Designing a Willing-to-Use-in-Public Hand Gestural Interaction Technique for Smart Glasses

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ABSTRACT
Smart glasses suffer from obtrusive or cumbersome interaction techniques. Studies show that people are not willing to publicly use, for example, voice control or mid-air gestures in front of the face. Some techniques also hamper the high degree of freedom of the glasses. In this paper, we derive design principles for socially acceptable, yet versatile, interaction techniques for smart glasses based on a survey of related work. We propose an exemplary design, based on a haptic glove integrated with smart glasses, as an embodiment of the design principles. The design is further refined into three interaction scenarios: text entry, scrolling, and point-and-select. Through a user study conducted in a public space we show that the interaction technique is considered unobtrusive and socially acceptable. Furthermore, the performance of the technique in text entry is comparable to state-of-the-art techniques. We conclude by reflecting on the advantages of the proposed design.

Figure 1. Our design concept enables unobtrusive interaction without hampering the high degree of freedom of smart glasses.

Author Keywords
Wearable computing; social acceptability; head-mounted displays; tactile feedback; multimodal interaction

ACM Classification Keywords
H.5.2. Information Interfaces and Presentation (e.g. HCI): User Interfaces

INTRODUCTION
This paper addresses the concern of social acceptability when using smart glasses in public from an interaction technique perspective. While wearing smart glasses could already get much attention, the way to interact with them could be even more obtrusive, which would result in unwillingness to use the smart glasses. For example, using voice control, as on Google Glass, can arouse much attention especially in a quiet shared environment and even disturb others. Another popular option is using mid-air hand gestures, which have even more social implications, such as pointing at a person. These concerns can reduce the willingness of the wearer to use smart glasses in public [40, 23, 25].

Research has targeted this issue through designing new interaction techniques. For example, Dobbelstein et al. [8] developed a sensor belt for subtle interaction with smart glasses. However, only limited interaction and applications are possible. Also, Bailly et al. [2] proposed ShoeSense, a depth camera integrated on the shoes, for enabling unobtrusive hand gestures. However, the computer vision-based technique suffers from occlusion issues and thus restricts the actions of users. Even though both cases have been shown to achieve unobtrusiveness, the interaction and applications are limited, which degrades the high degree of freedom manifested on smart glasses.

Our aim is to design an unobtrusive interaction technique for smart glasses so that people are willing to use it in public. At the same time, we want to maintain rich and versatile interaction possibilities, not to restrict the interaction to, e.g., event-based commands. Our approach is to examine the currently available techniques to identify challenges and causes of obtrusiveness. As a result, we derive a set of design principles as a reference toward this goal.

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To bring the principles into a practical design concept, we propose an integrated wearable system enabled by a sensor-equipped haptic glove as an exemplary design. The proposed system was evaluated under three fundamental 2D user interface scenarios, including text entry, scrolling, and point-and-select. The results show that the system maintains a high degree of freedom, intuitive[1] hand gestural interaction, and enhanced tangibility of the untouchable visual interface. Moreover, people are willing to use the system in public.

To sum up, we contribute a set of design principles for designing an unobtrusive interaction technique for smart glasses that people are willing to use in public, and demonstrate the design concept by an integrated, wearable system with a high degree of freedom. The result is applicable for designing interaction for similar head-mounted display technologies.

MOTIVATION AND RELATED WORK

We investigate into the domain of interaction techniques for smart glasses and identify challenges and causes of obtrusiveness in different interaction technique categories. The objective of this survey is to derive design principles for designing socially acceptable interaction for smart glasses.

Social Acceptability

The adoption and use of a device may be restrained by issues related to social acceptability. As noticed by Rico and Brewster [37], the social acceptability of a technology depends on the combination of different factors including its appearance, social status, and cultural conventions. The concept of social acceptability has been further elaborated by Montero et al. [31] who, following Brewster et al. [3], distinguish between the user's and the spectator's social acceptance. The former is the feeling of (dis)comfort the user experiences while using the technology, whilst the latter refers to the impressions bystanders build observing the technology being used by others. Another important factor affecting social acceptability when using gestural interaction is the duration: the longer the interaction the more discreet the commands could appear [8].

The majority of the research has tackled the social acceptability of devices and on-body gestural interfaces (e.g., [37]; [35]) and only a few works have explored users' attitudes toward gestural control of smart glasses. Denning, Delhawi and Koho [7] investigated the social acceptability of smart glasses from the spectator's perspective. They highlighted the key role played by the location where the interaction takes place and by the assumptions made by the bystander regarding the purpose for using the device. The perspective of both the user and the spectator was investigated by Koelle et al. [23]. They found that the usage of smart glasses is perceived more positively from a first person perspective. Regarding the spectator's perspective, the smart glasses seem well received in the workplace and when the purpose of use is known.

Recent research has also shown that hand gestural interaction might arouse the concern of social acceptability. Serrano et al. [40] compared the social acceptability of a hand-to-face input method for smart glasses. Participants showed concern in using the gestures in front of strangers or in public places. Moreover, not all the gestures proposed were found acceptable. Tung et al. [44] asked a group of participants to build a set of command gestures for a game on smart glasses in a public space. They found that mid-air gestures were preferred over on-body or on-device gestures. Furthermore, the majority of the gestures performed were oriented toward the chest area rather than toward the face, mainly for avoiding getting too much attention from the surroundings.

Touch and Handheld Device Input Techniques

It could be beneficial to deploy the already-familiar touch interface on smart glasses. Tapping and swiping gestures are familiar to users and might be learned quickly. However, since the visual contents are no longer touchable, direct interaction becomes difficult. Epson Moverio and Sony SmartEyeglass have a similar design in which a wired handheld device with a trackpad is attached to the glasses. Though subtle finger gestures are possible on the device, this design requires users to carry an additional device in the hand and is known to be less preferred w.r.t. mid-air gestures [44]. Google Glass has the touch interface installed on the frame. To interact with the glasses, it requires users to raise the hand to eye level, which attracts more attention. In an elicitation study on user preference on input method for smart glasses [44], less than 2% of the subjects used touch input on Google Glass.

Hands-Free Input Techniques

One category of interaction techniques aims at hands-free operation of smart glasses. Voice recognition technology has grown mature and been deployed in smartphones and smart glasses. However, it might be obtrusive in a shared environment [8, 44] and not preferred if compared with gestural and non-gestural input [24]. Gaze input [39, 43] and facial gesture detection [12] have also been integrated with head-mounted displays. Although only slight muscle action is involved in the interaction, which could reduce obtrusiveness, the technology requires excessive calibration and is prone to tracking errors. Ishimaru et al. [18] also proposed a technique combining the detection of head movement and eye blinking frequency to recognize users' high level activities, such as distinguishing reading from talking. Although the recognition rate can be as high as 82%, further development is needed for input purposes. Moreover, head gestures might not be preferred if hand gestures are available [24].

Hands-free operation might not be the most important consideration in designing interaction for smart glasses. Zheng et al. [49] conducted an experiment in which subjects complete designated tasks either hands-free with smart glasses or with paper/tablet instruction in hand. They found that there is no difference in completion time since subjects were very good at adapting their context in order to work with their hands.

On-Body Gestural Input Techniques

Various techniques have enabled on-body gestural input and could be integrated with smart glasses [46, 15, 36]. Either using external sensors or direct sensing on the contact surface, on-body gestural input requires users to perform gestures in

[1]In this paper, we adopted the definition of "intuitive use" as the subconscious application of prior knowledge that leads to effective interaction [32].

physical contact with part of the body. Earlier studies have shown the location and gestures performed on the body result in different perception on social acceptability [35, 40]. As reported by Tung et al. [44], touching on the palm is a preferred option (51%). An example is PalmType [45], which enables users to type with finger on the palm. Touching on the body can be of less concern regarding social acceptability since people often do it unconsciously. However, the interaction might be limited with touching events and both hands would be required in the case of PalmType.

Mid-Air Hand Gestural Input Techniques

Although hand gestures might have more social implications in various contexts, they have the potential of enabling natural and intuitive interaction. Computer vision-based technologies, such as 2D or depth cameras [26, 2], have been used for gesture detection in wearables. However, the required physical space might not be ideal in wearable computing. Other researchers have been developing gesture detection technologies to meet the compact size and more efficient performance, e.g., infrared (IR) based technologies [42, 6, 22, 47].

However, computer vision-based techniques not only suffer from possible occlusion, but also require gestures to be performed within the viewing angle of the camera. Hence, the gestures might need to be performed with an unnatural posture. On Microsoft HoloLens, the "air tap" gesture is recognized with the index finger pointing up followed by a "click." Moreover, if the camera is installed on the glasses, the gestures have to be performed in front of the face, which has been shown less preferable than in front of the torso (63% vs. 37%) [44]. Although studies have proposed integrated wearable systems with a camera on the torso, the shoes, or the wrist [2, 4, 21], they cannot fully solve occlusion issues.

Hand-Worn Devices

A way to exploit hand gestural interaction without suffering from occlusion and confined interaction is using sensor equipped hand-worn devices. As manifested on Belt and ShoeSense [8, 2], isolating the sensing technology from the glasses could avoid obtrusive action on the eye level. In our design of wearable peripherals for smart glasses, we thus have chosen to focus on hand-worn devices to enable robust on-body tracking of hand gestures and tactile feedback. Previous studies have explored various form factors worn on different parts of the hand, including fingers [19, 48], wrist [34], forearm [14, 30], and the whole hand [9]. Ideally, having the sensors directly on the hand makes the tracking of hand gestures more robust than with visual tracking.

Minimizing the size of the sensing device could have direct impact in enabling unobtrusive interaction. For example, TIMMi [48] is a textile-based control device worn on the index finger and senses pressure and bending. Lucero et al. [25] aimed at helping wearers focus their attention on the surroundings, and implemented a rub pad-based finger worn device enabling interaction with a minimalistic user interface. It was evaluated with push notification applications while walking in a city. Compared with the small-size prototype, the smart glasses seem to arouse more attention. However, supporting a richer interaction appears to be challenging.

A form factor that seems to be suitable for rich interactions, but rarely used with smart glasses, is a sensor-equipped glove. While also arm-based techniques such as Myopoint [14] can track pointing and rudimentary gestures, gloves can track more fine-grained gestures, such as bending individual fingers. Examples from outside the smart glasses domain include the Gauntlet [30], an arm piece that makes use of various sensors to track hand movements and gestures and contains a single rumble motor for tactile feedback; and a haptic glove for games [9], aiming for immersion and intuitiveness. A haptic glove capable of orientation tracking, gestural input, and multi-actuator tactile guidance has also been proposed for pointing and selecting in 3D environments [17] and mobile augmented reality (AR) [20].

Tactile Feedback in Enhancing Tangibility

Tactile feedback has broad applications for various purposes, such as abstract information delivery and presenting physical object properties [5]. A common application is to provide feedback in improving performance on a visual interface. For example, Forlines et al. [10] have validated that a small amount of tactile feedback could be beneficial in pointing and cross-selection tasks, in which vibration is triggered when pointing at targets and when crossing the edges with a stylus. Moreover, vibrotactile feedback could enhance the tangibility through representing physical properties. Gallotti et al. [11] constructed a haptic glove for simulating the sense of touch for a virtual reality environment. Their comparative study confirmed the value of tactile feedback on performance.

Performance Evaluation with Text Entry

Text entry can be an effective method for evaluating the performance of an interaction technique. Several mid-air text entry techniques have been proposed and evaluated. For example, with fixed sensing infrastructure, users could reach around 20 words per minute (WPM) after proper training [29, 41]. However, recent studies have shown lower performance on smart glasses. Users of PalmType [45], an infrared sensor-based technique, reached 4.6 WPM. A study by Grossman et al. [13], who used swiping gestures on Google Glass frame for text entry, achieved 8.73 WPM at the last block of an 80 minute experiment. There have also been glove-based wearable devices developed for mid-air text entry, such as the Chording Glove [38] (8.9 WPM after 80 minutes) and Airstroke [33] (6.5 WPM over 2 weeks). Twiddler [27], a handheld device, is an effective text input device (26 WPM after 400 minutes) and potentially could be integrated with smart glasses for unobtrusive use. The performance varies greatly between techniques depending on the context. In general, fixed infrastructure and a more precise sensing technique could result in higher performance [45].

DESIGN PRINCIPLES

Examining the domain of interaction techniques, we distilled a set of design principles for unobtrusive mid-air gestural interaction for smart glasses, while maintaining a high degree of freedom:

1. Isolating sensing technology from the glasses
As noted in the survey above, incorporating sensing technologies on the glasses has problems in terms of social acceptability. Touch interfaces on the glasses or tracking mid-air gestures by cameras mounted on the glasses require actions that may attract unwanted attention from the surroundings or cause fatigue issues. Using voice control may be disturbing or cause privacy issues. Therefore, we arrive at the conclusion that the primary sensing technology should not reside on the glasses, but be incorporated in a peripheral device.

2. Using relative pointing for adapting to various postures
Using relative pointing would allow users to more easily adapt their postures to various situations. Though exact mapping of hand posture to visual elements is possible with current technology, it would require users to perform the gestures in front of the glasses where the visual content is projected. Relative pointing would allow users to perform the gestures regardless of the absolute posture, as suggested in an arm fatigue study on mid-air interactions [16].

3. Designing small movements for subtle interaction
Large body movement could arouse much attention from the surroundings, and subtle interaction would reduce the concern of social acceptability. To enable subtle interaction, the system would adaptively adjust the granularity of the interface to reduce the extent of action required from the user. For example, to select a button in the corner of an UI, where there are no other interactive elements, the hand would not have to travel from the starting point to the target location. Instead, when the system detects the hand moving toward the target, the system already shows that the target can be selected.

Considering the nature of smart glasses and the gestures to be designed, we also propose the following principles.

4. Aiming for intuitive gestures
Though it may sound trivial, deploying intuitive gestures is still challenging, as can be seen in air tap gesture on Microsoft HoloLens or opening the palm for clicking on Myopoint [14]. Using meaningful hand gestures to interact with information has the potential to associate the interaction we have with our daily objects. Deploying familiar gestures in the interaction could ease the effort required from users to learn the interface.

5. Enhancing the tangibility
The visual interface on smart glasses lacks tangibility. As validated by Gallotti et al. [11], simulating the sense of touch in virtual environment through tactile feedback has impact on both the experience and performance. Tactile feedback could also enhance the tangibility of the smart glasses interface.

DESIGN CONCEPT

To design a usable and unobtrusive interaction technique for smart glasses, we identified from the design principles that one potential option is an independent hand tracking device to form an integrated wearable system with smart glasses. The benefit of isolating hand tracking from the glasses is that the hand movement would not be confined by the glasses. High degree of freedom and unobtrusive gestures are thus possible.

Figure 2. The haptic glove prototype.

As discussed in earlier sections, computer vision-based hand tracking technologies, which suffer from occlusion or restrained camera viewing angles that hamper the degree of freedom, are not considered in designing the interaction technique. Instead, Inertial Measurement Unit (IMU) is a matured technology for independent tracking of orientation, enabling a high degree of freedom. We decided to use IMU as the core element for hand gesture recognition.

A glove is a good form factor for the hand tracking device for various reasons. Firstly, multiple sensors can be mounted upon for capturing subtle hand and finger gestures, which would be challenging for wrist or forearm-worn devices. Secondly, actuators can be placed on proper locations, e.g. on each finger, for a richer experience enabled by tactile feedback. Moreover, a glove fits the context of an integrated wearable system that allows always-available interaction.

The Sensor-Based Haptic Glove

A haptic glove prototype is deployed as a proof of concept (See Fig. 2). For sensing hand orientation, the glove is equipped with a 9-axis IMU (InvenSense MPU-9150), which consists of a gyroscope, an accelerometer, and a compass. Flexible bend sensors (Spectra Symbol flex sensor) are deployed on three fingers (thumb, index, and middle finger). A set of three vibrotactile actuators (Precision Microdrives 10 mm shaftless vibration motor) is mounted for providing tactile feedback on the thumb, index, and middle fingers. The glove communicates wirelessly over Bluetooth with the smart glasses. An Arduino Pro Mini processes sensor signals and controls vibrotactile feedback. The glove has been constructed with thin elastic fabric for comfort and to suit various hand sizes. A similar prototype has previously been applied for tracking and guidance in a non-visual mobile AR system [20].

The combined sensing technologies on the glove allow us to track most hand gestures, such as pointing orientation, the posture of the hand, and how much the fingers are bent. By monitoring the sensor data, the system understands hand gestures of the user and commands can be issued accordingly. Moreover, information can be encoded in the form of vibrotactile feedback with the freedom to use both actuator location and vibration patterns to convey information.

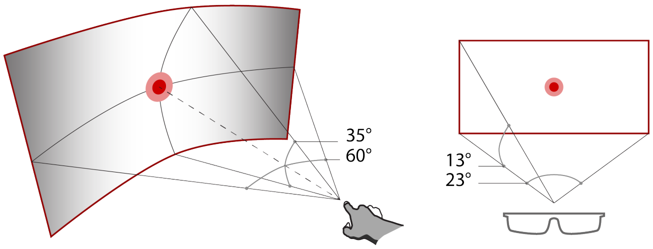

Figure 3. The reference orientation of the glove (Left) is mapped to the center of the glasses display (Right). The active region is defined by the reference orientation and the indicated angle span, which is mapped to display boundary on the glasses.

The Basis of the Interaction

The main idea is using relative pointing, in which a reference hand orientation is mapped to the center of the visual interface, from which a 60° (heading) by 35° (pitch) active region is defined (See Fig. 3). The boundary of the active region, with the reference orientation at the center, is mapped to the boundary of the display with a roughly 23° by 13° field of view on our chosen model of smart glasses, Epson Moverio BT-200. The hand orientation relative to the reference point then determines which part of the visual interface the user is interacting with. Our technique allows setting the reference orientation freely, which enables gestures to be performed in a comfortable and less obtrusive posture.

INTERACTION SCENARIOS

We present our design in three fundamental 2D UI scenarios. Interface design decisions are also described below.

Text Entry

The first scenario we choose is text entry. Text entry is required in many applications, e.g., searching for specific content or inputting personal data. Although voice recognition technology has evolved and been deployed in commercial devices for data input, it is not preferred by users due to social acceptability considerations. Moreover, it might be impractical, especially in authentication requiring a password.

Once the reference orientation is set, the hand movement can be mapped to the visual interface. The keys are grouped in three, in which only one of the groups will be highlighted according to hand orientation (Fig. 4). By bending one of the fingers (thumb, index, or middle finger), the user can type the corresponding character in the highlighted group.

Design Decision - Use QWERTY keyboard

We choose standard QWERTY keyboard for the scenario since it is most familiar to people. The gestures of typing also resonate with users' experiences in typing on a physical keyboard (design principle 4). Moreover, Shoemaker et al. [41] explored the effectiveness of keyboard layouts in mid-air typing with a large wall display. Comparing the performance among QWERTY, circle, and cube keyboard, they found that QWERTY is more preferable and has higher throughput.

Design Decision - Fixed Key Group Composition

The composition of the key groups is fixed so that panning the hand horizontally results in shifting three keys at once. This way, the precision required in the interface is reduced since the horizontal movement in the active region has granularity of 4x4, instead of 10x4. Moreover, each finger is then always mapped to a selection of specific keys. In the long run, muscle memory can facilitate improving efficiency.

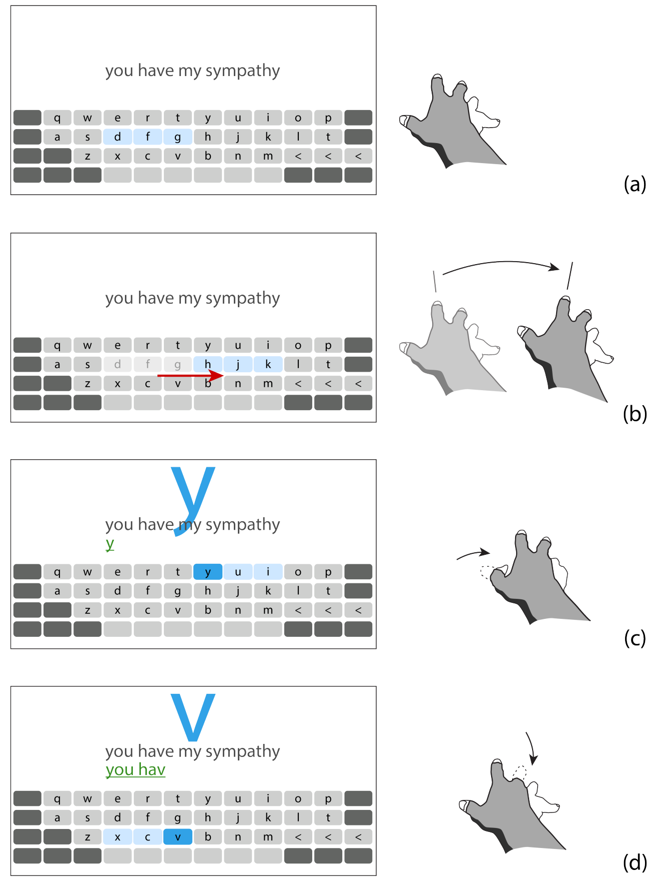

Figure 4. Text entry scenario. In a) and b) a key group is highlighted according to current hand orientation. A preset phrase appears for the evaluation. In c) and d) bending an individual finger would insert a corresponding key in the highlighted key group.

Design Decision - Additional Margin in between Key Groups

To make the interface more robust, we implemented a margin for each highlighted key group to avoid flickering at the edge between the groups. When moving from one key group to the next, the user has to move further beyond the edge for the amount of the margin. Once the focus has been switched to the next group, to move back to the original group, the user has to move to the opposite direction for two times the margin value in order to reach the edge first and then go beyond the new margin. This can effectively reduce flickering at the edge due to either sensor noise or fluctuation from the user.

Design Decision - Tactile Feedback

Tactile feedback is introduced in two places in the interaction to enhance the tangibility of the interface (design principle 5). When the user changes the focus of the key groups, i.e., crossing the key group edge, a vibration pulse (30 ms) is presented on the index fingertip. When a key is hit, a longer vibration pulse (100 ms) is triggered on the bending finger.

Select Single from Many

The second scenario is icon selection (Fig. 5). The visual interface shows a grid of icons for the user to select. When the user forms a pointing gesture (straightens the index finger and bends the middle finger, no requirement on the thumb), one of the icons will be highlighted according to the pointing orientation. The highlighted icon can be selected by bending the index finger (a selection gesture). Following design decisions made in text entry scenario, tactile feedback is presented when switching the focus and when making a selection. Additional margin is also implemented for eliminating fluctuation between icon edges. This type of interaction can be generalized to selecting items from vertical or horizontal menus, locating and clicking a button in the interface, etc.

In realistic scenarios, icons might spread over several pages. To switch between pages, users can perform a swiping gesture (Fig. 5(d)) by moving the hand toward the desired direction and making a fist, which simulates a dragging action.

Design Decision - Avoid Precise Control

The field of view of the display on commercial smart glasses is rather narrow (most below 30 degrees, rarely beyond 40 degrees), and it would be demanding for precise control. For example in Epson Moverio BT-200, the field of view is only 23°. Considering use cases of smart glasses in high mobility contexts, a traditional cursor-based interface would be challenging due to unconscious effort spent in examining the location of the cursor and the target boundary. In our design, the visual interface highlights (brightening the color and enlarging the size) a potential target among others according to pointing orientation of the user without showing a cursor.

Design Decision - Hand Gestures beyond Touch Metaphor

In the elicitation study by Tung et al. [44], several game input interactions have been given user-defined gestures. Some of them could be generalized to common 2D user interfaces. However, the gestures mostly inherit from personal experience of using touch interfaces. For example, to select an item on the display, the gesture is a direct tap action in front of the face or chest. Similarly, moving in 4 directions is similar to the dragging gesture on a touch screen. Our intention here is to explore more embodied interaction through hand gestures. Therefore, more complex yet natural hand gestures, e.g., bending fingers and closing the fist, are designed.

Scrolling

The scenario is presented with a long article viewing task in which users browse through the content that is beyond the display boundary, such as reading an online article. For showing the content below the lower boundary of the display, users can perform a scrolling up gesture by inclining the hand upwards and making a fist, which simulates a dragging up action (See Fig. 6). For the other direction, users can perform a scrolling down gesture by inclining the hand downwards and making a fist, which simulates a pulling down action. By opening the palm or returning to the reference orientation, the scrolling can be stopped. Users might find hyperlinks in the article when reading. Once a hyperlink is present, the user can switch from scrolling to pointing gesture to access the hyperlink. The type of interaction can be deployed in scrolling a list or document, or panning for pictures or maps.

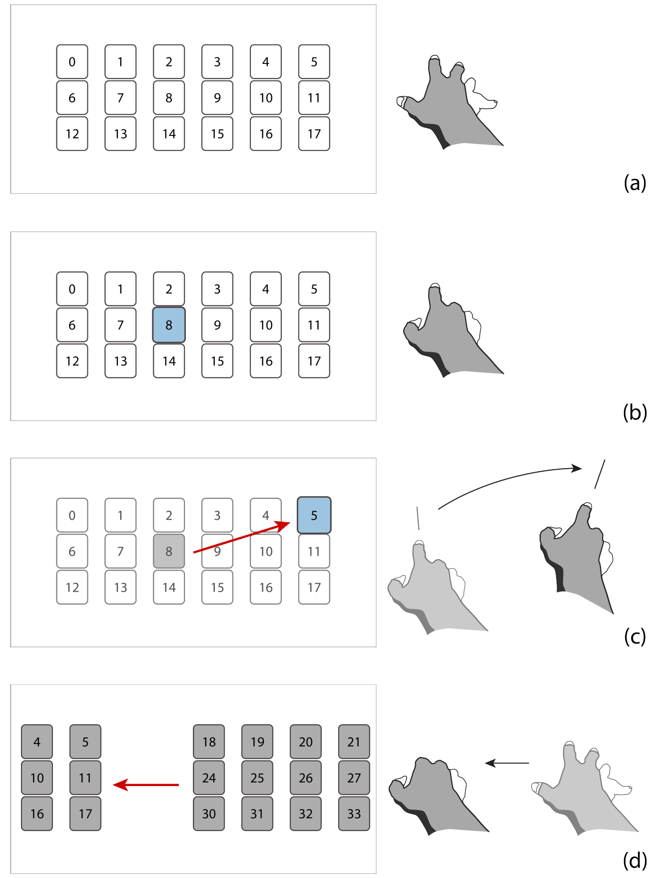

Figure 5. Selecting one from many scenario. a) An open palm results in no action; b) and c) making a pointing gesture highlights an icon corresponding to current orientation; d) making a swiping gesture triggers an animation for changing page content.

In the reading scenario with hyperlink, the distribution of interactive elements is less dense. We further manifest adaptive granularity as described in design principle 3 for enabling subtle interaction. Even though the hyperlink is presented at the far corner of the display, users would not have to travel for a long distance as mapped on the display (See Fig. 6(d)). Instead, the system would highlight the hyperlink already when the pointing orientation is inclined toward its overall vicinity, which would eliminate unnecessary hand movement.

Design Decision - Align Scrolling/Swiping Direction with Touch-Based Input

Hand gestures for manipulating visual element movement, such as in scrolling or swiping, could be interpreted inversely. For example, scrolling up with a mouse wheel or on touch screen results in page moving in opposite directions. We decided to align the behavior with touch screen based interaction since the gestures are more similar to that on touch-based input (design principle 4).

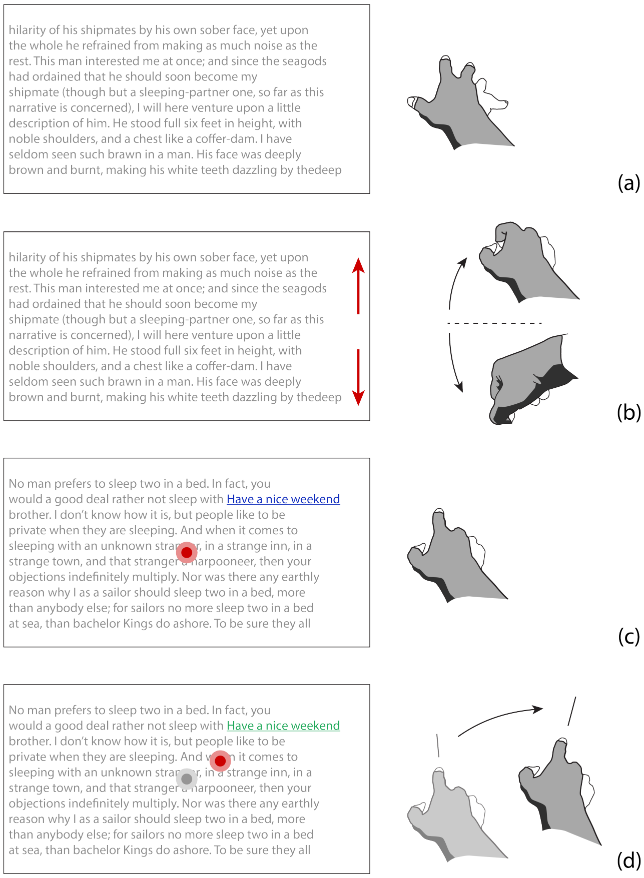

Figure 6. Scrolling scenario. a) An open palm results in no action. b) A pulling up/dragging down gesture starts scrolling the content in the corresponding direction. c) When the target is in view, a pointing gesture is required to select. d) Subtle movement toward the target highlights the target, which can be selected by bending index finger. Note: the red circle indicating the pointing orientation is not visible in the interface.

EVALUATION

To evaluate our design concept, we conducted a study in which users interact with a 2D visual interface in the above-mentioned scenarios. We were interested in validating the feasibility of the integrated system, subjective feeling of social acceptability when using the system in public, and whether tactile feedback could enhance the tangibility. We chose not to compare with handheld devices which might also achieve similar goals because they have been reported as less preferred by users [44]. Though it is not required in the evaluation method for social acceptability [37], to further enhance the validity of the responses collected from the subjects, we conducted the study in a public space, i.e., a busy corridor intersection where the space is composed of a sofa area and public computer working space in front of a coffee room, a laboratory, and toilets.

Participants

Overall, twelve subjects (five women) were recruited from a diverse collection of mailing lists. They were all right-handed. Ten subjects had none or limited experience in using smart glasses, haptic glove, and hand gestural interaction, while one subject rated intermediate in mid-air gestural interaction and another one in both haptic glove and mid-air gestural interaction. The mean age was 27.25 years (SD = 3.05).

Apparatus

The haptic glove was paired with Epson Moverio BT-200 Smart Glasses. The glasses contain a binocular, see-through LCD with resolution 960x540 pixels. The display field of view is 23 degrees. The operating system of the glasses is Android 4.0 running on a handheld device with touch-pad interface, which was not used in the study. The application was also installed on a Samsung S5 smartphone only for demonstrating the interface to subjects.

Procedure

The subjects gave informed consent and filled in a demographic questionnaire. Each task was explained and demonstrated on a Samsung S5 smartphone so that the interface was visible to both the experimenter and the subject. The participants were asked to complete the task on the smartphone before continuing the training section on the smart glasses. Once the participants felt confident enough, the formal test began. Resetting the reference orientation was the trigger to start each segment. Participants were instructed to perform a reset gesture by bending only the thumb and holding for 2 seconds in their own comfortable posture. They were allowed to flexibly reset the reference orientation any time during the test by performing the same reset gesture. Each task was divided into several segments. Between segments the participants were allowed to rest as much as they wanted. To continue with the subsequent segment, they had to perform the reset gesture to reset the reference orientation. A short questionnaire regarding the experience of the current task was given when the task was completed. After the three tasks were completed, a final questionnaire and an open-ended interview were conducted for evaluating the overall experience.

Text Entry

A virtual keyboard was displayed at the bottom of the interface with an assigned phrase on the top (Fig. 4). Subjects typed the phrase one character after another. The backspace button was used for correcting typos. A task was completed when the input phrase matched the assigned one. The phrase set was randomly selected from MacKenzie and Soukoreff's phrase sets for evaluating text entry [28]. All subjects followed the same phrase order. When a segment of 4 phrases was finished, subjects were able to rest before resetting the reference orientation to continue with the next segment. The entire task lasted for 20 minutes excluding breaks.

Select Single from Many

The interface showed a grid of icons whose dimensions (95x90 pixels) followed the current interface on Epson Moverio BT-200 (Fig. 5). The icons, numbered from 0 to 53, spread in 3 pages each with 18 icons in a 6x3 grid. Subjects performed point and select gesture to select a target icon with the assigned number. The pages could be swiped through. When the assigned target icon was selected, the procedure was repeated until all 54 icons, in a randomized order, were selected. The task was divided into 3 segments, each with 18 selections. Subjects were able to rest between segments.

Scrolling

The interface showed a long article with graphical dimensions 960(W) x 3785(H) pixels. A key phrase, "have a nice weekend," was assigned as a target to be inserted in a random location in the article. The starting view was in the middle of the article (Fig. 6). Subjects were required to scroll up or down to find the target phrase, which was presented in a different color simulating a hyperlink from a webpage. Once the target was in view, the subject could switch to pointing gesture and select the target. There were 40 trials divided into 4 segments. Subjects were able to rest between segments.

Data Collection

The measures recorded during the study included observations, questionnaires, and logged data. The entire trial was video-recorded for offline analysis of the users' behavior.

The questionnaires completed after each task were composed of three parts. The first investigated the ease of use of the gestures. The second addressed the usefulness and the pleasantness of vibrotactile feedback and the ease of interpreting it. All the questions were answered on a five-point Likert scale, where 5 indicated a full agreement. The third section addressed social acceptability in different locations (home, sidewalk, passenger on bus or train, café or restaurant, and workplace) and in front of different audiences (alone, partner, friends, colleagues, strangers, family) as proposed by Rico et al. [37]. The option of using the gestures in driving was eliminated from our questionnaire since it is impractical and unsafe to use hand gestures in such condition.

The questionnaires completed after the entire study explored overall feeling about the system, sources of obtrusiveness, and physical comfort. A System Usability Scale (SUS) questionnaire was filled in before the final interview.

RESULTS

In the evaluation we focused on social acceptability, the validation of the interaction technique and user experience.

Social Acceptability

The measuring of social acceptability follows the method proposed by Rico et al. [37]. However, in addition to "Yes, I would use the system in that situation" and "No, I wouldn't use the system in that situation," we added an additional category, "I don't know." as a response to neutral feeling. The percentage of positive, negative, and uncertain responses with respect to each situation can be seen in Fig. 7.

In general, subjects showed a positive attitude regarding the possibility of using the scrolling gesture both in private and public places. 100% of respondents would use the scrolling gesture at home; 91% would use it at their workplace. Almost 60% of participants would perform such gesture while on the bus or in a café. Only half of the sample affirmed to be willing to use it while on the sidewalk. Similarly, they seemed willing to use the system in front of people with different levels of intimacy. All of them would use it alone, with their partner, or with their colleagues. 91.67% would use it with friends and only 58.33% in front of strangers.

The icon selection gesture was generally well received. The gesture was considered appropriate to be used in the workplace by 91.67% of participants and at home by 83.33%. 66.67% of the respondents seemed willing to perform the icon selection gesture when in a café. 58.33% of the sample would use the gesture either on the bus or on the sidewalk. The entire sample affirmed they would use the gesture alone, with their partner or family, and with their colleagues. 91.67% would use it with their friends. Finally, 41.67% seemed to be willing to use the icon selection gesture with strangers.

The gestures for typing were more controversial to our respondents. 75% of them would use them at home and at their workplace. Half of the sample said they would use the gesture on the bus and 41.67% would use it in a café. Only 33.33% of respondents would use the gestures on the sidewalk. All the respondents would use the gesture alone, with their partner or family, or with their friends. 83.67% of the sample affirmed they would use the gesture with their colleagues and only half of the sample would use typing gestures with strangers.

Participants showed a positive attitude of using the system at home or in the workplace (on average, yes: 86.11%, no: 5.55%), and seemed more neutral to use it on a bus or train, in a café or on the sidewalk (yes: 52.78%, no: 25.93%).

Furthermore, they showed no concern in using the system alone and in front of acquaintances (yes: 95.83%, no: 0.69%), but seemed neutral on using it in front of strangers (yes: 50%, no: 25%). Subjects were told that this glove is a prototype, not a final product. Considering the sources of obtrusiveness, even with the exposed electronics on the prototype, subjects felt that wearing the glasses (3.17) is more obtrusive than either wearing the glove (2.5) or performing the gestures (2.5) on a 5-point Likert-scale questionnaire. No subject expressed concern of the electronics.

Performance

In text entry, we used standard words per minute (WPM), total error rate, and keystroke per character metrics for measuring text entry performance [1]. Since subjects were required to correct errors (delete errors and re-enter), speed has incorporated the cost of error correction. The average input speed from our 20-minute experiment was 5.39 (SD = 1.46) WPM with a total error rate of 5.45% and 1.14 keystrokes per character. The first 4 phrases resulted in input speed 4.34 (SD = 1.01) WPM, while the last 4 phrases resulted in 5.42 (SD = 1.27) WPM (Fig. 8). A major improvement is achieved in the first half of the task.

In icon selection, we report the time required for pointing at the target and making a selection gesture. If the icon was already in view and required no page swiping, the mean time was 3.79 s (SD = 2.10 s). If swiping was required to locate the target icon, 5.25 s (SD = 3.77 s) was required if swiping once, and 6.23 s (SD = 2.58 s) for swiping twice. The swiping animation duration (560 ms) was subtracted from the mean value. The time includes switching in between swiping and

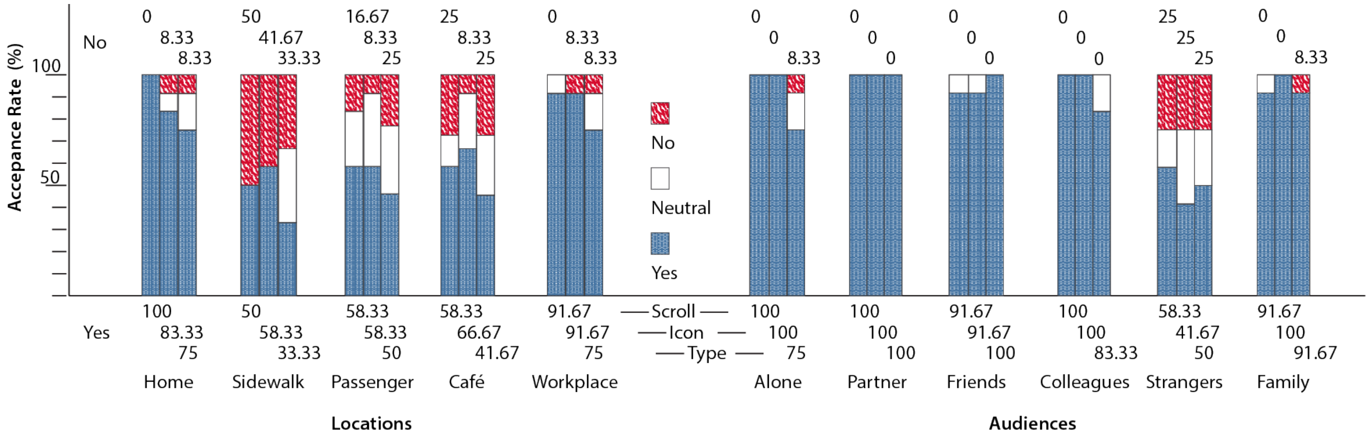

Figure 7. Results of the measurement on social acceptability presented with acceptance rates.

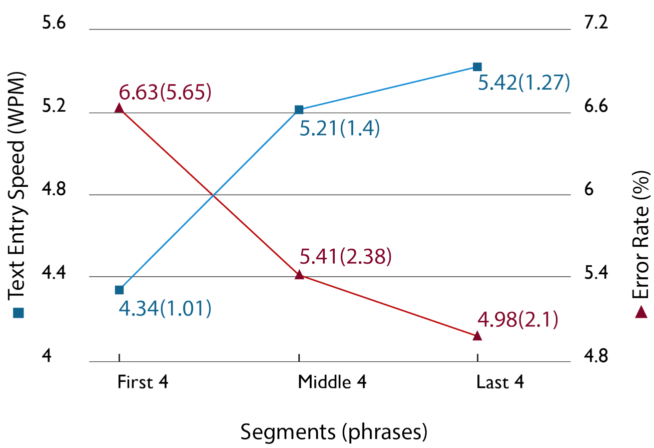

Figure 8. Text entry speed and error rate calculated with a set of 4 phrases in different segments of the 20-minute evaluation.

pointing gestures if changing page was required. The overshooting rate of pointing at the target was 19.25%, while for swiping the page it was 4.66%. Similar to text entry , a major performance improvement is observed in the first half, where the average task completion time goes from 7.08 to 5.01 seconds, after which it remains stable on average.

In scrolling, the average time to select was 7.57 s (SD = 5.06 s), which includes searching the hyperlink and switching gestures from scrolling to pointing. The time required for scrolling from middle to either top or bottom end was 2.65 s, while 5.08 s was required to scroll from top to bottom or the other way around. With article height of 3,785 pixels and display height of 540 pixels, the page was scrolled at a constant speed of 1.38 pages per second. The overshooting rate of scrolling for the hyperlink was 13.54%.

General User Experience

Overall, positive user experience was derived from questionnaire results. The gestural commands proposed were considered intuitive for icon selection (M = 3.58, SD = .79), scrolling (M = 4.5, SD = .5) and typing (M = 4.26, SD = 1.02). Participants seemed neutral about the difficulty of remembering the gestures for selecting an icon (M = 2.25, SD = 1.35), and less concerned about the gestures needed for scrolling (M = 1.58, SD = .79) and typing (M = 1.83, SD = 1.02). Regarding the clumsiness of the gestures, users were again neutral about those used for selection (M = 2.5, SD = .75) and typing (M = 2.9, SD = 1.08), while they seemed not to find clumsy the gestures used for scrolling (M = 2.08, SD = .79). The gestural commands were not considered obtrusive for any of the tasks (icon selection M = 2.25, SD = .75; scrolling M = 1.9, SD = .66; typing M = 2.25, SD = .96).

Concerning the tactile feedback, it was considered non-distracting for all the tasks (icon selection M = 2.4, SD = 1.16; scrolling M = 1.5, SD = .67; typing M = 2.9, SD = 1.24). Furthermore, participants found it easy to interpret (icon selection M = 4, SD = .85; scrolling M = 4.16, SD = .71; typing M = 3.9, SD = 1.08). Also the tactile feedback was useful (icon selection M = 3.88, SD = .83; scrolling M = 4.08, SD = .66; typing M = 3.66, SD = 1.3) and not disturbing (icon selection M = 2.4, SD = .99; scrolling M = 1.58, SD = .66; typing M = 2.83, SD = 1.33).

Gesture Postures

Subjects were given freedom to set their own reference orientation, which defines the active region. None of the subjects performed the gestures in front of the face, and the most common area was in front of the lower torso. Two of the subjects had a very relaxed posture of laying back on the sofa with the upper arm placed on the top of sofa back. All of the subjects set the reference orientation to the front. Three subjects set the orientation to the side in some part of the study. Only two subjects requested a break in between text entry segments, while others chose to finish all the segments at once even though they had the freedom to take a break.

DISCUSSION

Based on a broad survey of previous research, we derived design principles for designing a socially acceptable interaction technique for smart glasses and demonstrated the design with a glove-based prototype. The solution provides a peripheral wearable device that can be operated with subtle and intuitive gestures without attracting attention from the surroundings. Since the tracking of gestures and actions is done by sensors on the hand, the design is free from visual occlusion problems. Furthermore, the glove as a form factor enables the use of both tactile feedback directly on the action-performing body and a rich set of gestures, thus providing a versatile input device for diverse fundamental interactions, such as text entry, pointing and selecting, and scrolling.

The evaluation shows that our design met the aim of unobtrusiveness. Earlier studies [40, 23, 25] show that mid-air gestures can be obtrusive and, thus, reduce willingness to use in public. Especially performing the gestures in front of the face would arouse more attention than performing in a lower posture. The elicitation study on users' preference on hand posture [44], in which no real interaction took place, showed that 37% of the gestures were performed in front of the face. However, when evaluated with real tasks, none of our subjects performed the gestures in front of the face. Our system allows gestures in a less obtrusive posture and the results show that people are willing to use the system in various conditions. A handheld device could also have achieved unobtrusive use. However, they have already been found less preferred by users [44], which is also the reason why a comparative study between the glove and a handheld controller was not done. The present study confirms previous findings: location plays a key role in determining if interacting with gestural commands is socially appropriate, with private places considered more fitting for this purpose [7, 23, 40]. Furthermore, our data supports the positive view of interacting with smart glasses at work [23]. Finally, the intention of using hand gestural interaction seems limited by the presence of strangers [40], as can be seen from the results (Fig. 7), where in front of strangers and with icon tasks have the lowest acceptance rates since a lot of physical pointing is involved in the interaction.

The results from text entry performance show that, within only 20 minutes of evaluation, our system has a higher performance than PalmType [45], which is also a hand-worn text entry technique for smart glasses. Their results reached 4.6 WPM on an IR sensor-based prototype. Another study from Grossman et al. [13] using swiping gestures on a Google Glass frame for text entry achieved 8.73 WPM at the last block of an 80-minute experiment. However, error correction was not required in the experiment, and a higher error rate of 9.1% was presented as expected. Through a long-term study, novice users of keyboard-based Twiddler [27] could reach 26 WPM after 400 minutes and experts could even reach 47 WPM after 25 hours of practicing. Fig. 8 shows that our subjects are improving their speed and accuracy over time, mainly during the first half of the study. A performance improvement is also observed in the icon selection task during the first half, after which the performance reaches a stable state. We can argue that subjects were able to learn the fundamental interactions quickly. However, a long-term experiment is needed to provide more insights of the learnability and the limits of the technique.

In general, the subjects agreed that tactile feedback is useful and helps them feel the visual interface in a more tangible way. However, the vibration pulse for switching focus was less preferred in text entry than in icon selection. Text entry required subjects to continuously switch focus and input characters. Constant vibration pulse became distracting and not preferred. On the other hand, the crossing pulse was perceived as more meaningful and useful in icon selection, in which the vibrations were considered as independent events.

The interface could be optimized through customization. It was customized for a specific user who could not bend individual fingers distinctly enough. Through mild fine-tuning, the system was able to precisely catch the finger movement and the evaluation was successfully completed, which indicates that the system works for people with less autonomous finger-bending capabilities after careful calibration. Moreover, the conflicts in perceiving inverse scrolling/swiping direction could be solved through customization.

Limitations

A glove as the form factor might raise the question of why an additional garment is being worn. We believe that as more wearable devices emerge on the market, people will be more willing to put on additional gadgets. A glove has its challenges, e.g. very hot weather. Other wearables, such as belts, might have similar context-dependent issues. A belt can be considered as already a very common garment but might be challenging to operate if a long jacket is worn that covers it, for example, during cold weather [8]. What we envisioned is an integrated wearable system with more than one sensor on the body, therefore offering more interaction possibilities.

Another challenge in designing hand gestural interaction in a wearable system is false positives, which would require careful design for the activation and closure of the interaction. We use our hand to interact with objects surrounding us everyday. When the glove is worn, it becomes difficult for the system to understand whether the wearer intends to initiate an interaction with the smart glasses or not. Although our system has a preliminary design of active region and action beyond the region could be ignored, further study is still required to enable seamless switching between ordinary daily tasks and operating the smart glasses.

CONCLUSION

This paper addressed the issue that obtrusive interaction would affect the willingness of using smart glasses in public. As current unobtrusive solutions hamper the high degree of freedom manifested on smart glasses, we re-examined the domain of available techniques in deriving design principles for a socially acceptable but versatile interaction technique. We proposed an integrated wearable system in which a sensor-equipped haptic glove could independently track mid-air hand gestures for operating the smart glasses. The results show that, as expected, people can perform the hand gestures regardless of the posture relative to the glasses and are willing to use the system in public.

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