EarPut: Augmenting Ear-worn Devices for Ear-based Interaction

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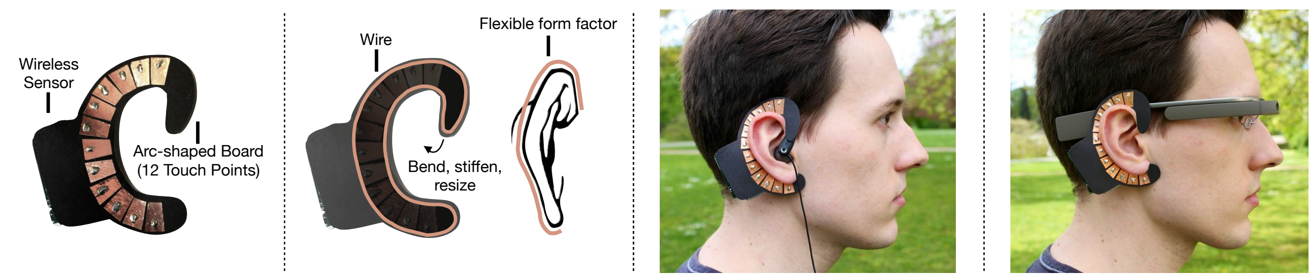

(a) EarPut (b) EarPut (inside) (c) Augmented Earphones (d) Augmented Glass

Figure 1: (a) EarPut is a novel interface concept and hardware prototype that instruments the ear as an interactive surface for touch-based interactions. (b) The flexible form factors allows users to bend and stiffen the earpiece to account for differently shaped ears. (c) EarPut serves as an interaction enabler for otherwise non-interactive devices such as ordinary earphones. (d) It complements interaction capabilities of head-worn devices, e.g. as an extension to Glass' touch-enabled frame.

ABSTRACT

One of the pervasive challenges in mobile interaction is decreasing the visual demand of interfaces towards eyes-free interaction. In this paper, we focus on the unique affordances of the human ear to support one-handed and eyes-free mobile interaction. We present EarPut, a novel interface concept and hardware prototype, which unobtrusively augments a variety of accessories that are worn behind the ear (e.g. headsets or glasses) to instrument the human ear as an interactive surface. The contribution of this paper is three-fold. We contribute (i) results from a controlled experiment with 27 participants, providing empirical evidence that people are able to target salient regions on their ear effectively and precisely, (ii) a first, systematically derived design space for ear-based interaction and (iii) a set of proof of concept EarPut applications that leverage on the design space and embrace mobile media navigation, mobile gaming and smart home interaction.

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Author Keywords

Ear-based interaction; ear-worn; mobile interaction; eyes-free; device augmentation; touch; multi-touch.

ACM Classification Keywords

H.5.2 User interfaces: Graphical user interfaces (GUI), Input devices and strategies, Interaction styles

INTRODUCTION

One of the pervasive challenges in mobile interaction is decreasing the visual demand of interfaces to support eyes-free interaction while being on the move. A large body of research is concerned with instrumenting body parts as interactive surfaces [8, 12, 16, 15, 17]. These works rely primarily on obtrusive and complex instrumentation. Other approaches focus on lightweight instrumentation of specific mobile devices with additional functionality, such as touch interaction on earphone cables [27], on headsets [6], with clothing [19] or hover gestures around devices [20, 23]. In the same vein, recent commercial products such as Google's "Project Glass" provide touch input on the side of the glasses frame. Compared to body-part instrumentation, these approaches have the drawback of device-based interactions: users either have to look for the device (e.g. earphone cable) or are unaware of precise absolute positioning of interface elements due to the lack of visibility (e.g. headsets).

In this paper, we propose to augment accessories that are worn behind the ear (such as glasses, ear hook earphones or headsets, see Figure 1) with a device that unobtrusively instruments the ear as an interactive surface. We call this novel interface concept *EarPut*. It augments arbitrary ear-worn accessories to enable eyes-free, mobile, touch-based interaction on the ear.

Ears are particularly interesting for eyes-free mobile interaction due to four main reasons: (1) ears afford *one-handed interactions*, (2) the human sense of proprioception [29] allows us to do so reliably *without visual attention*, (3) the *ear as an interactive surface* provides more degrees of freedom for interaction than, for example, headphones with integrated controls and (4) touching the ear provides natural tactile feedback. These observations lead to the central questions of this paper: First, how can the specific characteristics of the human ear be capitalized for *precise* and *effective* eyes-free, mobile interaction? Second, how can this understanding be translated into an *interaction language* for ear-based interaction? And last, how can ear-based interactions be leverage as a key input modality for mobile applications?

The remainder of this paper is organized as follows: After discussing related work, we present results of a controlled experiment to assess both precision and effectiveness of touch-based interactions on the ear. The experiment lays ground towards more complex interactions. We then systematically derive a first design space for ear-based interactions with a set of interaction primitives that cover *touch*, *grasp* and *mid-air* interactions. Finally, we discuss the design and hardware implementation of EarPut, showcase implemented applications and outline future work.

RELATED WORK

The work presented in this paper draws on research from the fields of *around* and *on body* interaction as well as *ear-based* interaction. In the following subsections, we situate and illustrate our contributions within this space.

Around the Body Interaction

Work in the area of around the body interaction typically leverages on interfaces that can be used to sense body-based inputs, such as gestures, to interact with digital content in the vicinity of the user's body. This field has been heavily driven by advancements in wearable computing that e.g. created sensors that are sufficiently small to be worn on the body, on garments, and the like.

Various projects mounted cameras on shoes [4] or onto the chest [11, 24] to be able to track body movements. In all cases, the hands of the users are tracked to leverage on hand-based interactions. OmniTouch [14] uses a depth sensing camera and a pico projector that is placed on the user's shoulder to allow interaction on arbitrary surfaces. Another example is Armura [15]: a ubiquitous projection system tracks a user's hands to provide input capabilities. Furthermore, it uses the hands as a projection surface. Others tried to augment devices that users already wear, e.g. rings [2], cords [27] (e.g. for earphones) and clothes [19], with input capabilities.

On-body Interaction

Various research has focussed on instrumenting a user's body as an interactive surface for *on-body interaction*. One prominent example is the work by Harrison et al., where users interact with projected content on the forearm [16]. Another example is a research thrust that focuses on so-called imaginary interfaces. Pioneering research was carried out by Gustafson et al., who investigated how to map a phone UI to a user's palm [12, 13], as well as by Dezfuli et al. who investigated palm-based imaginary interfaces for TV remote interaction [8].

uTrack [7] allows tracking the 3D position of a user's thumb with two magnets on the back of the hand and a magnet on the thumb. Amento [1] has introduced a wristband enhanced with a microphone that can sense the sound produced by the hand such as tapping, rubbing and flicking. Similarly, SenSkin senses skin deformations with multiple small proximity sensors embedded into armbands [26]. Wagner has developed a body-centric design space [31] and investigated the effectiveness of on-body input while pointing towards interactive walls. Another research thrust has focused on enabling on-body interaction through implanting technology into the body for implanted user interfaces [17]. A profound literature overview of body-based interactions can be found in [15, 13].

The systems described above mostly require high instrumentation effort (e.g. implantation) or additional, rather bulky devices to provide interaction capabilities. Our vision is to design and implement an unobtrusive device that instruments the ear as an interactive surface with as little setup as possible.

Ear-based Interactions

There is only a limited amount of previous works that focussed on interaction around the human ear. Earphones have been enhanced in order to recognize hover gestures [23] or touch input on the headphones [6, 34]. Blindsight [21] investigated back of device interaction with mobile phones allowing eyes-free interaction around the human ear. One exemplary application is to allow users to access their calendar with the mobile phone buttons while holding the phone upside down during phone calls. Whisper [10] is a wrist-worn handset compound of a microphone for voice input that also transmits a sound signal from the wristband to the users finger. The user can then listen to the sound by placing or even "plugging" the finger into one's ear.

None of the above projects leveraged the human ear as an interactive surface, e.g. for touch-based interaction. However, the human ear exhibits unique affordances that we believe to be highly beneficial for a variety of applications:

- ***Proprioception:*** The human sense of proprioception [29] enables us to relatively position our own body limbs to each other without looking at them. Thus, a user does not necessarily require a visual interface for on-body interaction. This particularly holds for the human ear.

Natural Tactile Feedback: The mechanoreceptors in the human skin provide means for immediate natural tactile feedback [25]. This applies to both finger and ear during touch-based interaction on the ear.

Eyes-free Interaction: The two observations above lead to eyes-free interaction: Using eyes-free interaction has major advantages in the following categories [33]: environmental (e.g. allowing interaction under bad lighting condition or improve safety in task-switching), social (e.g. avoiding interruption to social activities), device features (e.g. enable operation with no/small screens), and personal (e.g. lower perceived effort).

Easy Access: The human ear is easily accessible, be it for single-handed or bimanual interaction. Single-handed interaction is particularly relevant in mobile settings, when it cannot be taken for granted that a user has both hands to her avail.

These four observations motivated us to conduct a controlled experiment to shed light onto whether and how ear-based user interfaces can be effectively designed to foster eyes-free and easy mobile interaction. The experiment and salient results are described in the following.

CONTROLLED EXPERIMENT

The sense of proprioception allows us to reliably touch our own ear. However, it is unclear how (1) precisely and effectively users can touch certain areas, and equally important, (2) how many different areas can be targeted at all. We investigated these questions in a controlled experiment with 27 participants. The apparatus used in the experiment allowed us to measure both precision and effectiveness of single touch interactions on the ear. The latter is the crucial basis for more advanced interactions. Moreover, we conducted semi-structured interviews to obtain qualitative user feedback.

Apparatus

In order to track and identify touch-based interactions with the ear, we used capacitive sensing based on electrodes that are placed onto an arc-shaped area. Touch recognition was based on the MPR121 Capacitive Touch Sensor [28]. All 12 electrodes of the sensors are connected to 12 distinct areas on the arc. The beginning of the ear helix is mapped to the first electrode and the earlobe to the last electrode. When either a finger or parts of the ear approaches an electrode, the electronic capacity increases, which is detected by the MPR121. We did not design a printed circuit board (PCB) in our first iteration. Instead we used a breakout board of the MPR121 sensor. The breakout board is connected to a Arduino system, which reads the sensor data and forwards is to the computer via USB. The combined device (i.e. the electrode arc and the touch sensor) was then used to augment the ear hook of existing wearable accessories (see Figure 2), allowing for touch-based interactions on the ear arc (i.e. helix and lobe).

Experimental Setup and Methodology

The experiment consisted of simple touch tasks, where the participants had to map a visualized 1D region-based user interface (comparable to a linear menu) to their ear arc and touch the highlighted area (see Figure 3). The beginning of the ear helix is mapped to the top and first menu item and the ear lobe is mapped to the last menu item respectively. Menu items in between are mapped equidistantly along the ear arc.

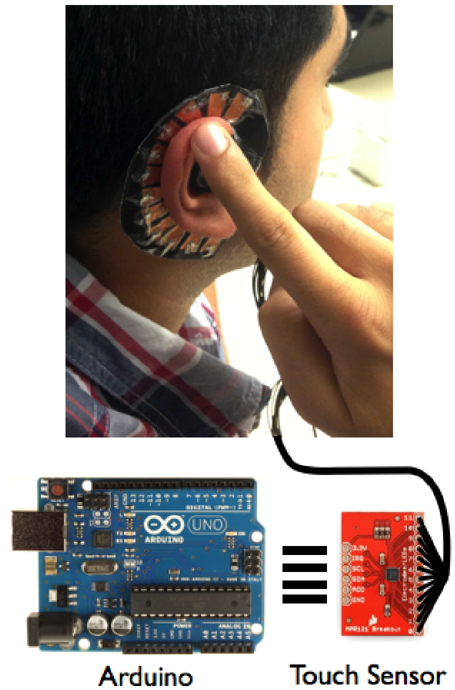

Figure 2: Hardware apparatus used in the controlled experiment.

The experiment was subdivided into two parts: a learning phase and the actual experimental phase. During the learning phase, the on-screen interface provided visual feedback for the touched area. Thus, the participants could familiarize themselves with the functionality of the prototype. During the experimental phase, the on-screen interface only showed the target area and did not provide any visual feedback with respect to the participant's performance. The system advanced to the next target after each touch, regardless of whether the participant had successfully touched the area.

We chose a within-subject design with 27 participants (23m, 4f, avg. 27 years). The independent variable was the

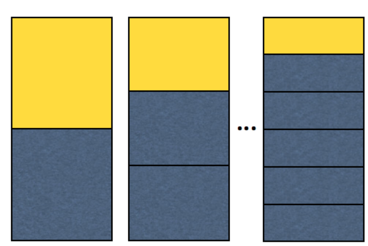

Figure 3: Region-based user interfaces used in the experiment. The UIs were subdivided into 2 to 6 areas, requiring the participants to touch the highlighted areas.

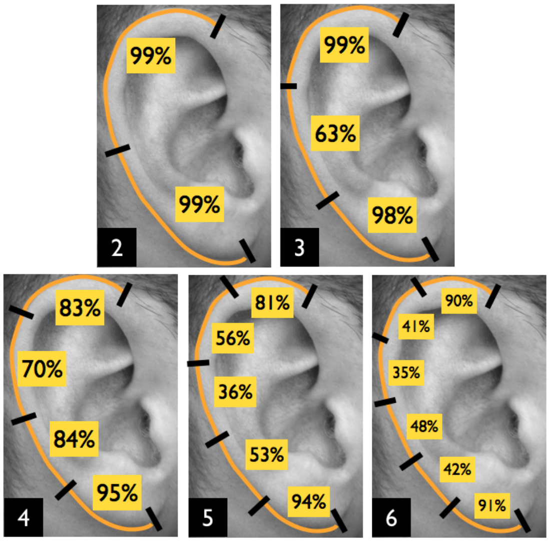

Figure 4: The average touch effectiveness for each individual area per region-based user interface.The numbers in the lower left corners indicate the number of areas.

number of areas, considering region-based interfaces with 2 to 6 different equally-sized areas. The dependent variable was the success rate of a user touching the highlighted region. During the experiment, the participants were seated. After each task, we asked the participants to touch the table to prevent relative positioning of the touches. Each session lasted about 15 minutes, excluding the learning phase.

Results

For each region-based interface, the participants had to touch each individual area 3 times (e.g. the interface with 2 regions resulted in 2x3 touch tasks). The order of the target areas was fully counterbalanced. Overall, each participant had to complete 60 [1] touch tasks leading to 60 x 27 = 1620 data points in total for the experimental phase. We did not collect any data during the learning phase.

The average touch effectiveness of the individual touch areas for each region-based user interface is visualized in Figure 4. In the case of 2 areas, the participants touched both areas equally well. In the other conditions, the upper and lower parts of the ear arc were touched more effectively than the parts in the middle. Across all conditions, the average effectiveness for touching the ear lobe was above 90% and at least 81% for the upper part of the ear helix.

Figure 5 shows the average effectiveness of targeting areas per region-based user interface. The effectiveness decreased monotonically over all conditions. The average effectiveness is above 80% for region-based interfaces with up to 4 areas and decreases to 64% for 5 and 58% for 6 areas, respectively. ANOVA tests with Bonferroni post-hoc tests revealed that all differences but the one between 3 and 4 areas are statistically significant ($p<0.001$). The decrease in effectiveness is in line with qualitative findings from the semi-structured interviews.

[1] 60 = 3 repetitions x (2 + 3 + 4 + 5 + 6 areas)

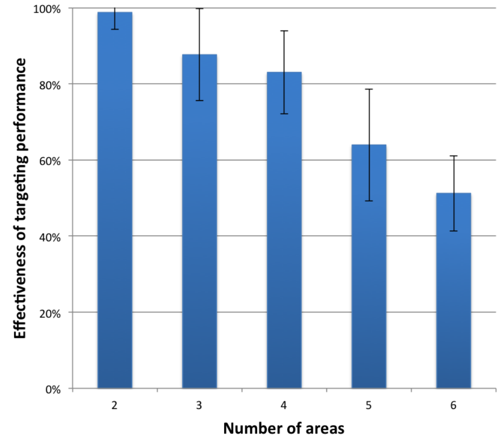

Figure 5: The average effectiveness of targeting areas per region-based user interface.

The participants stated that it was hard to precisely distinguish between more than 4 areas. Moreover, despite region-based interfaces, the participants envisioned more advanced interactions, such as gestures, multi-touch or grasping.

Discussion

The results from the experiment show that users can touch certain areas of their ear arc precisely and effectively, such as the ear lobe (>90%). For an odd total amount of areas, the middle part of the ear arc is more difficult to touch precisely. Thus, both upper and lower parts of the ear arc afford more fine-grained interaction than the middle part (see Figure 4). Consequently, interface elements should not be distributed equidistantly alongside the ear arc, but instead elements placed at the middle part of the arc should be larger than those at the ends.

This finding is also interesting for continuous interactions, such as sliding along the ear arc. To give a simple example: the results suggest that gestures starting at the outer parts of the arc (either lobe or upper helix) toward the middle tend to be less error-prone than gestures starting in the middle.

Furthermore, our results provide evidence that users can distinguish up to 4 salient regions on their ear arc effectively (>83%). We envision this to be leveraged as region-based shortcuts, as well as for multi-touch interactions on multiple areas for future ear-based interfaces.

In the interviews, the participants repeatedly suggested to use a variety of other atomic interaction primitives, besides single touch, for ear-based interaction. We transcribed the interviews, selected salient mentions of primitives and analyzed them using an open coding approach. This enabled us to get a first, systematic understanding of the interaction design space, which we present in the following.

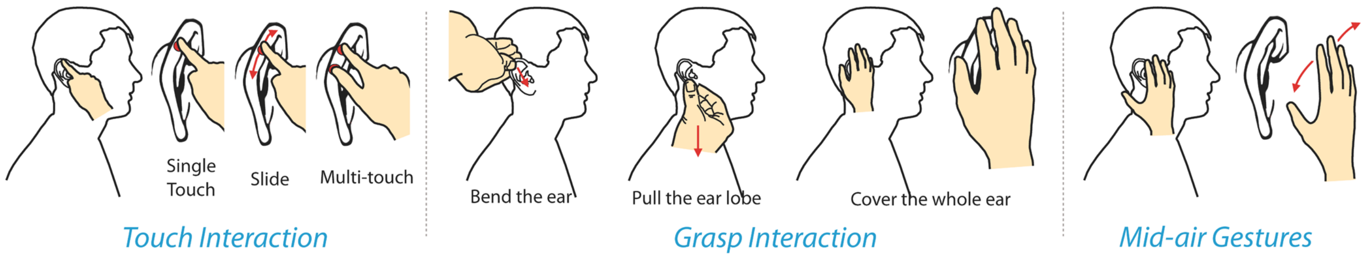

Figure 6: Input Design Space for Ear-based Interaction

Interaction Design Space

The coding yielded three major categories for ear-based interaction: (1) touch interaction, (2) grasp interaction, and (3) mid-air gestures. Within these, various interaction primitives can be used to facilitate ear-based interactions. Figure 6 illustrates both categories and interaction primitives.

Touch Interaction: The whole ear arc can be used for *single touch* and *multi-touch* input, enabling the user to perform discrete and continuous gestures similar to those found in traditional touch surfaces, e.g., a one-finger *sliding* gesture or a two-finger *pinch*.

Grasp Interaction: Grasp interactions comprise *bending* or *pulling* the earlobe or the upper helix, as well as *covering* the whole ear. The deformation of the ear is sensed and can be used as both continuous and discrete input.

Mid-Air Gestures: Mid-air gestures close to the ear can be sensed and used as continuous or discrete input, similar to [23]. *Hovering* with the hand above the ear can be sensed for distance-based interactions. Then *swiping* the hand near the ear allows for directional interactions.

EARPUT

The results from the controlled experiment underline the general feasibility of ear-based interactions (partially published in non-archival work [22]). Building upon these results, we designed and implemented EarPut: a novel interface concept and hardware prototype that instruments the ear as an interactive surface for eyes-free, mobile interaction. It can serve as both an interaction enabler for otherwise non-interactive devices such as ordinary glasses or earphones (cf. Figure 1c) and a complement to existing interaction capabilities of head-worn devices, serving as a touch-based extension to e.g. Glass' touch-enabled spectacle frame (cf. Figure 1d).

Concept

The main concept of EarPut is that of a wearable device that can be easily *attached to* and *detached from* a variety of accessories that are worn behind the ear. Attaching it enables additional interactive functionality (cf. interaction design space) with respect to the augmented object. Detaching it removes the functionality. EarPut is envisioned as a flexible piece of hardware that users can bend, resize and stiffen to account for differently shaped ears.

The general objective was to develop a hardware prototype that is unobtrusive, lightweight and that requires little setup. Since EarPut primarily focuses on input, we envision it as a companion device that piggybacks onto existing feedback mechanisms, e.g. to wirelessly trigger auditory or vibro-tactile feedback through actuators of a smartphone.

Hardware Design

To achieve an appropriate hardware footprint, we developed a custom PCB (see Figure 7). The main components of the board are an MPR121 Capacitive Touch Sensor [28] used for recognizing touch events, a Bluegiga BLE 113 for Bluetooth communication [5], and an Atmel ATmega1284P microcontroller [3] to coordinate the measurement and the communication. The EarPut device is powered with a lithium-polymer battery 3.7V at 110mAh.

We use a similar approach as in the controlled experiment to identify touch-based interactions with the ear. As in the experimental apparatus, electrodes are placed onto an arc-shaped cardboard area (see Figure 1a). The arc is then used to augment devices worn on or behind the ear. This enables interaction along the entire ear arc. The electrodes on the ear arc are connected to the circuit board through a ribbon cable. Wires run within the earpiece to support a flexible adjustment of the earpiece in terms of bending, stiffening and slight re-sizing (see Figure 1b).

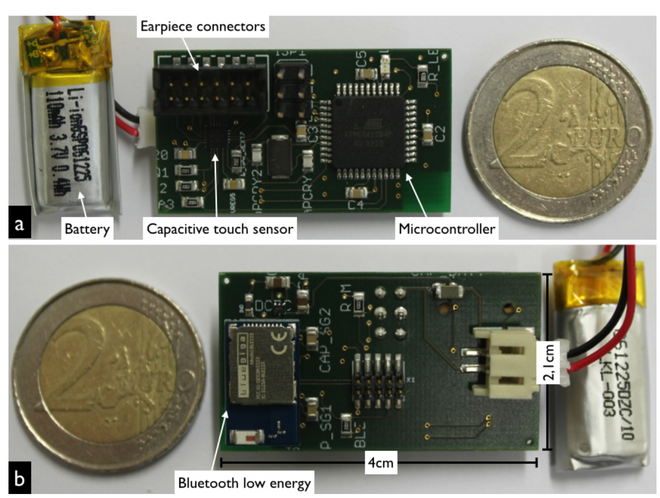

Figure 7: EarPut circuit board (a) front and (b) back

Limitations

The current hardware implementation leverages capacitive sensing. Thus, it can only be used for touch-based interaction if not covered by e.g. objects worn on the head such as hats or caps. A possible solution to this could be to implement an additional proximity sensor to temporarily switch the sensing unit off and back on again, respectively.

Furthermore, the current version of the EarPut hardware does not support mid-air gestures. Similarly to [23], proximity sensors could be added to overcome this limitation.

The current earpiece design has only limited resizing capabilities due to the utilized material. In the future, more flexible material [32] could be used to also allow for more extensive resizing operations.

EARPUT APPLICATIONS

The interaction primitives outlined in the design space can be combined to more complex interactions in various applications. Particularly salient are remote control applications such as mobile media appliances. When listening to music on the go, users often wear earphones with an integrated remote, enabling them to control their phone without visual attention. However, such interfaces are rather clumsy to use: The user has to find the remote and identify the right key based on her sense of touch. EarPut can provide more direct interaction based on the users sense of proprioception.

In the following, we present three salient application scenarios for EarPut: (a) Interaction with mobile media appliances, (b) control of home appliances and (c) mobile gaming. The implementations assume EarPut to be connected to a Bluetooth-enabled smartphone. The applications are also showcased in the video figure accompanying this paper (please see **`http://goo.gl/Vz4WxZ`**).

Remote Control of Mobile Devices: Music Player

EarPut is highly suitable for remotely controlling mobile devices around the user. In the following, we exemplary show how to leverage the interaction primitives to design a music player application. We implemented the music player interface for the current EarPut device that connects to an Android phone, controlling the stock Android 4.3 media player.

Basic Navigation

Simple navigation tasks in a media player comprise *play/pause*, navigation to the *next* or *previous* track and adjustment of the *playback speed* (i.e. fast-forward/rewind). We map these tasks to touch interactions as shown in Figure 8a. The ear is subdivided into three regions. A single touch onto the middle region corresponds to play/pause. Tapping the upper or lower regions lets the user navigate within the playlist to the next or previous track. The playback speed can be adjusted by multi-touch gestures in two steps: First, the seeking mode is enabled by tapping the upper and lower region simultaneously (see Figure 8b). Second, by holding one of the two touches, the user controls the seeking direction. The user fast-forwards by releasing the lower tap and holding the upper one (see Figure 8b top) or rewinds by releasing the upper tap and holding the lower one, respectively (see Figure 8b bottom).

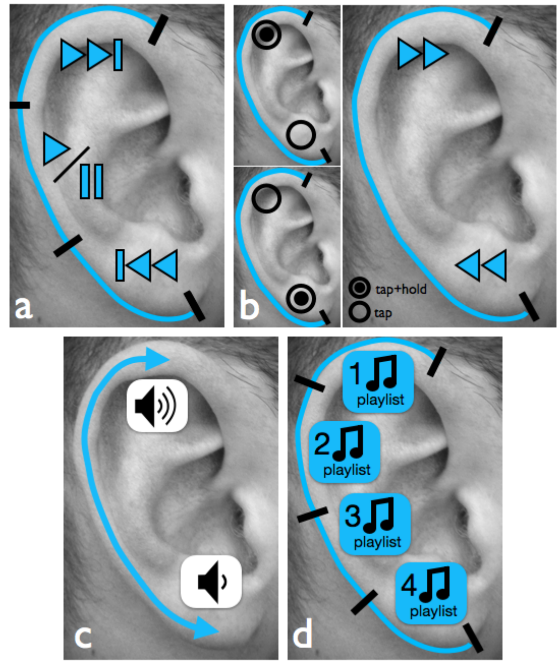

Figure 8: Interaction primitives are mapped to design a music player: (a) single touch, (b) multi-touch, (c) slide gestures and (d) grasp and single touch interactions.

Volume Control

Adjusting the playback volume maps naturally to the following sliding interactions alongside the ear arc: Sliding from the ear lobe toward the upper ear helix translates to *increasing* the volume; sliding from the ear helix downwards toward the ear lobe translates to *decreasing* the volume (see Fig. 8c).

Quick Access to Shortcuts

As a more advanced task, we envision particular regions on the ear to serve as shortcuts to previously defined playlists. In line with the findings from our experiment, we subdivide the ear arc into 4 salient regions (see figure 8d). A single touch onto one of the regions then switches to the corresponding playlist and starts playback.

We employ a cover gesture to allow for an easy mode switch between basic navigation tasks and shortcut access. This is necessary since both interactions employ region-based touch interaction. By covering the whole ear, the user switches between the two modes. The current mode is then indicated through auditory feedback. Similarly, the user could map other interaction primitives such as bending/pulling the ear or performing mid-air gestures to custom tasks individually.

Controlling Home Appliances

We envision EarPut to be particularly helpful for controlling home appliances as an omnipresent and eyes-free input devices. In the following, we first show how interaction primitives from our design space could be mapped onto the ear, e.g. to select and switch between home appliances. Second, we present an EarPut interface for two application scenarios at home: controlling light sources and a TV remote control.

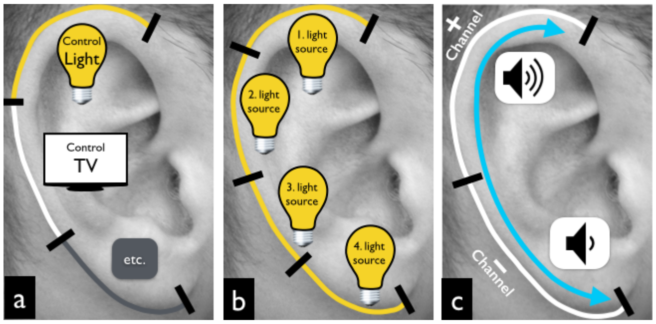

Figure 9: (a) A user can select home appliances via single touch on a specific region on the ear (b) single or multi-touch can switch a light source on or off (c) single touch controls the channels and slide gesture controls the volume.

Select and Switch Control between Home Appliances

A cover gesture wakes up the EarPut in the *home appliances selection mode*. The user is then able to select up to four different home appliances on their ear arc by a single tap on the corresponding region (see Figure 9a). After selecting an appliance a grasp gesture can bring the user back to the home appliances selection mode.

Control Multiple Light Sources

The user can control up to four light sources. EarPut could serve as an interface to Internet-connected light bulbs such as Philips Hue [18]. Multiple light sources can then be mapped to a linear menu (cf. setup in controlled experiment). A single or multi-touch on one or more regions then selects the corresponding light sources (see Figure 9b). A sliding gesture alongside the ear arc then controls the light intensity.

Basic TV Remote Control

Probably the most frequently used functions of a TV remote are are switching channels and changing volume. EarPut can serve as an interface for Samsung Smart TVs (inspired by [9]). Navigation controls are mapped to a two region interface (see Fig. 9c) and the volume is controlled with a slide gesture.

Gaming: Simon Says

Another application scenario for EarPut is mobile gaming. We implemented a game inspired by "Simon Says" [30].

In Simon Says, the player has to memorize a sequence of colors. There are four different colors in total. The colors are presented in a sequence and for each correctly recalled color, another color is appended to the sequence. For example, when the game starts, the game shows the color blue which the player recalls correctly by selecting blue in the interface. In the next round, the color red is appended and the sequence blue → red is therefore shown, and so forth. Consequently, the sequence becomes longer each turn and the game puts the working memory of the player to the test.

For playing the game using EarPut, four different regions on the ear arc are mapped to four different buttons (see Figure 10; visual interface only shown for example). Instead of colors, the regions are enumerated from one to four. When the game starts, the sequence to remember is read to the user

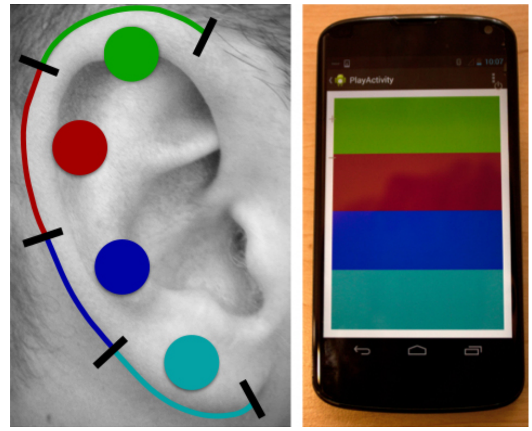

Figure 10: Simon Says game: mapping of the ear (left) to the mobile device (right).

through auditory feedback. The user has to repeat the sequence by pressing the corresponding area on the ear arc. Hence, the user can play the game in an eyes-free manner, e.g. on the go, by simply listening to the audio cues.

CONCLUSION

In this paper, we contributed EarPut, a novel interface concept and hardware prototype that instruments the ear as an interactive surface for touch-based interactions. The central idea is to unobtrusively augment a variety of accessories that are worn behind the ear. EarPut can thus serve as both an interaction enabler for otherwise non-interactive devices such as ordinary glasses or earphones and a complement to existing interaction capabilities of head-worn devices, serving as a touch-based extension to e.g. Glass' touch-enabled frame.

In a controlled experiment with 27 participants, we assessed both precision and effectiveness of single touch interactions with EarPut. The results provide empirical evidence that people are able to distinguish up to 4 salient areas on their ear arc. The results show that the upper and lower parts of the ear arc afford more precise interaction than the middle part. This finding is particularly interesting for region-based interfaces and suggests that a non-equidistant spacing of interface elements alongside the ear arc is more effective.

Based on qualitative findings from post-experiment interviews, we systemically set up a first interaction design space for ear-based interaction. We showed how the primitive interactions can be combined to design and implement a variety of ear-based applications: a media player, a mobile game, a TV remote and a remote control for home automation.

As future work we will further investigate how to optimize region-based user interfaces for the ear arc, particularly considering non-equidistant spacing of interface elements. Also, it remains to be investigated how EarPut can effectively serve as an additional input dimension to already highly interactive ear-worn devices such as Google Glass. Furthermore, future work should investigate how to design interfaces for varying feedback modalities provided by the ear-worn devices EarPut piggybacks onto (e.g. while a headset supports auditory feedback, spectacles provide literally no feedback channel). Last, we envision the functionality of EarPut to be adapted depending on the augmented accessory (e.g. a music control for earphones, an everyday home appliance control for ordinary glasses), enabling ubiquitous and context-adaptive personal eyes-free remote interaction.

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