a pico-projector, webcam, near-IR camera and modified wireless presenter control. The FACT system [13] allows the user to interact with augmented paper documents through the fine-grained physical-digital interaction mapping approach. A content-based approach is used to establish homographic transformation. SixthSense [18] is a wearable projector and webcam system, which proposes superimposing the projected information onto surfaces in the real environment. Interactive dirt [17] is a wearable projector and camera system, focusing on increasing mobile team collaboration for military purposes. Wilson and Benko propose the LightSpace prototype [33] to augment everyday surfaces in a smart space using depth cameras and projectors. This work not only enables interactions on surfaces but also facilitates mid-air interactions between displays. In the work of AMP-D [34], Winkler et al. envision the concept of an ambient mobile pervasive display (AMP-D) and propose a wearable PROCAM system that supports floor and hand interactions in front of the user instrumented with depth camera and projector. AMP-D provides design guidelines and principles for mobile interaction on-the-go.

For wearable projection, pico-projector stability and projected image viewability should be considered during interaction design. The appropriate position of the wearable projector, the projected size and the projected location are investigated and evaluated in the work of [22], and vary according to the different situations, contexts and projected contents. Konishi et al. [11] propose a method to stabilize projection from the shoulder or the chest to the palm in mobile settings. A hip-mounted projector for floor projection was explored by Tajimi et al. [28].

7.3 Evaluations of on-the-go mobile interfaces

Mobile devices, such as smartphones and personal digital assistants (PDAs), provide opportunities and convenient access with information and data at anytime, anywhere. Natural mobility enables people to use mobile devices in a mobile and dynamic environment. Many users use mobile devices in the street outside their home or office. Increasingly more mobile phone users show how they use their phone while walking [19, 26]. Based on these behaviors of mobile device users, research into the use-in-motion of mobile devices discusses evaluation of mobile interfaces while walking, including correlation between performance and walking speed [9], workload and effort expended in different situations such as walking [19, 26], how mobility influences input quality of new input techniques [16, 21], how to evaluate mobile systems in a controlled environment [2, 10]. The study in [9] explored how situational factors like walking tasks, speed, path, etc., impact interaction and performance when the user is moving. The results in [26] showed that while performance decreases, cognitive load increases significantly when reading and selecting targets when walking. According to [19], visual performance suffers from increasing walking speed, and the effects are greater on reading velocity for pseudo-text search. In terms of mobility influence on mobile interaction, the comparative work in [16] revealed that user's interactions and preferences differed between the levels of mobility. Results show that while there was no significant difference in performance between tap-and-drag and touch-and-go input techniques, both techniques significantly outperformed scrollbars. Besides, users showed a preference for one technique over the other two methods. Results in [21] showed that, independently of hand condition, mobility significantly decreased input quality and led to specific error patterns with mobile touch devices. Moreover, target size can compensate the negative effect of walking when two-hand interaction does not provide additional stability or input accuracy. The work in [10] discussed and explored techniques for usability evaluation of mobile systems and concluded the findings that an increased amount of physical motions would make the test subject experience a significantly increased subjective workload. Six techniques, for example walking at constant speed on a course that is constantly changing, were developed to describe mobility in terms of physical motion and attention needed to navigate while moving. This work investigated techniques that could facilitate evaluation of mobile systems in a controlled environment while being as similar to a real use situation as possible. To go a step further, the work in [2] deepened the study by Kjeldskov and Stage [10] and proposed guidelines for mobile device evaluation when device output is expected to play a significant role in interaction.

Existing work on mobile projection interaction revolved more around investigation into stable settings such as sitting or standing, which cannot fully satisfy the requirements of mobile interaction in sophisticated daily life, especially when people are moving. Based on these evaluation methods and the results of other mobile devices, an evaluation was conducted under mobile settings with an innovative wearable PROCAM system. It is important for such mobile systems, although this has not been explored by other researchers, to figure out how and to what extent the mobility influences different gestures, whether different gestures are performed significantly differently in different settings and what are the reasons for these differences.

8 Conclusions and future work

This work was motivated on the basis of missing studies in mobile settings. This paper has presented the authors' work relating to exploration of the wearable projector system with gestures and projected interface in both stationary and mobile scenarios. The design of reference-cells for the projected interface with either the pinch gesture or the hover gesture has been proposed. Finally, the performance of gestures was evaluated in three scenarios (sitting, standing and walking) to explore primarily how mobility impacts gesture interactions at different levels and why. The study results imply that mobility impacts on gesture and action inputs at different levels. The pinch gesture undergoes less influence than the hover gesture in a mobile setting. Both gestures in walking state were impacted more than in the sitting and standing states by all four negative factors (lack of coordination, jittering hand effect, tired forearms and extra attention paid). Participants were mainly impacted by tired forearms with both gestures in standing state. In the sitting situation, both gestures were not impacted noticeably by all four factors. While the ear side position is a convenient place, more effort should be put into improving stability and lowering the weight of the device unit. Although 50 % of participants thought that manual focus influenced interaction, all were satisfied with the projected interface. The authors' contributions focus on fine-grained exploration on wearable projection interaction in mobile situations. The pinch gesture and the hover gesture are the example gestures for such systems. The gesture set could be enlarged, and more gestures and actions could be included in this system. Participants responded better to some aspects under different situations of one gesture than to another gestures. It is important to consider that gesture interactions are impacted by mobility at different levels and by different factors.

This paper, which explored the wearable projector system with gestures and projected interface in both stationary and mobile scenarios, is a first step and paves the way for more fine-grained research on this topic. In future work, on the one hand, the authors plan to investigate more actions of gestures, such as zooming in, zooming out and rotating interactive items. In addition, they plan to propose more gestures as input and investigate their performances in mobile states. On the other hand, adjustment of mobile settings and exploration of the conditions such as "go upstairs," "go downstairs," fast moving and slow moving are considered to simulate a real mobile environment. Finally, provision of a design space and guidelines is also considered to direct design toward more effective interactions for these wearable systems.

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