PocketThumb: a Wearable Dual-Sided Touch Interface for Cursor-based Control of Smart-Eyewear

DAVID DOBBELSTEIN, Ulm University
CHRISTIAN WINKLER, Ulm University
GABRIEL HAAS, Ulm University
ENRICO RUKZIO, Ulm University

We present *PocketThumb*, a wearable touch interface for smart-eyewear that is embedded into the fabrics of the front trouser pocket. The interface is reachable from outside and inside of the pocket to allow for a combined dual-sided touch input. The user can control an absolute cursor with their thumb sliding along the fabric from the inside, while at the same time tapping or swiping with fingers from the outside to perform joint gestures. This allows for resting the hand in a comfortable and quickly accessible position, while performing interaction with a high expressiveness that is feasible in mobile scenarios. In a cursor-based target selection study, we found that our introduced dual-sided touch interaction is significantly faster in comparison to common single-sided *absolute* as well as *relative* touch interaction (~19%, resp. ~23% faster). The effect is largest in the mobile conditions *standing* and *walking* (up to ~31% faster).

CCS Concepts: • **Human-centered computing** → **Graphics input devices**; **Pointing devices**;

Additional Key Words and Phrases: Wearable input; dual-sided touch; smart-eyewear

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1 INTRODUCTION

Smart-eyewear allows for information access and retrieval that is potentially always available and quickly accessible when the device is worn. This is envisioned to serve as an augmentation to the user's memory [32] and to enable short bursts of interaction that minimize interruption from the task at hand [2]. With current technology such as Google Glass, however, interaction is yet a problem. Much like other wearable devices, input capabilities are negatively affected by the user's mobility, by sensing capabilities as well as by a limited input space at the device due to a desired miniaturization for wearability.

Smart-eyewear potentially allows for rendering a large virtual display into the user's field of view while maintaining a small form factor. The displayed virtual information, however, is neither tangible nor touchable, which makes direct touch interaction that would be familiar from mobile touch devices

Author's address: D. Dobbelstein, C. Winkler, G. Haas, and E. Rukzio, Ulm University, Institute of Media Informatics, Building O27, James-Franck-Ring, 89081 Ulm, Germany; email: david.dobbelstein@uni-ulm.de.
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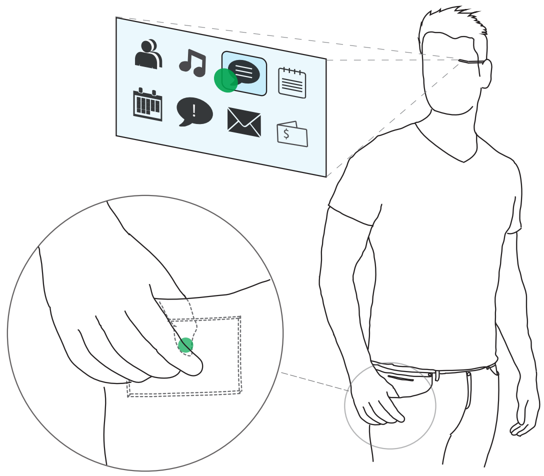


Fig. 1. *PocketThumb* is a dual-sided touch interface embedded into the fabric of the trouser's front pocket. The user controls an absolute cursor with the thumb by sliding along the touch surface from within the pocket (green dot) and can tap to select from outside.

difficult to achieve. Mid-air pointing gestures suffer from arm-fatigue [9] and may cause unwanted social implications, since the pointed virtual content is only visible to the user themselves. For this reason, current devices restrain to indirect interaction techniques, e.g. Google Glass uses two input methods, voice commands and touch input on the side of the eyewear. Both methods, however, are limited in many mobile scenarios. Voice input has the inherent limitation, that it can disturb other people in shared environments, such as lectures and meetings, while touch interaction at the eyewear near the user's temple is limited by the small surface space that only allows for horizontal one-dimensional swiping and thus has a very limited input expressiveness.

Moving touch input from the temple to a more accessible location could enable for richer wearable interaction. Some commercial eyewear products (Epson Moverio, Vuzix and Sony SmartEyeGlass) are shipped with a handheld touch controller as an input device. This however implies that an additional device has to be carried along and retrieved from the pocket for each short burst of interaction, which to some extent contradicts the vision of quick access and enabled microinteractions [2] in mobile contexts. To allow for quick access, the touch interface can instead be worn at the body as a textile interface. By this, the sensing capabilities are interwoven or embedded into clothing to combine fashion and technology [24].

Wearable interfaces allow to quickly interact while being mobile. However due to a lack of available input space and difficulties providing hand stablization in mobile conditions, most wearable touch interaction systems provide only very limited basic gestures, such as dimensional swiping, the detection of a general finger tap or individual fixed buttons. While this can be sufficient for very narrow use cases that do not rely on many different options, such as accepting or declining a phone call, or pausing music, it does not allow for complex interfaces with many options as familiar from other mobile devices that allow to directly point at icons using a finger or indirectly using a cursor.

In this paper, we show the applicability of cursor-based pointing and selection in wearable contexts. We propose to use a combined dual-sided touch interaction at the front pocket of the user's trousers. By sliding the thumb into the pocket, the hand is stabilized into position where a capacitive multi-touch sensor is embedded into the fabric (see Fig. 1). The thumb is always in contact with the interface through the fabric and serves as a pointer that is rendered into the virtual image of the wearable display. The cursor positioning is *absolute*, so that the whole display can be reached by sliding the thumb along the interface. Thus it doesn't need to be lifted from the interface during interaction, which enhances comfort and hand stabilization at the pocket. The other fingers can access the dual-sided touch sensor from outside the pocket to tap for selection and to furthermore perform swiping gestures while jointly pointing with the thumb. We show that this can be used to increase the input expressiveness of wearable touch interaction.

The contributions of our paper are: (1) the *PocketThumb* concept of dual-sided cursor-based pointing located at the pocket, (2) a target selection study highlighting the efficiency in mobile conditions and (3) the introduction of interaction techniques utilizing dual-sided touch for combined pointing and finger gestures.

2 RELATED WORK

2.1 On-Body Interaction Around the Pocket

The pocket and upper thigh area has already been of interest in the literature for wearable touch interaction. Thomas et al. [34] investigated the placement of a body-attached touchpad mouse for wearable displays in terms of body position and body posture and concluded the front of the thigh to be the most appropriate position when sitting, kneeling and standing. Holleis et al. [10] built capacitive touch buttons into various garments. People most often mentioned the thigh area for where to potentially accept wearable touch controls.

By contrast, Profita et al. [27] found the pocket to be less socially acceptable than other body locations due to its proximity to the user's private parts. Dobbelstein et al. [7] investigated the perceived social acceptance of touch interaction on a belt. Participants were most comfortable at the belt area above the front pockets, but least comfortable with the more anterior area located next to it near the belt buckle. This reconfirms that a certain distance to the trousers' fly is crucial to avoid socially sensitive sentiments. Thus, for *PocketThumb* we carefully chose to locate the touch sensor facing most sidewards at the pocket (see Fig. 2), which also made it closer to the resting position of the hand.

Pinstripe [15] is a textile interface that allows to pinch-and-roll a fold of garment between two fingers for continuous one-dimensional input. In a user study on rating potentially suitable areas, multiple participants suggested the trouser pocket as a new location to include, with placing the thumb inside the pocket and the fingers outside. This was unexpected, since this location was technically not a grabbed fold that can be sensed by the prototype implementation. The pocket was included for the evaluation and graded among one of the best locations to perform the pinch-and-roll gesture, especially when walking.

FabriTouch [8] is a flexible touch sensitive fabric integrated into the front thigh area of a pair of trousers. When placed onto clothing and the body however, the flexible touchpad had a significantly reduced input speed compared to a rigid support surface (i.e. a table), so that only basic gestures were feasible (i.e. horizontal and vertical swiping). For this reason for *PocketThumb*, we embedded the capacitive sensor into a thin rigid support casing (see Fig. 4).

Through-pocket techniques have been introduced to interact with a phone without having to take it out of the pocket for quicker access. Tap Input [29] and Whack Gestures [12] utilize the phone's accelerometer to detect taps (resp. whacks) from outside. Both however have only a very limited input vocabulary. Saponas et al. [30] showed that capacitive sensing through fabric is feasible. They re-calibrated a capacitive sensing grid to enable touch interaction through pockets and investigated signal strength for various fabric materials. It was shown that stroke-based gestures could be performed from outside with most fabrics. We built on top of this finding, by embedding a thin capacitive layer in-between trouser and pocket fabric to allow for sensing not only from the outside but also from the inside of the pocket for combined dual-sided interaction.

2.2 Wearable Interaction and Input Expressiveness

So far no wearable interaction technique could be established as *the* state-of-the-art for smart-eyewear, nor for wearable devices in general. It is a huge challenge to design an always available wearable interface that yet allows for rich interaction.

Many interfaces reach for being subtle, e.g. Nenya [1] is a magnetically tracked finger ring that can be turned and by that allows for one-dimensional input, and Nailo [14] is a nail-mounted miniaturized touch sensor that can sense directional swiping of another finger tip ontop of the nail. Fingerpad [5] enables subtle and private pinching gestures of thumb and indexfinger, but requires to mount a magnet and hall sensor ontop the finger nails.

Finger gestures and hand postures can be tracked by a wrist-worn camera [16] or electromyography (EMG) [31]. This, however, is limited to detect a set of distinguishable gestures to avoid false triggering by accident. Seamless interaction is one of the goals of wearable computing [35], however lack of seam can also cause problems of distinguishing planned interaction from natural occuring interaction such as random hand movements, e.g. rich interaction has been proposed for finger gestures [5][17] but a delimiter remains unclear.

An appropriate seam could be to place the input onto the body. iSkin [36] is a flexible silicon-based touch sensor that can be worn on the skin as a tattoo-like visual design, while SkinTrack [39] enables touch tracking directly on the skin by using a continuous high frequency AC signal and a sensing wristband. Holz et al. [11] go one step further by proposing to implant an interface underneath the skin. Google ATAP's Project Jacquard [26] aims to make textile interfaces available to commercial manufactures by optimizing a novel conductive yarn for existing textile weaving technologies. As a first collaboration, a commuter bike jacket by Levi's was announced[1] allowing for simple gestures like tapping and swiping on the sleeve to adjust music volume or to silence a call.

One common characteristic among most wearable touch interaction techniques is the limitation to basic gestures. This fits the vision of microinteractions [2], i.e. of very short interaction lasting only a few seconds, but it remains unclear how basic gestures can be used to create rich interaction that is beyond very simple and restrained use cases, like a music player, to utilize the full potential of smart-eyewear. Hand stabilization during mobile scenarios dictate the wearable interaction to be fairly restricted, so that only simple tasks and applications are feasible. A notable exception is the Twiddler [2], a handheld controller that is strapped into the user's palm to offer a joystick and a chording keyboard for rich pointing and typing interaction. The device is used by experts [18], but has a high learning curve for novices [19].

The main goal of this work is to enable wearable touch input with a high input expressiveness for rich interaction by presenting a cursor-based selection technique that is feasible in mobile scenarios (e.g. when walking). Furthermore, we investigate joint gestures that can be performed while pointing at a target utilizing the dual-sided touch sensor.

2.3 Dual-Sided Interaction

Using the front and backside of a device for combined touch interaction has first been introduced with HybridTouch [33], where a user, operating a PDA with a stylus, could simultaneously scroll with a finger on the rear. Wigdor et al. [37] introduced the concept of *pseudo-transparency*, where the occluded fingers

[1]Project Jacquard. https://atap.google.com/jacquard/
[2]Twiddler 3. http://twiddler.tekgear.com

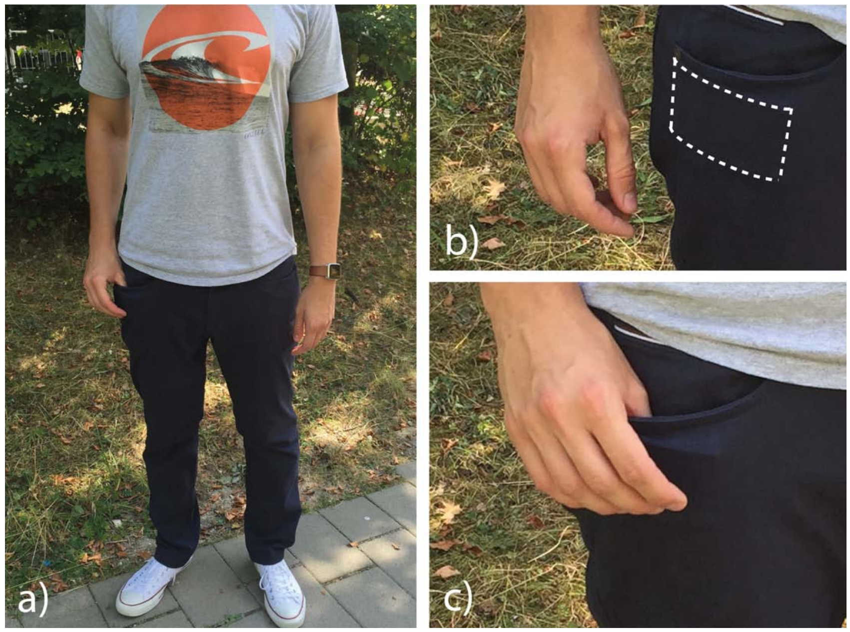


Fig. 2. The *PocketThumb* touch interface is embedded into the fabric of a trouser's pocket (a). The interface (highlighted in white) is in close distance to the resting position of the hand (b). By sliding the thumb into the pocket, the user can start to interact (c).

on the backside are getting visualized onto the display. By this, all fingers could be used for interaction while holding a device for combined multi-touch. Baudisch et al. [3] showed that using the backside for interaction enables touch interaction on very small devices, since positioning the finger on the back doesn't occlude the displayed content.

Wolf et al. [38] investigated thumb-based pointing towards fingers on the rear of a grasped handheld device. Users only see their thumb on the front, but can use it as a proprioceptive reference for the other fingers on the backside. They call this *pinch-through*, since users can target their fingers with their thumb. Similarly, Corsten et al. [6] use haptic landmarks on the back of a phone for proprioceptive pinching used for absolute indirect touch. By this, the user doesn't have to look on the phone and can instead focus on another larger display during screen mirroring.

For handheld devices, dual-sided interaction was introduced to avoid the fat finger problem [3] or to enhance the interaction expressiveness by allowing multiple fingers to jointly interact while holding the device [37]. In the wearable context of *PocketThumb*, the body-worn touch interface doesn't have to be actively held on during interaction, leaving a high degree of freedom for finger movements. Albeit, the positioning of the interface at the pocket allows the user to willingly grasp it to enhance the hand stabilization when being mobile.

3 POCKETTHUMB CONCEPT

We introduce *PocketThumb*, a wearable dual-sided touch interface for smart-eyewear that is embedded into the fabrics of the front trouser pocket. The user can access both sides of the interface by sliding the thumb into the pocket. Inside the pocket, the thumb is then leaning against the fabric which is embedding a capacitive touch sensor (see Fig. 3). The surface area of the thumb is tracked and its tip used as an indirect cursor for selection of targets in a wearable display. By sliding the thumb to the right, to the left, or deeper into the pocket, the whole touch surface can be reached for an absolute 2D-mapping. Unlike a traditional indirect touchpad (e.g. in a laptop), the pointing finger (i.e. the thumb), is not also used for tapping to select a target. Thus it doesn't need to be lifted and by leaning against the interface from inside the pocket can increase the hand stabilization. Instead, the fingers on the outside can tap to perform a selection. This resembles a *pinch-through* gesture (see Fig. 3), where the thumb is used as a proprioceptive point of reference for the other fingers allowing to pinch the thumb blindly [38].

3.1 Access time

Ashbrook [2] highlighted the importance of wearable systems to be quickly accessible to enable an efficient ratio of access and usage time. The *PocketThumb* interface is very quick to access due to its immediate proximity to the resting position of the human hand (see Fig. 2b). Only very little motion is required to blindly slide the thumb into the pocket. Users can as quickly interrupt or abandon the interaction when it is required to return to another task at hand [17].

3.2 Hand stabilization

The saddle joint of the thumb has a higher level of movement-dependent degrees of freedom than any the other finger of the human hand [38]. When interacting with physical objects it stabilizes the grip of the hand [23]. For *PocketThumb*, the thumb can stabilize the hand by anchoring its joint to the pocket. The thumb itself is furthermore stabilized by the fit and tension of the encompassing pocket fabrics. In mobile scenarios, this stabilization can help to increase the input efficiency.

3.3 Social Acceptance

By embedding input sensory into a conventional wearable item such as clothing, interaction can be unobtrusive, which is essentual to use the device in everyday situations [28]. It is a common sight to rest one's hand at the pocket or to unconsciously keep one's hand busy so that we believe that the small movement required to access the pocket for *PocketThumb* can be performed subtly and without calling attention upon the user. The interface itself is concealed in the fabric and potentially unnoticeable to bystanders and by that does not expose itself as a technical input device. Although, it is possible to highlight the interface by adding stitchings or fabric color to communicate its presence.

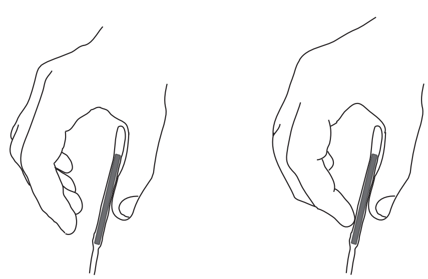


Fig. 3. The thumb is leaning against the rigid touch interface (gray) from within the pocket and serves as a cursor. By tapping with the index finger from the other side, the user can perform a selection.

Dobbelstein et al. [7] showed that for an on-body interface, the willingness of users to interact in public is depending on the interaction length. People feel comfortable interacting for a few seconds, as long as the interaction looks like a random movement, but feel less comfortable when the interaction time is longer. Social acceptance is also a function of time and cultural perception [21]. Wearable devices like headphones and even mechanical wrist watches a century ago only gained social acceptance upon continued exposure, when function and placement proved to be useful [27].

3.4 Interaction seam

Chalmers et al. [4] discussed the notion of *seamlessness* and *seamfulness* in wearable computing, where seamless integration and interaction is seen as a design requirement to focus on the task rather than the device, but can also take away some of its characteristics. For *PocketThumb*, we embrace *seamlessness* when it comes to immediate access to the interface, but take advantage of *seam* to avoid accidental triggering of input. The user might accidentally touch the interface and by that render a cursor, but does not trigger a selection until performing a *pinch-through* gesture from both sides.

We also allow for a *seamless* transition from subtle small gestures to richer interaction with a higher expressiveness when the circumstances allow for it, i.e. combined pointing and gesture interaction utilizing the dual-sidedness of the interface.

4 IMPLEMENTATION

For our *PocketThumb* prototype, we disassembled a Microsoft Touch Mouse and reused its capacitive touch layer as well as inbuilt processing chip and Bluetooth capability. Microsoft provides a sensor API [3] with a 15x13 touch sensing resolution with each pixel providing a measured capacitive intensity between 0 and 255 allowing to interpolate touch positions. We carefully detached the capacitive layer that is glued to the plastic casing beneath the mouse's surface and cut it into shape to match the 16:9 aspect ratio of a Google Glass, leaving a touch resolution of 15x8 pixels.

4.1 Rigid body and integration

The capacitive layer was embedded into a thin 3d-printed casing (82x59x4mm). The sensor response of capacitive sensing relies on a relative change in permittivity [22]. A rigid body encasing the sensor is required to attribute this change to a touch of a capacitive material (i.e. the finger), rather than flexible movement of the capacitive layer. This is unlike resistive touch sensing that allows for flexible touch sensors (e.g. [8][25]), but requires pressure of the finger during touch. The rigidity of the interface allows to feel its dimensions as tactile feedback and serves as a support surface during interaction.

The casing is slightly curved to match the curvature of the thigh and by its dimension taking up only a small portion of the pocket surface to minimize bulging (approx. the width of a common smartphone, but a smaller height and thickness). The interface was embedded between trouser and pocket fabric of a common pair of trousers (see Fig. 4). It was sewn to both fabrics along the rim to create surface tension and to avoid folds that could have created resistance when sliding along a finger.

The processing chip is loosely stored inside the pocket, as well as three small alkaline button cell batteries (LR44) to power the device.

4.2 Dual-Sided Touch on a Single Capacitive Layer

PocketThumb is the first dual-sided touch interface utilizing a single capacitive touch layer for sensing on both sides. The capacitiy intensity of finger touches is similar on both sides. Thus, the sensing grid

[3] Microsoft Touch Mouse Sensor API
https://www.microsoft.com/en-us/download/details.aspx?id=52502

Fig. 4. Integration of the *PocketThumb* interface into a common pair of trousers (a). The interface is slightly curved to match the curvature of the thigh (b). The capacitive layer was embedded into a thin (4mm) rigid body (c) and sewn between trouser (d) and pocket fabric (e).

cannot distinguish and assign its measured signal to a respective side which generates ambiguity. However, its measured intensity is *additive*, so that a *pinch-through* gesture has a high intensity that cannot be reached by only touching from one side (see Fig. 5). By this, no separating and shielding layer is required, enabling the interface to be thinner.

When slid into the pocket, the thumb's surface is in contact with the touch interface, rendering a large blob into the sensor image. We use a weighted average of the bottom of the blob as the cursor position representing the tip of the thumb. As long as in pocket, the thumb remains leaning against the interface even during movement, so that it's *absolute* position is always rendered as an *absolute* cursor into the display. This way, the thumb does not need to be lifted from the interface (as required by *relative* touch interfaces) and can remain leaning against the fabric, which enhances hand stabilization.

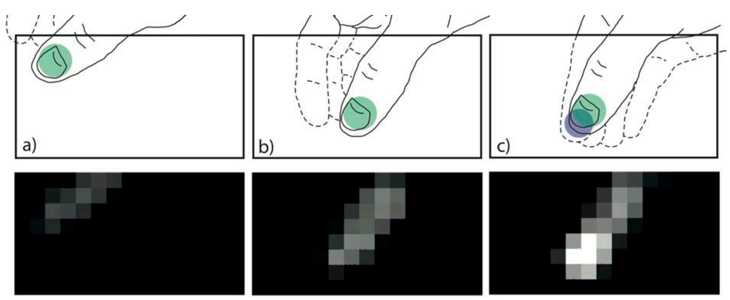


Fig. 5. The thumb is sliding along the interface and by that moving the cursor at its tip (a&b). As soon as the index finger touches the interface, the *pinch* generates a higher capacitive intensity and can thus be detected (c).

The thumb is distinguishable from finger touches by blob size due to the larger surface area in contact. Upon *pinching*, we use the cursor position before the event to prevent cursor shifting during selection. Begin and end of a *pinch* are detected by a rapid surge, resp. fall, in the overall blob intensity of the thumb, as well as the blob's peak (pixel with highest intensity) exceeding a threshold (see Fig. 5).

The processing chip automatically calibrates the sensor's capacitive intensity when turning on, but we also added a software calibration step to normalize the measured intensity along the pocket fabric.

5 TARGET SELECTION STUDY

We conducted a user study to investigate cursor-based target selection with our proposed dual-sided *PocketThumb* interaction. We furthermore were interested in the potential and efficiency of this interaction in mobile conditions. As a baseline, we compare our approach to single-sided *absolute* as well as *relative* touch interaction using the index finger, as familiar from current touch devices: *absolute* touch is known from direct touch interaction with mobile devices, while *relative* touch is frequently used for indirect cursor-based control in touchpads (e.g. in laptop computers). In the context of wearable touch interaction, we compare these techniques positioned at the pocket location for the thigh being the on-body location with the highest touch efficiency [34]. Due to hand stabilization, we expected dual-sided touch interaction to be significantly faster for selecting targets.

The study was conducted as a repeated measures factorial design with two independent variables. As independent variables we chose *interaction technique* (*absolute, relative,* and *dual-sided*) and *mobility* (*standing, walking,* and *sitting*).

5.1 Interaction technique

We implemented the introduced *dual-sided PocketThumb* interaction with the addition that participants could tap anywhere with their index finger to commit a selection. This allowed us to analyze whether participant would follow the mental model of pinching their thumb. For *absolute* as well as *relative* touch interaction, a finger tap (also anywhere on the interface) committed a selection as familiar from existing technology. For all three techniques, the cursor position *before* the finger tap was used for selection, while the selection was committed with the *end* of the tap. All technique were implemented using the same control-display ratio, so that moving a finger from the left to the right edge of the interface resembled the distance of cursor movement from the left to the right edge of the display.

5.2 Mobility

We used three conditions for mobility. For *walking*, participants would walk along a 1.20m wide and 8m long path cornered by tables in an empty seminar room. The path included three side turns and participants would reverse at each end to face an equal amount of left and right turns. We allowed participants to find their own pace where they felt comfortable to move and interact at the same time. For the conditions *sitting* and *standing*, participants were sitting on a chair, respectively standing in the room.

This resulted in 9 combinations (3 *interaction techniques* x 3 *mobilities*) which were presented using a 9x9 latin square for counterbalancing. The dependent variables were *selection time* and *error rate*.

5.3 Target selection

As the wearable display, we used a Google Glass with a display resolution of 640x360px. 8 circular targets were arranged in a 4x2 grid across the display, 160px apart along each axis. Targets had a diameter of 90px and the cursor 80px, respectively, to resemble the size of a finger tip (see Fig. 6). The center of the

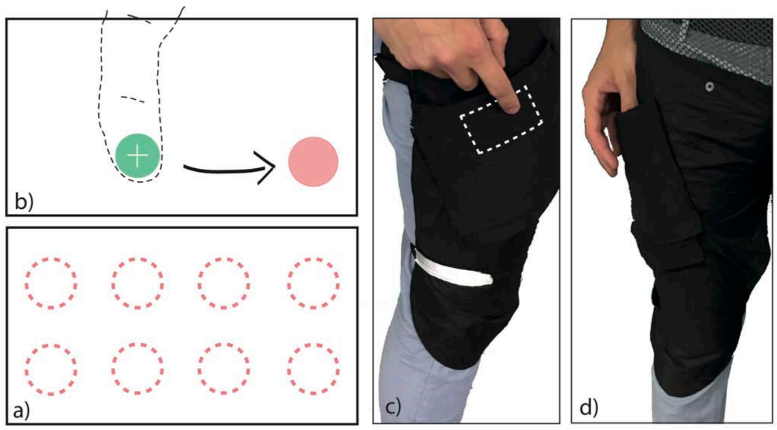


Fig. 6. Target locations were aligned in a 4x2 grid (a). Each target selection consisted of a start and target location along this grid (b). We built a second prototype for the user study that could be strapped ontop of regular trousers. c): Side-view of using the index finger as with *absolute* and *relative* touch interaction. d): Front-view of *dual-sided* touch interaction using the thumb for pointing.

cursor featured a haircross for an actual cursor size of 1px. When positioned over a target, the target was visually highlighted.

For each condition, participants selected at least 56 (8x7) targets, with each target location as the *start* and *destination* of a trial combination. Targets were selected successively after another in random order uniformly distributed with each target selection being automatically the start location of the next trial. We refrained from using a circular arrangement of successive targets (as defined in the ISO9241-9 standard [13]) to make use of the full 16:9 aspect ratio of display and touch interface. If a participant failed to successfully select a target the trial combination was repeated at a later point in time. An intermediate trial was inserted to set the cursor back to a valid start location for the subsequent trial. Intermediate trials were exempt from analysis to maintain a uniform distribution. Each condition was preceded by a random training set of 20 targets for the user to get familiar with the respective *interaction technique* and *mobility*.

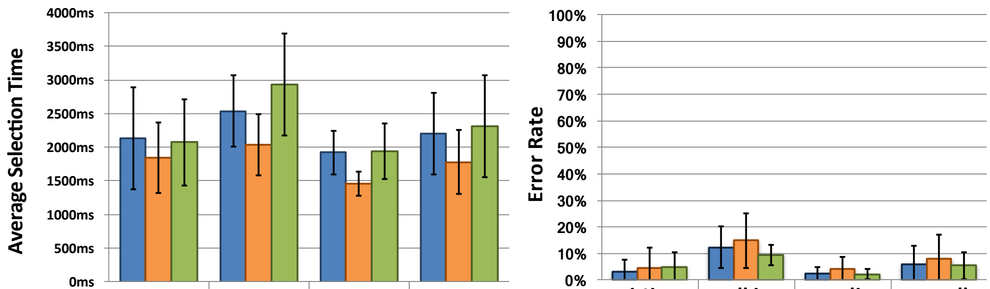
5.4 Prototype

We built a second prototype for the study due to hygienic reasons and because of different clothing sizes of participants. An artificial trouser pocket was sewn onto a pair of rainlegs[4] (see Fig. 6). This way, the prototype could be tightly strapped ontop of the participants' worn trousers.

5.5 Participants

We randomly recruited 18 participants (11 male, 7 female) from our institution with an average age of 27 (range: 22 to 36). All but one had an academic background being either students or had studied at the university. All were right handed and used their dominant hand for interaction. Nine of the participants had never used a head-worn display before and only two stated having experience due to previous studies on the subject of wearable interaction. The study took 45 minutes on average and each participant received €10 as compensation.

[4]Rainlegs. http://www.rainlegs.com/en/home



	sitting	walking	standing	overall
absolute	2135ms	2539ms	1920ms	2198ms
dual-sided	1841ms	2037ms	1461ms	1780ms
relative	2072ms	2934ms	1934ms	2314ms

	sitting	walking	standing	overall
absolute	3.14%	12.32%	2.23%	5.90%
dual-sided	4.64%	14.89%	3.97%	7.83%
relative	4.73%	9.29%	2.17%	5.39%

Fig. 7. Average selection time and error rate for the different variables. (+/- standard deviation of the mean). *Dual-sided* interaction was significantly faster than *absolute* and *relative* touch interaction.

5.6 Results

Our analysis is based on 18 participants selecting targets on 8 locations each from 7 different start locations using 3 different interaction techniques under 3 different mobilities resulting in over 9072 selections.

5.6.1 Selection time. For the selection time, a 3x3 (*interaction technique* x *mobility*) repeated measures ANOVA showed significant main effects for *interaction technique* ($F(2,34)=32.200$, $p<.001$) as well as for *mobility* ($F(2,34)=19.212$, $p<.001$). Pairwise comparisons revealed that users were significantly faster using *dual-sided* touch interaction (M=1780ms, SD=470ms) than using *absolute* (M=2198ms, SD=609ms) and *relative* touch (M=2314ms, SD=755ms) for selecting targets (p<.001 for both pairwise comparisons; Bonferroni corrected). As expected, users selected targets significantly slower when *walking* (M=2503ms, SD=627ms) than when *standing* (M=1772ms, SD=383ms) and *sitting* (M=2016ms, SD=647ms) (p<.001 for both pairwise comparisons; Bonferroni corrected).

Under all conditions, users were fastest using our proposed *dual-sided* touch interaction (see Fig. 7). Interestingly this effect became largest when walking, where it was 24%, resp. 31%, faster than *absolute* and *relative* touch interaction, while in the *sitting* condition it was only 14%, resp. 11%, faster. For *absolute* and *relative* touch users would lift their pointing finger for tapping. This way, the finger would point and select alternately. In contrast, with *dual-sided* interaction, pointing and selection is seperated to thumb and index finger, increasing efficiency. Furthermore, *dual-sided* interaction benefited most from hand stabilization at the pocket, which became most apparent under the *walking* condition. When *sitting* this stabilization was less required since users could rest their hand at the horizontal thigh.

5.6.2 Error rate. An error was defined as a selection attempt that did not hit the target. A 3x3 repeatured measures ANOVA showed significant main effects for *mobility* ($F(2,34)=53.602$, $p<.001$). A pairwise comparison revealed that as expected users made significantly more errors when *walking* (M=12.17%, SD=9.17%) than when *standing* (M=2.79%, SD=5.04%) and *sitting* (M=4.17%, SD=6.97%) (p<.001 for both pairwise comparisons; Bonferroni corrected). Unlike for the selection time, the *interaction technique* had no significant influence on the error rate.

5.6.3 Pinching analysis. We furthermore observed and analyzed the tapping behaviour of participants using the *dual-sided* touch technique. We were interested in whether participants would follow the mental model of pinching their thumb with their index finger or if they would touch anywhere on the touchpad to commit a selection. Users had two strategies: 11 participants moved the thumb mainly via wrist joint rotation (left and right) and arm movement (up and down). In this case the hand moved in union and upon tapping, the selection resembled a *pinch-through* gesture (see Fig. 8a). 7 participants instead moved the thumb mainly via its saddle joint. In this case, the other fingers were moved more independently. As a result the tapping finger had a large offset skewing towards the bottom left where the tip of the index finger is located. (see Fig. 8b). This shows that both interaction is feasible: *pinching* the thumb using the index finger with the thumb as a proprioceptive point of reference, but also moving fingers more independently utilizing the high degree-of-freedom of the thumb's saddle joint.

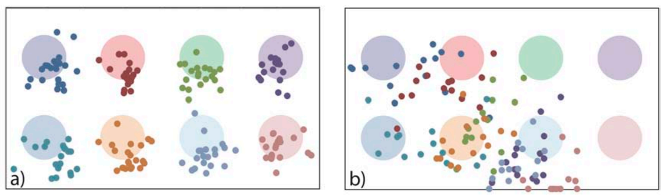


Fig. 8. Landing locations of the index finger when successfully selecting a target with *dual-sided* interaction. Left: A user (P1) following the mental model of *pinching* their thumb, hence the landing location of the index finger is closeby the target location. It is sligthly shifted to the bottom due to the index finger being longer than the thumb (see Fig. 3 and 5c). Right: A user (P8) not *pinching* but tapping anywhere with their index finger, i.e. moving index finger and thumb independently.

5.6.4 Movement within pocket. We looked at selection trials that were based on solely horizontal (160px, 320px, 480px) and vertical (160px) movement of the thumb using the *dual-sided* touch technique. Interestingly horizontal movements of the same distance were faster in all three mobility conditions (see Fig. 9). This suggests that thumb movement via wrist joint rotation (left and right) is more efficient than sliding the thumb slightly more into or out of the pocket to move up or down.

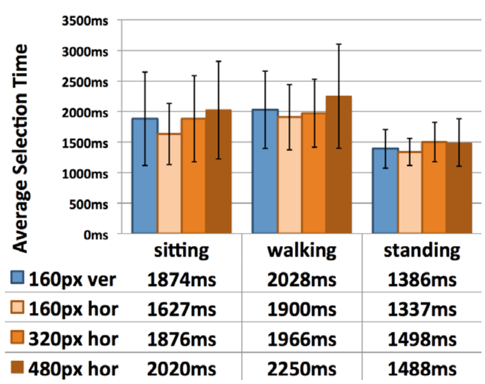


Fig. 9. Average selection time of trials based on solely horizontal or vertical thumb movement of the *dual-sided* touch technique. (+/- standard deviation of the mean). For the same distance, horizontal movement performs better than vertical movement.

6 DUAL-SIDED TOUCH INTERACTION

It was shown that using the thumb for cursor-based pointing on a dual-sided touch interface is feasible. It can however not only be used as a cursor, but also as a spatial point of reference for the remaining hand. Hence, we want to explore the capabilities of using the thumb for pointing and the remaining fingers for jointly performed gestures.

For single-sided touch interaction, the capabilities for pointing and joint gestures are very limited due to the pointing finger reducing the degrees of simultaneous movement of the remaining hand. The only finger that can independently be moved over its saddle joint is the thumb. This is utilized in current touch systems for *pinch-to-zoom*, where thumb and index finger are moving with a high degree of freedom. However, when other fingers are concurrently used, they are very dependent on each other and bound to move together, such as when swiping with multiple fingers into the same direction (e.g. for *scrolling*). This limitation in hand motion leads to users either pointing at a target with a finger or performing a complex gesture, but not doing both at the same time with the same hand.

By using the thumb as a pointer in dual-sided touch interaction, the high degree of freedom of the thumb's saddle joint enables independent movement of the remaining hand and by that concurrently performed gestures. Since the thumb is opposing the other fingers, it is not obstructing their movement and can instead serve as a point of reference in the user interface.

6.1 Spatial tapping

Users can use their thumb as a proprioceptive reference for tapping with their fingers. This is used for the introduced *pinching* gesture, where users aim for the thumb for selection. It is however also possible to aim *beside* the thumb. By this, users can willingly tap left or right of the pointing cursor, which can be used as an analogy to left and right clicking of a mouse to increase the expressiveness of a touch selection.

Spatial tapping can be dinstinguished from the thumb via blob size and touch duration. Also, the capacitive intensity of these touches is lower as when pinching the thumb. With the current implemented absolute mapping of touch interface and display, *spatial tapping* faces limitations when selecting targets near the border. This however can be prevented by extending the touch interface or adjusting the cursor-display ratio.

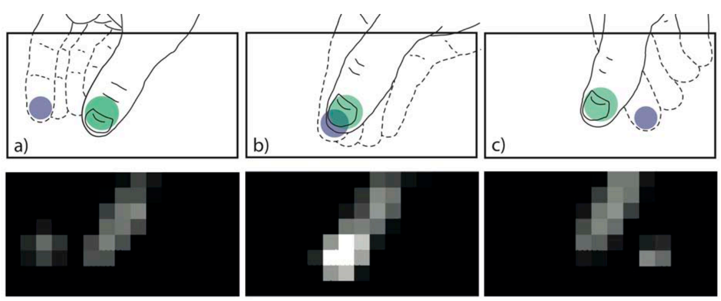


Fig. 10. Users can not only pinch the thumb (b), but also tap left (a) and right (c) of it. The latter enables to *"right-click"* interface elements with the cursor similar to a computer mouse.

6.2 Grab-and-drag

Dragging is a basic operation in many touch-based interfaces to move a target along the display that is pinned to the pointing finger. For the dual-sided *PocketThumb* interface, a target can be grabbed from both sides and then dragged along the display. This corresponds to physical interaction, where the thumb is opposing the rest of the hand and providing force to grab and move an object [23].

The *grab-and-drag* gesture can be distinguished from *pinching*-for-selection by movement of the pinching-blob along the interface.

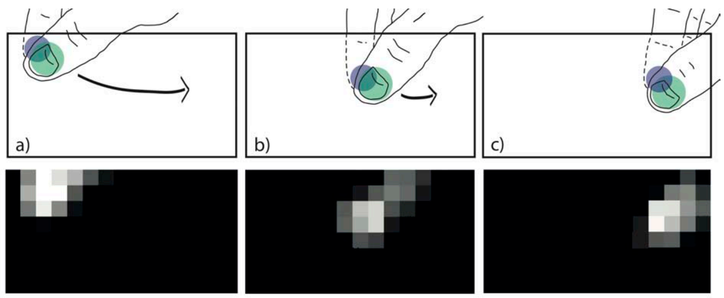


Fig. 11. *Grab-and-drag*. Users can grab (*pinch*) a target and then drag it along the display.

6.3 Pinch-and-circle

When the dominant characteristic of a human grip is *precision*, the gripped object is pinched between index finger and the opposing thumb [23]. This allows to flex and axially rotate both fingers and by that precise manipulations. We utilize this for a *pinch-and-circle* gesture where the user can pinch their thumb and then circle the opposing index finger around it for fast and precise interaction. In an user interface, this allows ro rotate a virtual knob or to quickly navigate through a list by continuous circling without having to lift the finger. The latter resembles continuous scrolling using the click-wheel of an iPod. In contrast, *pinch-and-circle* is performed while simultaneously pointing at a target and thus allows for varying contexts of the gesture.

Pinch-and-circle can be distinguished from *pinching* by the continuous circling movement of the pinching-area (see Fig. 12). This movement can be detected in the sensor image as well as in a computed differential sensor image containing differences to the previous frame. We calculate the imaginary center of the circle movement [20] to identify the angular movement around it.

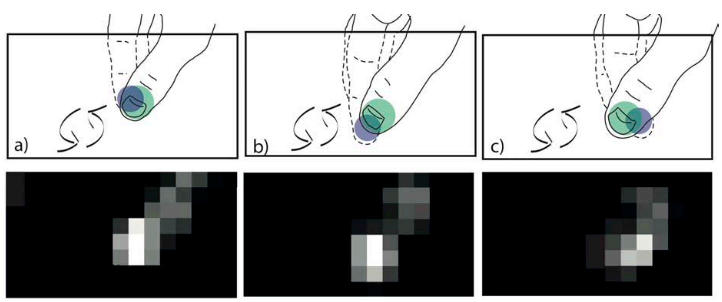


Fig. 12. *Pinch-and-circle* allows for continuous precise manipulation of a target, such as rotating a virtual knob.

6.4 Point-and-swipe

Swiping is commonly used for touch-based interaction to navigate through content such as when scrolling a page or switching through displayed interfaces. For *PocketThumb* users can use their fingers for swiping while pointing with the thumb to quickly navigate through complex menu structures. This can be used to switch the current application (left and right swipe) or to invoke or close menu interfaces related to a pointed target (up and down swipe).

When performing a *swipe* across the thumb, the finger-blob merges with the thumb on the sensor image upon crossing. This is detected by the measured intensity (see. Fig. 13b). The trajectory of the pinching-area resembles the movement of the finger (similar to *point-and-circle*), resolving the ambiguity.

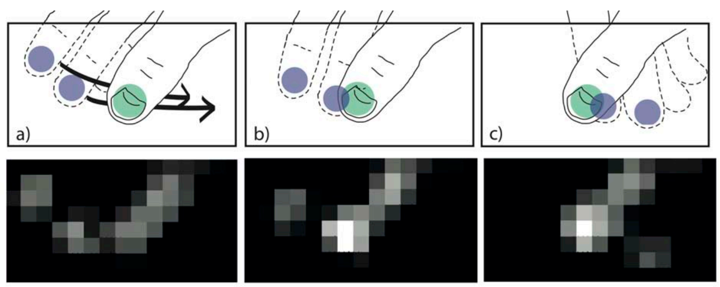


Fig. 13. A user swiping with two fingers while pointing with their thumb.

By performing the proposed gestures (*tapping*, *dragging*, *circling* and *swiping*) with multiple fingers, the input expressiveness can further be increased (e.g. swiping with two or more fingers).

6.5 Limitations

For *PocketThumb*, we utilize a single capacitive layer for dual-sided touch interaction. Using only one sensor for front and back of the interface creates ambiguity which although can be resolved under the assumption that the thumb is the only finger continuously in contact and not moving during finger gestures. Using two individual capacitive layers, as in previous research with handheld devices [38][37], would allow for simultaneous thumb movement, but would also increase the thickness of the interface.

An electronic interface embedded into clothing might raise the question of how the integration of the interface is practicable with varying pairs of trousers (one typically owns more than one pair) and how it might survive the washing process. We believe that the *PocketThumb* interface can be built as an insert of the inner pocket of trousers to be quickly swappable among multiple pairs. This would also allow taking it out before washing.

The trouser pocket as an input location is inherently limited in that not all alternative garments like skirts and dresses contain a pocket. However, we believe that when combining fashion and technology, it is very unlikely to find one solution that aligns with all the great versatility of fashion choices.

6.6 Conclusion and Future Work

PocketThumb is a wearable touch interface embedded into the trousers' front pocket for combined dual-sided interaction utilizing a single capacitive touch layer for rich interaction. The thumb stabilizes the hand from inside the pocket and allows for cursor-based interaction, which in a selection study showed to be more efficient than familiar single-sided touch interaction, especially in mobile conditions such as walking. The input expressiveness can furthermore be increased by using the thumb as a spatial point of reference for finger gestures performed on the front of the interface.

In the future we want to conduct an in-the-wild study to investigate the appropriateness of *PocketThumb* interaction in public. We expect that it is possible to perform subtle selections without drawing attention upon the user, but believe that spacious quickly performed gestures might raise attention. We therefore want to investigate the tradeoff of mobile efficiency and public exposure, and the cost of seamless transition from subtle to rich interaction.

6.7 Acknowledgments

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