Back-of-Device Force Feedback Improves Touchscreen Interaction for Mobile Devices

Jens Maiero, David Eibich, Ernst Kruijff, André Hinkenjann, Wolfgang Stuerzlinger, Hrvoje Benko, Gheorghita Ghinea

Abstract—Touchscreen interaction suffers from occlusion problems as fingers can cover small targets, which makes interacting with such targets challenging. To improve touchscreen interaction accuracy and consequently the selection of small or hidden objects we introduce a back-of-device force feedback system for smartphones. We introduce a new solution that combines force feedback on the back to enhance touch input on the front screen. The interface includes three actuated pins at the back of a smartphone. All three pins are driven by micro servos and can be actuated up to a frequency of 50Hz and a maximum amplitude of 5mm. In a first psychophysical user study, we explored the limits of the system. Thereafter, we demonstrate through a performance study that the proposed interface can enhance touchscreen interaction precision, compared to state-of-the-art methods. In particular the selection of small targets performed remarkably well with force feedback. The study additionally shows that users subjectively felt significantly more accurate with force feedback. Based on the results, we discuss back-to-front feedback design issues and demonstrate potential applications through several prototypical concepts to illustrate where the back-of-device force feedback could be beneficial.

Index Terms—User interfaces - Haptic interfaces, Human computer interaction - Back-of-device interaction, Mobile applications

1 Introduction

Researchers have been fascinated with the possibilities of back-of-device (BoD) interaction, since the appearance of the first prototypes about a decade ago. Motivated by efforts to minimize screen occlusion through fingers, early prototypes like LucidTouch [1] made use of pseudo-transparent displays. At the back, users could interact with the full screen content using touch input without occluding content. One hope was that back interaction could compensate for poor pointing performance, especially for the selection of smaller objects.

Within this paper, we take an alternative approach to BoD interaction. Instead of touch input on the back, we explore the potential of force feedback at the back to enhance thumb-based touch interaction on the front-of-the-device (FoD) screen. Adding force feedback to smartphones has great potential, as many force events currently are substituted through tactile (vibration) or visual-only feedback mechanisms, which affects the perception of those events [2]. Consider pressing a button: in real life, we receive physical (force) and tactile (surface) feedback while pressing the button down. With current smartphones, usually audio-tactile feedback ("click") and a change in button color indicates that a button is pressed, which is not compliant with real-world interaction. Based on previous work, we assume that force feedback could affect performance positively, in particular for thumb-based interaction that often suffers from occlusions. Moreover, as we will investigate in our studies, force feedback might improve performance in tasks that, in the real world, do not depend on such feedback.

Studies have shown that tactile feedback can increase performance in target selection tasks [3] [4]. However, the exploration of force feedback in smartphones is rare. A major cause is that adding force feedback actuators to the front display has many physical form factor constraints, which makes physical construction challenging. For example, mounting an actuator on the front would occlude part of the display, and likely hinder input. In contrast, the main research problem our approach faces is how well force feedback at the BoD works.

1.1 HapticPhone contributions

Through a novel device for exploring the haptic design space on the back of smartphones, this paper presents a new BoD approach (see Figure 1). We use BoD feedback to overcome physical form-factor challenges for adding force feedback to the front of the device and explore this novel design space by looking into the human and technical aspects of our new interface approach. The direction of this haptic feedback method is orthogonal to the back of the mobile phone, similar to a pin moving out of the back and pushing the finger away.

The four core contributions of this paper are:

- A novel *interface and feedback metaphor*, which extends a smartphone with relayed back-to-front force feedback to enhance touch-based interaction on the front screen.

- *Jens Maiero, David Eibich, Ernst Kruijff and André Hinkenjann are with the Institute of Visual Computing and the Department of Computer Science at the Bonn-Rhein-Sieg University of Applied Sciences, Germany. E-mail: forename.surname@h-brs.de*
- *Wolfgang Stuerzlinger is with the School of Interactive Arts + Technology at Simon Fraser University in Vancouver, Canada. E-mail: w_s@sfu.ca*
- *Hrvoje Benko is with Facebook Reality Lab, US. E-mail: hbenko@gmail.com*
- *Gheorghita Ghinea and Jens Maiero are with Department of Computer Science, Brunel University, London, U.K. E-mail: george.ghinea@brunel.ac.uk, jens.maiero@brunel.ac.uk*

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- A *psychophysical perception study* that confirmed our force feedback mechanisms produces a Weber Fraction (8.29 %) comparable to similar force devices, confirming the rendering effectiveness of our design.
- A *performance study*, which illustrates that relayed back-to-front force feedback can improve accuracy, even in comparison to vibration. The performed study shows that our approach can improve interaction accuracy up to a factor of 1.5 (selection) and up to 1.3 (drag-and-drop), compared to conditions without additional feedback (visual-only).
- Several *applications* that explore how back-of-device force feedback can be used for higher-level functionality.

2 Related Work

2.1 Back-of-Device Interaction

Touch is a compelling input modality for smartphones. Yet, it suffers from limitations as the user's finger can easily occlude screen content. To overcome this limitation, Wigdor et al. presented a system called LucidTouch to explore how BoD interaction can overcome the occlusion problem [1]. Extending results from earlier prototypes, this paper ignited interest in BoD interaction. Similar systems include Wigdor et al.'s "under the table" interaction [13], the HybridTouch system [5] that explored manipulation on the front and the back of a PDA, and the Behind Touch system [6] studying text input at the back. Furthermore, LimpiDual offered a transparent display system with two touchscreens, one at the front and one at the back [7]. Fukumoto introduced a passive soft-gel based transparent film that provides a button-push feeling, which can be attached to either the front or back of the device [14].

Through an initial study, Wigdor et al. showed that with their pseudo-transparent display approach, users preferred BoD interaction due to reduced occlusion, higher precision and the possibility of multi-finger input [1]. Since then, various studies have looked into different interaction aspects of BoD interaction, including gestural interaction [15] [16], the performance of dual touch input [7], the performance of hand postures in front and back interaction [17], and text input [18]. Others have explored simultaneous back-and-front-of-device interaction [9], [19]. BoD interaction also affords the creation of smaller scale interactive display devices, as identified in [8]. Overall, studies underlined that BoD interaction can improve performance in a number of aspects.

Finally, UniPhone explored the use of auxiliary finger input in one-handed mobile interaction, which showed that pressure-sensing areas at the edge (instead of the back) of a smartphone can improve one-handed interaction [20].

2.2 Haptic Feedback on Mobile Devices

Combining force feedback with smartphone interaction is a largely unexplored area. While flexible media systems such as Flexpad [21] and jamming interfaces [22] have explored the potential of haptic and elastic input [23], these systems have limitations in terms of actuation and feedback. More accurately controllable haptic-based methods have been demonstrated for other actuated devices, especially mouse-like input [24].

Other work has illustrated promising results for under-finger force actuators using rod-like systems [3]. Akamatsu showed that tactile feedback can improve completion time when selecting targets with a mouse [25]. Our approach is related to this way of actuation, as we support similar finger-tip based feedback. In contrast to force feedback, tactile interaction has been explored far more intensely, mostly using built-in vibrotactors of mobile devices or tactile screen overlays. Tactile interaction has been shown to improve task performance on touchscreen displays [26], for example for virtual keyboard interaction [11], button clicks [27] and in combination with simultaneous screen operation [28]. Some researchers also demonstrated improvement in task performance under cognitive load [29]. Furthermore, tactile cues have been used to simulate various surface [30] [31] or friction characteristics [32]. Finally, some researchers have looked into passive shapes, like wedges or dimples at the back of a phone, to improve performance [33], which has some relevance to the shape of our actuator used in our pilot studies.

Another area that is closely related to BoD interaction are systems that use tactile grids on smartphones, e.g., [4] [34]. The usage of tactile grids supports not only eyes-on, but also eyes-off interaction, i.e., blind operation of a smartphone. Non-visual interaction has also been explored previously, e.g., [35] [36] [37] [38], showing the potential of using such methods for in-the-pocket operation of a smartphone, or for visually impaired people [39]. Yannier et al. have shown that haptic feedback on the back can improve children's reading experience and make it more memorable [40]. Finally, while we use servos for actuation, our work resembles other actuated display systems such as TouchMover [41] and ForceTab [42]. However, due to the form-factor and way of actuation, our approach is principally different. A few researchers have also looked into actuation at the side of mobile devices. The Haptic Edge Display introduced a linear array of tactile pixels at the side of a smartphone and presented a psychophysical study to measure ideal resolutions [12]. In general BoD haptic feedback has been used for, e.g., shape recognition, in pocket interaction, and GUI interaction. In contrast, our proposed prototype introduces a novel set of application areas and a performance study to demonstrate that haptic feedback is able to improve touch precision.

2.3 Thumb-based Interaction

In our interface approach, we build on previous findings in thumb-based interaction [43] [44] [45]. Current research focuses on improving interactive metaphors that consider the physical limitations of the thumb. For instance, a novel way to increase the thumb interaction space [46] was motivated by three problems of thumb-based interaction: reachability, occlusions and limited multi-touch interaction. This approach also took the space above the smartphone into account. Furthermore, the system presented by [43] uses the contact size of the thumb on the touchscreen for single-handed mobile interaction. We extend the state of the art in this area by implementing a novel approach to relay

TABLE 1
Classification of state-of-the-art approaches to show how the back of the device is used (input/feedback) and which applications or goals are targeted by each approach, presented in tabular format.

Approach	Input		Feedback		Research focus/Context				
	touch	pressure	tactile	force	precision	occlusion	manipulation	typing	eyes-free
Wigdor et al. [1]	x	-	-	-	x	x	x	-	-
Sugimoto et al. [5]	x	-	-	-	-	x	x	x	-
Hiraoka et al. [6]	x	-	-	-	-	x	-	-	-
Iwabuchi et al. [7]	x	-	-	-	-	x	-	-	-
Baudisch et al. [8]	x	-	-	-	x	x	-	-	-
Liang et al. [9]	x	-	-	-	-	-	x	-	-
Corsten et al. [10]	-	x	-	-	-	x	-	x	
Corsten et al. [4]	-	-	x	-	-	-	-	-	x
Brewster et al. [11]	-	-	x	-	-	-	-	x	-
Jang et al. [12]	-	-	-	x(edge)	-	-	-	-	x
Our Approach	-	-	-	x	x	x	-	x	x

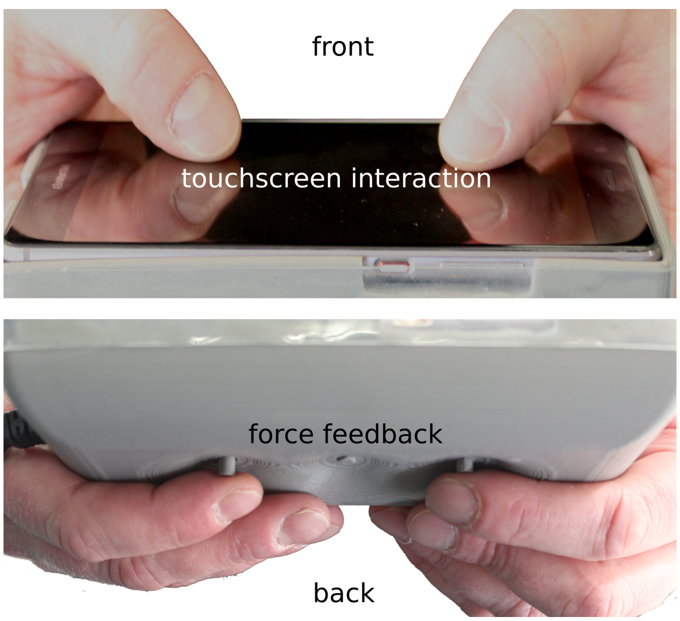

Fig. 1. Illustration of the prototype, a touchscreen for thumb interaction is shown on top and the force feedback pins in landscape orientation are depict below.

force feedback on the BoD to touch input on the front, where feedback on the index finger (at the back) is synced with touch input (through the thumbs) on the front. Results indicate that this approach can increase touch interaction accuracy and it can also increase perceived performance, in terms of completion time, accuracy, and quality of the feedback.

Table 1 gives an overview about the main research results in the field of BoD input and feedback on mobile devices. The table also shows that force feedback at the BoD is not well researched yet. Most of the BoD systems focus on finger occlusion issues and overcome this challenge by moving touch input to the back. Other researchers use BoD interaction to introduce novel manipulation and typing metaphors. We extend previous work by introducing a BoD force feedback interface and approach to increase touch precision and to enhance subjective user performance.

3 HapticPhone System Design

Here, we illustrate our system design and implementation, and describe the underlying design rationale. As the literature review shows that force feedback has improved interaction [42] [12], our main design goal was to combine BoD interaction and haptic feedback with thumb-based interaction. We assumed that continuous, assisting force feedback can provide a secondary cue for improved touch performance and increase the user experience in terms of subjective performance. One-handed interaction is a well-established method of interacting with a smartphone [47]. Therefore our work explores thumb-based interaction, as one-handed interaction uses the thumb for input control. To do so, we have attached a force feedback mechanisms to the back of the device that relays feedback to touch-input on the screen at the FoD. As such, our design couples front touch-based screen interaction and BoD feedback.

3.1 Technical Design Rationale

To overcome physical form-factor constraints – such as screen occlusion, input hindrance, and un-ergonomic grip positions – at the front of smartphones, we explore the feasibility of adding force feedback at the back of the device to support relayed feedback for FoD touch input.

We designed the new system for both one-handed (portrait) and two-handed (landscape) interaction. Input is performed by either the left or the right thumb, or both, on the FoD, while haptic feedback is relayed to the index fingers at the BoD. After several hardware design iterations that looked into ease-of-use, grip stability, and reachability of the feedback elements, and informed by the results of Le et al. [47] on appropriate finger locations for one-handed BoD interaction, we chose a three pin layout. The arrangement and dimensions are shown in Figure 2. This layout allows

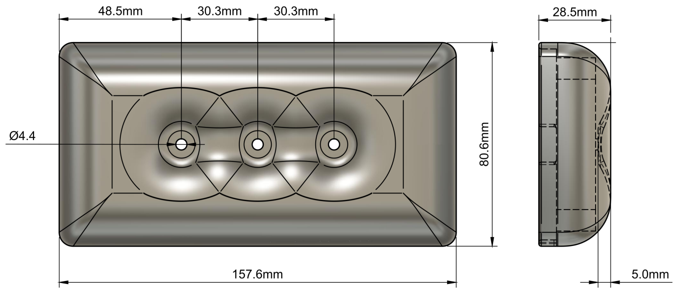

Fig. 2. Technical drawing of our interface and the chosen pin layout, with dimensions for the top and side views.

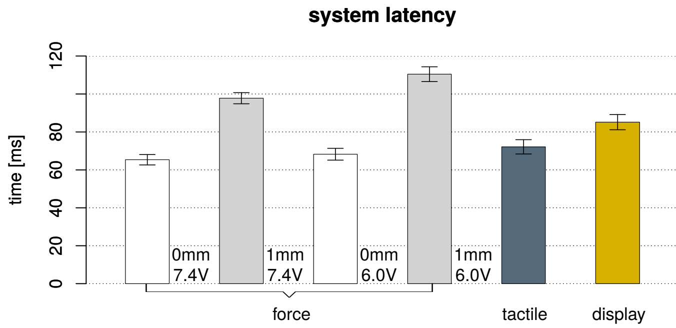

Fig. 3. System latency measurements (in milliseconds) for force, tactile and display, shown as a bar plot. The actuators were operated either with $6\,\mathrm{V}$ or with $7.4\,\mathrm{V}$ and latency was measured with $0\,\mathrm{mm}$ or $1\,\mathrm{mm}$ pin height.

users to use the outer pins comfortably while interacting in landscape mode, while the middle or top pin is used for one-handed portrait interaction.

The remaining fingers grasp the ergonomically shaped bottom part of the device, to stabilize and balance the device during interaction and feedback. To improve the grip on the device, we attached a rubber based grip tape around the edge of the unit. The grip has also been designed to afford comfortable device usage in both portrait and landscape mode. However, one-handed usage may suffer from limitations, as previous work has shown that one-handed interaction can lead to more fatigue, less precision, and a less secure grip of the device [43].

Force feedback is provided by three actuated pins at the back of the device (see Figure 2), at the locations where the left or the right index finger naturally rest. Three dimples in the housing help to keep the fingers at the ideal locations, where force feedback is provided.

3.2 Hardware

Our interface comprises three high voltage (7.4V) micro servos (BMS-22HV), each measuring 23.0 x 12.0 x $25.4\,\mathrm{mm}$, running with a speed of $50\,\mathrm{ms}$ per $60°$ rotation at no load. Each servo has a pulse width of $1200\,\mathrm{\mu m}$ and a maximum torque of $0.245\,\mathrm{N/m}$. We estimate that the servos have a resolution of $0.2°$ as follows: a pulse width of $1200\,\mathrm{\mu m}$ for $120°$ results in 1200 steps for $120°$. With a dead band width of $2\,\mathrm{\mu s}$ this results in 600 controllable steps for $120°$. All in all, the servos can be controlled with a resolution of $0.2°$, which corresponds to a radian measure of $0.049\,\mathrm{mm}$ with an arm length of $14\,\mathrm{mm}$(see Figure 4 left).

For each of the three pins a modified scotch-yoke mechanism was developed to convert the servos rotational movement into a linear movement (see Figure 4). For smaller pin movements, e.g., amplitude $1\,\mathrm{mm}$, our approach achieves a frequency of $50\,\mathrm{Hz}$. In idle mode, when no counter-force is applied, the power consumption of the prototype is about 10mA. With a strong counter-force the consumption is about 500mA.

The design enables a feedback range along a single axis from 0 up to $5\,\mathrm{mm}$. All hardware components are mounted in a self-contained unit at the back of an Android 7 Huawei P9 Plus mobile, which also supports pressure-based input. All other parts, such as the case or the scotch-yoke mechanism, are 3D printed, which ensures easy reproducibility. The entire prototype measures 157.6 x 80.6 x $28.5\,\mathrm{mm}$, weighs about $200\,\mathrm{g}$ and has a resolution of 1920x1080. A 16-bit Adafruit Feather (M0 Basic Proto) micro controller, directly connected via USB (OTG) to the smartphone, handles the communication between feedback elements and the application, which means that touch input is forwarded with low latency to the pins.

The current prototype relies on a cabled solution. However a completely self-maintained unit can be created using an Arduino Nano and communication over Bluetooth. Servo motors could be powered with a buck-boost converter, which can increase or decrease the input voltage and which can permit the use of small battery packs.

Figure 3 lists the latency of the systems hardware components in milliseconds. In a experimental setup, latency of the touchscreen (visual), the vibration (tactile), and the proposed feedback (force) were measured. Force feedback was measured under multiple conditions, with $6\,\mathrm{V}$ vs $7.4\,\mathrm{V}$ and pin heights of $0\,\mathrm{mm}$ vs $1\,\mathrm{mm}$ to show the influence of the described parameters on latency. A two pole relay was used to trigger a touch screen using a microcontroller, similar to Deber et al. [48]. After triggering the touchscreen a photodiode (Tru Components 5013M1C) was used to measure the time between touchscreen event and visual feedback. To obtain tactile feedback latency, the photodiode was replaced by a vibration sensor (Phidgets 1104). To obtain force feedback latency, an electric circuit was mechanically closed. This mechanism allows to measure the elapsed time of the touch screen event and its associated feedback, known as latency. For each feedback modality, 100 measurements were performed automatically. Figure 3 shows the average measured latency and the standard deviation of the measurement data. Opinions differ on the influence of latency on performance [49] [50] [51]. Yet, since the measured values are very close to each other and mostly below $100\,\mathrm{ms}$, we believe that a performance comparison of the three components is valid and sensible.

3.3 Implementation

In our implementation, we support two different types of touch input, namely position- and force-based interaction. The latter makes use of the pressure-sensitive touchscreen of the smartphone.

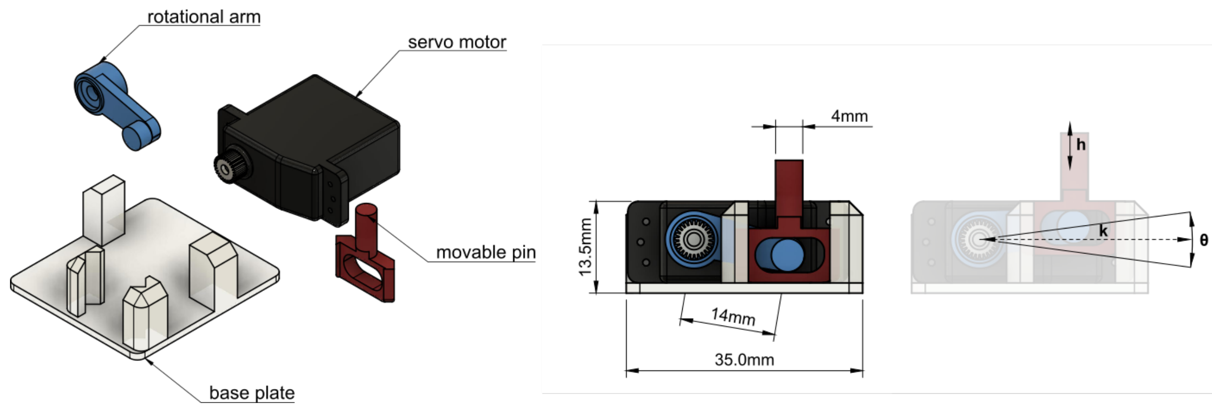

Fig. 4. Modified scotch-yoke mechanism to translate rotational into linear movements. An exploded diagram to introduce the used components (right), a dimensioned front view (middle), and the parameters for controlling the pins height (left). Height is determined by $h = k * tan(\theta)$.

In contrast to conventional tactile feedback through vibration on the screen, the introduced force feedback can support several clearly distinguishable levels of intensities, as our psychophysical study will demonstrate below. These intensities can be rendered in a continuous and discrete way. For the proposed haptic feedback two main software components are important. First, the application on the smartphone, which takes the orientation of the smartphone into account and offers developers the possibility to address the three pins individually. The smartphone communicates with a micro controller via I^2C. The second component, the software on the micro controller, receives data from the smartphone and passes it directly to the motors.

4 Psychophysical Perception Study

We conducted this study to determine the relationship between stimuli and sensation at the index finger using the introduced interface. The study examines haptic perception aspects and constraints of the BoD system. We performed a just noticeable difference (JND) experiment to address the question - which force signals can users easily distinguish? In addition, we studied the relationship between thumb and index finger movements through a second, spatial compliance, task. This investigates if it is possible to transfer movements of the index finger to the thumb and how the users perceive such movements.

4.1 Participants

12 users (3 female, age M=30.7/SD=5.8) volunteered to participate in this study. All were right handed. Participants had various experiences with force feedback, ranging from no to regular experience. All participants used smartphones regularly. Each participant completed all 60 trials, which took on average 12 minutes. The index fingers of the subjects were $88.3\,\mathrm{mm}$ (SD=$9.6\,\mathrm{mm}$) and the thumbs were $64.0\,\mathrm{mm}$ (SD=$4.9\,\mathrm{mm}$) long on average.

4.2 Apparatus

Users operated the mobile system as described in the system design section, while being seated comfortably at a desk. Users could rest their arms on the desk, and were allowed to take small breaks between tasks. During the whole user study, users wore noise-canceling headphones that played white noise to prevent users from hearing the servo actuation, as the servo sound could provide some information about the force feedback.

4.3 Tasks and Procedure

The psychophysical perception study consists of two tasks. The first task investigates the just noticeable difference of force stimuli afforded by the pins, while the second task looks at spatial compliance. Both tasks were performed in a counterbalanced order. Participants were asked to use their dominant hand for interacting with the system. This ensured that the dominant thumb was used for touch interaction and the index finger of the same hand for the relayed feedback. To do so users were asked to place their index finger on one of the outer two pins, while holding the device two-handed in landscape mode. In addition, users were advised not to apply force to the pins.

The JND experiment was performed based on the principle of constant stimuli with a two-alternative forced choice protocol, similar to Geschneider [52]. This protocol specifies that n times a randomly chosen stimulus from an appropriate interval must be compared to a standard stimulus. This can take place either spatially or temporally shifted.

In the experiment the standard stimulus S was set to $1\,\mathrm{mm}$ while the comparison stimuli C_n were one of 1.2, 1.4, 1.6, 2.0 or $2.4\,\mathrm{mm}$. Stimuli were defined by the distance the pin was moved towards the index finger, i.e., away from the device. Each participant completed 10 repetitions. Each repetition was fully randomized, resulting in a total of 60 trials. For each trial, users were prompted to press a start button, to enable them to prepare themselves for the task. Each stimulus was presented for 2 seconds, with a pause of 1 second in between. The order of stimuli was chosen randomly, meaning the standard stimulus was presented either first or second. Users then had to determine which of the two stimuli was higher. Before the experimental tasks, users were allowed to do three practice trials. All training trials were marked visually so that the users knew when the actual study started.

The other task focused on the psychophysical perception of depth and height, which combines visual feedback and touch interaction (thumb) on the screen with BoD force

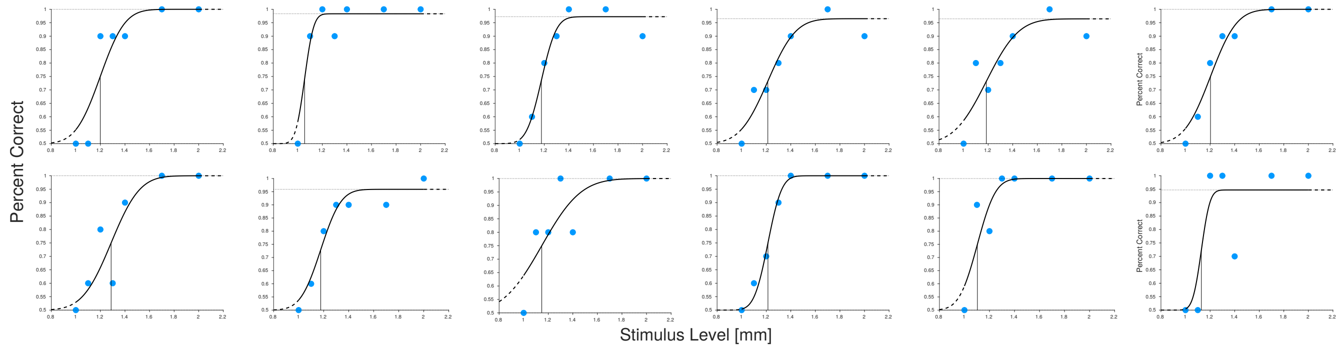

Fig. 5. Results of the psychophysical perception study. The pyschometric curves of all 12 participants are plotted in this Figure. Obtained data of the individual observers were fitted using Weibull function. Each plot shows the stimulus level on the x-axis and the percentage of correct stimuli detected on the y-axis.

feedback on the index finger. With this task we explored the spatial compliance between index finger and thumb, where we assume that the thumb can "perceive" height data from the index finger. This addresses the question if users perceive a valley at the thumb when the distance between thumb and index finger increases or if participants will perceive a hill and vice versa. In this task, participants were asked to explore a 3D Gaussian-like shape with the thumbs on the touchscreen. Since the screen has 2 physical dimensions, the 3rd dimension was mapped to the index finger, like a height map.

The maximum feedback (height/depth) was set to $2.4\,\mathrm{mm}$ whenever the thumb reached the maximum of the shape displayed on the screen. While visual feedback remained constant over all trials, force feedback was designed so that either the distance between the index finger and the thumb became smaller or larger. Because the task was simple and easy to understand, only 8 trials were performed in random order per user. After each trial, users were asked if they felt that the 3D Gaussian-like shape was directed either into (valley) or out (hill) of the display.

4.4 Results

The JND experiment was analyzed using the psignifit MATLAB toolbox, similar to previous work [12]. Three relevant values were determined: point of subjective equality (PSE) and stimulus values at $25\,\%$ and $75\,\%$ probability. With these three values the JND and the Weber Fraction (WF) were determined. The results of the psychophysical perception study are summarized in Table 2 and the psychometric curves are plotted in Figure 5. The (index finger) depth perception threshold of our system is on average $0.1\,\mathrm{mm}$. Our results are in line with what Jang et al. [12] reported, who found an average JND of $0.15\,\mathrm{mm}$.

The evaluation of the answers shows that in the second part of the study $83\,\%$ of all subjects felt a valley whenever the distance between index finger and thumb decreased and $91\,\%$ felt a hill whenever the distance increased. Since users were asked what they perceived with their thumbs on the touchscreen this indicates that users seem to experience the sensation that their thumbs sink into the smartphone when the distance between index finger and thumb increases and vice versa.

TABLE 2
List of the results of the psychophysical perception experiment

depth perception			
participant	PSE [mm]	JND [mm]	WF [%]
1	1.20	0.11	8.89
2	1.28	0.07	5.88
3	1.06	0.04	3.90
4	1.23	0.13	10.80
5	1.21	0.11	9.43
6	1.21	0.12	9.62
7	1.29	0.12	9.62
8	1.23	0.10	7.82
9	1.21	0.06	4.91
10	1.15	0.17	14.74
11	1.10	0.08	7.01
12	1.14	0.04	3.83
Mean	1.18	0.10	8.29
SD	0.06	0.04	3.43

5 Touch Accuracy Study

This study mainly examined touch accuracy of the BoD feedback mechanisms, comparing force with tactile and visual-only feedback. Since thumb interaction offers a relatively smaller interaction area due to physical constraints for reaching compared to using the index finger, a higher accuracy might offer the possibility of comfortably controlling denser interaction elements on a smaller area. To determine touch accuracy we used two tasks, a drag-n-drop and a selection task. The drag-n-drop task is designed to determine the accuracy of a constant force feedback stimulus and to compare this with other feedback metaphors. The selection task pursues the same goal, however, the intensity of the force feedback was varied as well in this task. Furthermore, in a questionnaire we explored the user experience in terms of subjective performance of completion time, precision, and quality of the feedback. Since our proposed system employs thumb-based interaction, we excluded multi-touch metaphors from the study.

5.1 Participants

12 users (5 female, age M=29.8/SD=4.9) volunteered to participate in the laboratory experiment. Again, all participants

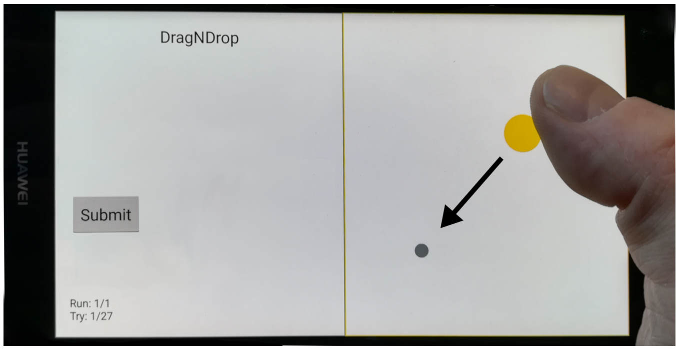

Fig. 6. Exemplary illustration of the drag-and-drop study. Users had to drag the orange disk onto the grey one. The black arrow was not visible to the participants.

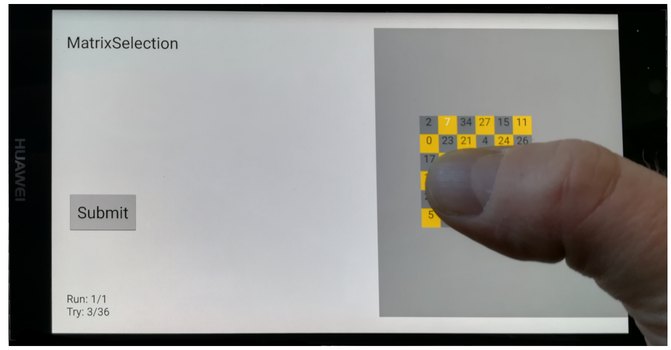

Fig. 7. Illustration of the selection task. Users had to select a specific cell in the stimulus matrix. Cells have alternating intensities (tactile) or heights (force).

were right handed. Participants had varied experience with force feedback, ranging from none to regular experience. Each participant completed all of the 90 trials, which took an average of 12 minutes.

5.2 Apparatus

The apparatus for landscape interaction was similar to the one used in the first study reported above. In addition, we investigated interaction in portrait mode in this study, where the thumb of the dominant hand was used to handle the touch input and the corresponding index finger receives the force feedback through the middle pin. Users were allowed to use the other hand to keep the smartphone stable.

5.3 Design and Procedure

Before the actual study began, users were encouraged to explore the new feedback mechanism to understand the principle of the feedback. Participants had to complete two tasks, a drag-and-drop and a selection task. Since the proposed BoD approach is comparable with more common feedback metaphors, users were asked to use all three different feedback metaphors (force, tactile, visual-only) to gain an understanding of each feedback modality and their differences. The order of the two tasks was chosen randomly.

For the drag-n-drop study, the center of the rectangular interaction area ($30\,\mathrm{mm}$ x $45\,\mathrm{mm}$) was above the corresponding pin, the size was chosen so that all participants could reach all elements in this area. The size of the interaction area for the selection task was determined by the size of the stimulus matrix, which was at most $30\,\mathrm{mm}$ x $30\,\mathrm{mm}$.

Can interaction of the thumb be influenced by controlled movements induced on the index finger? To investigate this question, this study focused on the interplay of relayed feedback from the index finger at the BoD to the thumb with the aim of increasing accuracy of thumb interaction on the FoD. In addition, since the offset between fingers could also affect touch accuracy, we also investigated the influence of the offset in the axis orthogonal to the touchscreen between the thumb position on the touchscreen and index finger on the back. All tasks were performed in landscape and portrait mode, as both modes are common in every-day smartphone interaction.

After the study, users completed a questionnaire, in which we queried them about the three parameters accuracy, completion time, and quality for each feedback modality using a 7-Point Likert scale, ranging from "strongly disagree" to "strongly agree", through statements such as: *I could perform the task precisely*, *I could complete the task quickly*, and *The quality of the feedback was excellent*.

5.3.1 Drag-and-Drop Task

In this study, participants were asked to perform a drag-and-drop task by moving a disc as accurately as possible onto another. We used a within-subject design to examine touch accuracy and user experience, through a (3x3x2) factorial design with 3 independent variables: screen orientation (levels: landscape and portrait), target disc size (levels: 1.0, 1.5, $2.0\,\mathrm{mm}$) and feedback type (levels: force, tactile and visual-only). The factors disc size and feedback type were fully randomized over the trials, whereas the factor screen orientation was counterbalanced. The dependent variables were touch accuracy and user experience. Touch accuracy was measured with an error rate in mm, representing the distance to the center of the target disc. The user experience was measured through the questionnaire described above.

To examine touch accuracy, users had to drag one disc (the action disc) and drop it onto another (target) disc. Participants were asked to do this as accurately as possible. Throughout the entire study the size of the action disk (diameter=$4\,\mathrm{mm}$) was the same. The size of the target disc varied (diameter=1.0, 1.5, $2.0\,\mathrm{mm}$), with the largest target size chosen so that users still had a chance to see or estimate where the disc is located, without completely covering the target. In contrast, the smallest target was completely covered by the thumb when both centers intersect. Both discs appeared at random, but reachable, locations. Once participants assumed, that the center of the action disc was above the center target disc, participants had to submit their position result by pressing a button with the other thumb.

We designed the visual feedback to be similar across different feedback types, while the perceived stimuli at the index finger/thumb were different. To initially select the action disc, users had to select it for at least $50\,\mathrm{ms}$. Thereafter, participants were able to drag the disc with their thumb. In the 'visual-only' mode there was only visual feedback. In the other conditions, tactile respectively force feedback was enabled whenever the center of the action disc was inside the target disc, which means that either a 2 mm force feedback event was rendered on the BoD or standard vibration was turned on. Then force or vibration stayed on until the action disc center went outside the target disc or the user confirmed the location with their other thumb.

5.3.2 Selection Task

In the selection task a within-subject design was used to examine touch accuracy and user experience. We used a 3x3x2 factorial design, with 3 independent variables: cell size (levels: 3, 5, 7 mm), feedback type (levels: force, tactile and visual-only) and screen orientation (levels: landscape and portrait), . Each user had to complete 3 repetitions, overall 54 trials. The factors cell size and feedback type were fully randomized over the trials, whereas the factor screen orientation was counterbalanced, so that participants completed all trials for the same screen orientation in one block. This avoids users having to constantly rotate the screen, which could lead to unnecessary fatigue and increased stress. The dependent variables were touch accuracy and user experience. Touch accuracy was measured with an error measurement in mm, corresponding to the distance of the touch center to the center of the selected cell. User experience was assessed with the questionnaire described above.

We used a stimulus matrix of abstract targets, as a representation similar to common interaction targets, such as menus, toolbars, tool palettes or links. Users were asked to search and select an element in a 6x6 matrix, in landscape as well as portrait mode (see Figure 7). The center of the stimulus matrix was located exactly above the feedback pin. For each cell of the matrix a unique number from 0 to 35 was randomly generated. The number to be selected was visually marked. Users could then use the thumb of their dominant hand to select the cell as best they could, as close as possible to the center of the cell. To submit the target position participants had to press a button with the other thumb. We chose three cell sizes of 3, 4 and 5 mm for this study, based on earlier research on appropriate target sizes for thumb interaction [46], [53].

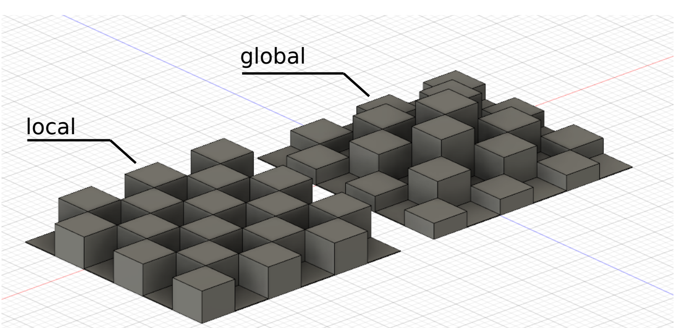

Fig. 8. Illustration of the 2 different feedback approaches for a 6x6 stimulus matrix. Right: constant feedback intensities (pin heights) over the whole matrix and Left: feedback intensities increasing towards the middle to help the user perceive the global position of the matrix.

Depending on the feedback type, we implemented different approaches to search for and select a cell. For visual-only feedback, as the name suggests, no additional cues were rendered. For tactile feedback, we provided vibration via the in-built functionality of the touchscreen device. This means that the feedback was rendered to the whole device, including the front screen. Since Android does not natively offer the possibility to change the intensity of the vibration, we used a binary approach, i.e., only on or off. Thus, vibration feedback was either continuously switched on and off, alternating with the cells (see Figure 7). This enables the user to sense the transitions between cells. For force feedback, two approaches were introduced. First, *local feedback*, an alternating feedback per cell with a constant pin height of 2mm (for yellow cells) and 0 mm (for grey cells). Second, *global feedback*, an alternated feedback per the cell, but with an increase for the intensity of the feedback towards the center of the (whole) stimulus matrix, up to a maximum of 2.4 mm in discrete steps, depending on the size of the matrix. For example, the step size was 0.8 mm for the 6x6 matrix. We chose to increase the feedback towards the middle of the matrix so that users could not only sense the transitions from cell to cell (local position), but also determine the (global) position within the stimulus matrix based on the intensity. At the end of the study, a question was asked about the perception of localization in the matrix. Pin heights (feedback intensities) for local and global force feedback are shown schematically in Figure 8.

Before each experiment, users were asked to explore each of the feedback modalities for about a minute. Completion time was measured per trial and logged for both tasks.

5.4 Results

5.4.1 Drag-and-Drop

As the data were not normally distributed, we used a Kruskal-Wallis test to analyze the data of the drag-and-drop task. For the sake of completeness, the completion times in milliseconds per trial and feedback are listed in Table 3.

TABLE 3
Mean time and standard deviation per trial for the drag-and-drop task in seconds (standard deviation in brackets).

	portrait	landscape
visual-only	3.17 (1.56)	3.79 (3.16)
tactile feedback	3.95 (3.01)	3.87 (2.11)
force feedback	3.84 (2.10)	4.01 (2.53)

Through the error distance measure we identified that users performed the task significantly more precisely with tactile and force feedback for both landscape (χ^2 = 9.81, $df = 2$, $p < .01$) and portrait mode (χ^2 = 18.34, $df = 2$, $p < .001$), see Figure 9. A pairwise comparison identified a significant effect between tactile and no feedback (landscape $p < .05$ / portrait $p < .001$) and force and no feedback (landscape $p < .01$ / portrait $p < .001$). There was no significant effect between tactile and force feedback according to a Nemenyi *post-hoc* test.

The results for the questionnaire data (see Figure 10) showed that force and tactile feedback were perceived to be more precise. The Fisher Exact test identified a significant effect ($p < .001$) for the accuracy ratings. Participants felt more accurate with force (M = 6.3/SD = 0.7) and tactile

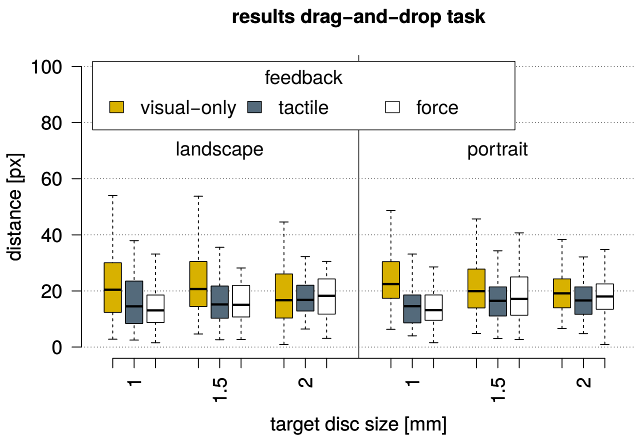

Fig. 9. Box-plot for touch accuracy in the drag-and-drop study. For smaller target sizes, force and tactile feedback have a significantly lower error than visual-only.

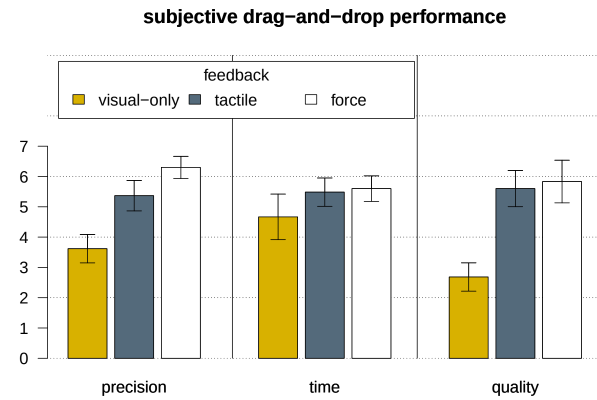

Fig. 10. Subjective drag-and-drop performance in terms of precision, completion time and feedback quality.

feedback (M = 5.4/SD = 1.0) than with visual-only (M = 3.6/SD = 0.9).

The responses for the completion time question were not significant. Users felt faster with force (M = 5.6/SD = 0.8) and tactile feedback (M = 5.4/SD = 0.9) than with visual only (M = 4.7/SD = 0.9), but not significantly so.

In conclusion, in both landscape and portrait mode tactile and force feedback were on average 1.33 times more accurate compared to visual-only feedback. Considering only small targets where the thumb covers the entire disc, the average error in touch accuracy of force and tactile feedback compared with visual-only is about 1 mm. The results also indicate a higher variance for the average accuracy for visual-only feedback compared to other feedback modalities. This can be interpreted as that the users felt more confident in their selection with tactile and force feedback than with visual-only feedback. Additionally, any potential offset between touch and pin position seems to have had no observable influence on accuracy and time per trial in the study.

5.4.2 Selection

We were primarily interested in touch accuracy for the selection task. As the proposed BoD force feedback condition involved several intensity levels, this meant that participants were able to determine not only their local but also the global position in the matrix. Therefore, we assumed that the touch accuracy would be higher with force feedback compared to the visual-only or tactile conditions. As the data were not normally distributed, we applied a Kruskal-Wallis-Test instead of an ANOVA. We conducted a Nemenyi-Test to calculate pairwise comparisons between feedback groups for the *post-hoc* analysis. For sake of completeness, the means and standard deviations of the completion times per trial are listed in Table 4.

We found a significant effect of touch accuracy for small cell sizes (3mm) in landscape mode (χ^2 = 10.626, $df = 3$, $p < .01$). A pairwise comparison with the Nemenyi *post-hoc* test between visual-only, tactile, force local and global feedback showed a significant difference for all 3 feedback modalities compared to visual-only (force global/$p < .05$, force local/$p < .05$, tactile/$p < .05$).

The analysis of the selection accuracy in portrait mode also indicated a significant effect for the selection of small sized cells (3mm) (χ^2=8.3779, $df = 3$, $p < .05$). The *post-hoc* analysis for portrait mode reveals a significant difference of touch accuracy for force global and visual-only feedback ($p < .05$). This shows that BoD force feedback can increase touch accuracy in both conditions.

Our results illustrate that small targets can be selected more precisely with a secondary cue (force and tactile). Users were able to select all cell sizes (3 mm, 4 mm and 5 mm) with a similar probability of 69.8 % (force global), 70.8 % (force local), 66.2 % (tactile) and 59.3 % (visual-only) in both modes (landscape and portrait). Considering only the smallest cell size, (3 mm), users could select the cells correctly with a probability of 54.2 % (force global), 54.2 % (force local), 50.0 % (tactile) and 36.1 % (visual-only). Figure 11 depicts the results for all cell sizes.

TABLE 4
Mean time and standard deviation per trial in seconds for the selection task (standard deviation in brackets).

	portrait	landscape
visual-only	3.65 (2.18)	3.78 (2.29)
tactile feedback	3.92 (2.19)	4.05 (3.0)
force local feedback	4.55 (3.10)	5.27 (5.70)
force global feedback	3.91 (2.46)	4.82 (4.70)

Figure 11 shows that the pure visual state has the highest error rate, whereas secondary feedback, whether tactile or force, performs much better. The comparison between global and local force feedback in the selection task did not reveal any statistical differences. However, in the questionnaire right after the study, users rated the global feedback as more positive and supportive than the local feedback (M = 4.8/SD = 1.4).

The questionnaire data was evaluated using the Fisher Exact test, which indicated that both accuracy ($p < .001$) and time per trial ($p < .01$) were significant (see Figure 12).

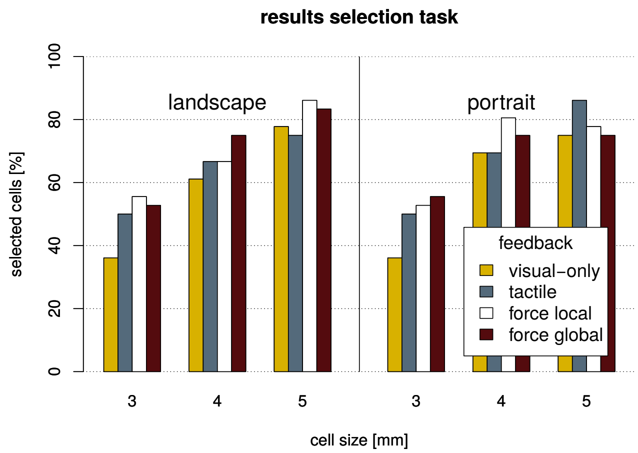

Fig. 11. Percentage of successfully selected cells per size and mode. The influence on accuracy for visual-only feedback decreases strongly as soon as the thumb covers the target.

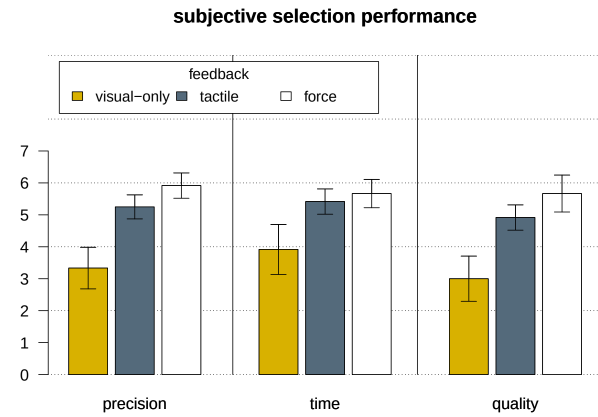

Fig. 12. Subjective selection performance in terms of precision, completion time and feedback quality. For all three parameters participants liked force feedback most.

Participants felt more accurate with force (M = 6.1/SD = 0.9) and tactile feedback (M = 5.6/SD = 0.8) than with visual-only (M = 3.0/SD = 1.2). Additionally, users felt also faster with force (M = 5.6/SD = 1.1) and tactile (M = 5.3/SD = 0.6) feedback than with visual-only (M = 4.1/SD = 1.1).

The improved selection accuracy of smaller targets is an important finding, extending previous research in BoD interaction, such as [1], showing that haptic feedback is also a valuable method to overcome occlusion problems. When looking at the smallest cell size of 3 mm, force and tactile feedback can on average increase accuracy by a factor of 1.5 compared to visual-only feedback. This means that the presented feedback mechanism can improve selection tasks, including text selection, considerably.

Participants filled out the SUS questionnaire to evaluate system usability. They rated our new system on average at 81 with a standard deviation of 13. According to Bangor et al. [54] this means that the average is between "good" and "excellent" usability.

6 Applications

To show how HapticPhone supports higher-level tasks, we implemented three applications that extend the basic (low-level) functionality demonstrated in the user studies (see Figure 13). These applications demonstrate other instances where force feedback at the BoD is also useful.

Pressure input. We implemented a *3D Volume Viewer* application based on stacked images that can be explored through pressure input. In the first iteration, the applied pressure was directly transferred to the intensity of the servo motor. In this case force feedback was used to enhance scene navigation, as force feedback indicates where the user is in the scene: feedback is spatially compliant, as it is based on displacement with more/less pressure. Specifically, the user can directly feel if the currently viewed slice is further up or down in the 3D volume stack, aligned with the displacement axis. Thus, we assume that force feedback can be useful to afford more precision for finding a given layer in a volume.

Height perception. We created a *Map Exploration* application that supports simultaneous exploration of multivariate, map-related data. With normal map viewers, exploring multivariate data in parallel can become difficult. Thus, complex visualization methods are normally needed for such scenarios. In our application, we pass different geographic data to different feedback elements, e.g., output elevation profiles via a servo and map environmental pollution data to tactile stimuli. This choice effectively implements multi-channel feedback to provide feedback about different aspects of the data. The application builds on the JND results, which showed that the users can interpret fine differences through force feedback. We assume this accuracy can assist users in finding, e.g., a location on a map that is desirable in multiple dimensions.

Gaming experience. Finally, in a *2D Racing Game*, we explore a combination of pressure input and height perception. Here, the car is steered through the touch position and input pressure is mapped to speed, while force feedback gives indication of the speed, by mapping the speed to the force pin. While force feedback has been shown to improve fun and immersion [55], we specifically targeted subjective control accuracy here.

7 Discussion

In our first study, we assessed if relayed feedback at the back of a device can support touch-based interaction on the front. Doing so, we explored different back-to-front feedback mappings to investigate both perception (psychophysical limits) and performance. Through a second user study, we showed that relayed feedback can indeed improve both objective and subjective performance. In some instances results are comparable to tactile feedback, while in others (selection accuracy of small targets) objective and subjective performance and preference are better, which demonstrates the potential of our approach.

Here, we discuss important factors that need to be considered when applying back-to-front relayed feedback in applications.

Fig. 13. Exemplary application scenarios for the proposed BoD force feedback approach: (top), a volume viewer, a racing game, a map viewer, all supported by force feedback on the back of the smartphone. For the Volume viewer, for example, the pressure on the touchscreen is directly translated to the pins' height. When mapping the position, the information at the point of contact is taken (e.g. elevation data) and transferred to the pin.

Design space. In our device design and studies, we only explored a subset of the whole design space afforded by interaction on the back of a smartphone. A smartphone provides many different input and output modalities at different locations, which can be combined to create different mappings. E.g., a microphone, speaker, buttons, or notification LED are normally located at the front, while a fingerprint scanner, torchlight, or camera, are often located at the back of the device. Consequently, the design space has many dimensions, as the same hardware mapping can be used to elicit different back-to-front feedback N:M mappings, especially for force feedback at the BoD.

Direct vs. indirect mapping. Feedback can be directly or indirectly mapped. While we studied only directly mapped feedback, where a direct connection between the type of action and feedback exists, indirectly mapped back-to-front actions are also possible. Moreover, similar to tactile or auditory warnings, back-of-device feedback can communicate information about other processes than the one the user is involved in, for example to draw attention to a notification. Additionally, the presented prototype could also be used to enable in-pocket or other eyes-off interaction.

Spatial compliance. In our work, we explored spatially compliant and non-compliant feedback. Our feedback mechanism provides displacement along a single axis, afforded by the mechanical constraints of the servo. When users press down on the screen, force feedback that moves the index finger away from the phone is spatially consistent, which matches the direction of the touch input action. Our analysis of the results indicate that users could interpret such spatially consistent feedback well, also because such consistency was preferred by users. Users stated that spatially inconsistent feedback, for example mapping up/down dimple displacement to sliding left/right, was more difficult to interpret.

Integration or separation. Spatial compliance also directly affects one of the key issues for back-to-front feedback, namely the physical separation of feedback (on the index finger) from the actual input channel (the thumb). This also opens the question if integrated feedback is possible at the back. While we currently only made use of feedback at the back of the device, the back could be extended with sensing hardware, e.g., through force sensitive resistors. Then, feedback does not have to be relayed. While this is different from our core idea of back-to-front feedback relay, it opens up an interesting venue for systems that couple front-input or front-display with back-input-and-feedback.

Single- vs. multi-channel feedback. Another issue is the number of input or feedback channels being used. Here, we used a type of single-channel, integrated solution: the same type of feedback was mapped to both left and right fingers, where input location defines which finger was actuated. However, and as discussed in the next section on applications, a system could separate both feedback channels, for example by providing different kinds of force feedback at the actuators at the back for different types of events.

Range and resolution Remapping values to work within the provided (force) range is an issue for spatial consistency, in particular when fine-grained feedback is required. The resolution of actuation is both a technical and human issue. Technical limitations may affect the physical range and levels of feedback one can provide. With our current device, the range was a physical displacement of $5\,\mathrm{mm}$, with a resolution of $0.2°$, which corresponds to a radian measure of $0.049\,\mathrm{mm}$. Through the just-noticeable difference experiment, we showed that users can detect differences of around $0.1\,\mathrm{mm}$.

8 Conclusion

In this paper, we presented the concept of back-to-front relayed feedback on smartphones and discussed the results of our evaluations. The studies involved HapticPhone, a novel smartphone interface that provides servo-actuated force feedback at the back of the device, which overcomes physical form-factor constraints for providing force feedback on the front. Through our evaluations, we showed that relayed feedback can improve interaction on the frontal display. Based on the results, we discussed several factors affecting the relayed back-to-front feedback paradigm. We briefly summarize our main findings:

- Psychophysical analysis revealed that perception of force stimuli using the presented mechanisms resulted in a Weber Fraction ($8.29\,\%$), which is comparable to other devices and confirms that the feedback works appropriately and affords the perception of fine differences.
- Both selection and drag-and-drop task show encouraging results. In most situations, force and tactile feedback performed about equally well. For both

selection and drag-and-drop, as expected, feedback yielded better objective performance than without. Accuracy for small targets was increased by factor of 1.5 (for selection) and 1.3 (for drag-and-drop). Especially for selection of smaller targets, force feedback can produce better results than tactile, extending previous findings that showed the potential of back-of-device interaction for selection of smaller targets [1]. Users preferred force feedback over tactile or no feedback, feeling more accurate, yet not faster. Thus, in terms of subjective performance, force feedback was the best option.

As a next step, we intend to look more closely into multi-channel, separated back-to-front feedback, which relays both force and tactile feedback about different events controlled at the front of the display. Also, the discussion of the factors affecting relayed feedback points to the potential for many different types of devices, for example those that can flip or move. We did not discuss these options, as this is beyond the scope of back-to-front feedback relay. Finally, as HapticPhone already is a fairly compact design, we are considering if it can be offered as a compact extension to existing smartphone setups.

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Jens Maiero received the Diploma in mathematics from the Stuttgart Technology University of Applied Sciences, Stuttgart, Germany, in 2006, the M.Sc. degree in Computer Science from the Bonn-Rhein-Sieg University of Applied Sciences (BRSU), Sankt Augustin, Germany, in 2009, and is currently working toward the Ph.D. degree in Computer Science at Brunel University, London, U.K., and BRSU.

David Eibich received his Bachelor in Computer Science from the Bonn-Rhein-Sieg University in 2017. He is currently doing the Masters programm and his research interest are augemented reality and interactive environments.

Ernst Kruijff received the Ph.D. (Hons.) degree from Graz University of Technology, Graz, Austria, in 2007.

He is an Interim Professor for computer graphics and interactive environments with the Department of Computer Science, Bonn-Rhein-Sieg University of Applied Sciences, Sankt Augustin, Germany, where he is the Head of the 3-D Multisensory Interfaces Group. He has widely presented his work at the main ACM and IEEE conferences. He has coauthored the book 3D User Interfaces: Theory and Practice (Addison-Wesley, 2004). His research interests include the human-factor-driven analysis and design and validation of 3D user interfaces, with a particular focus on multisensory cues.

André Hinkenjann (M11) is a Research Professor for computer graphics and interactive environments with the Department of Computer Science, Bonn-Rhein-Sieg University of Applied Sciences (BRSU), Sankt Augustin, Germany, and an Adjunct Professor with the Department of Computer Science, University of New Brunswick, Fredericton, NB, Canada. He is the Founding Director of the Institute of Visual Computing, BRSU. His research interests include high-quality rendering, interactive data exploration, and high-resolution display systems.

Prof. Hinkenjann is a Member of ACM SIGGRAPH, Eurographics, and German GI. He is a regular reviewer for international conferences and journals on the above mentioned topics.

Wolfgang Stuerzlinger is a leading researcher in spatial and three-dimensional user interfaces. He got his Doctorate from the Vienna University of Technology, was a postdoctoral researcher at the University of Chapel Hill in North Carolina, and professor at York University in Toronto. Since 2014, he is a full professor at the School of Interactive Arts + Technology at Simon Fraser University in Vancouver, Canada.

He has been program chair for 8 scientific events, has been a member of numerous program committee, and serves on several steering committees.

Hrvoje Benko is a research science manager at Oculus Research in the field of Human Computer Interaction. Prior to his current role, he was a researcher at Microsoft Research. His interests span augmented and virtual reality, interactive projection mapping, haptics, new input form factors and devices, as well as touch and freehand gestural input.

He has been active in the Human-Computer Interaction research community and He has served on various program committees (CHI, UIST, SIGGRAPH, ISMAR, ITS/ISS) and was the general chair for ACM UIST 2014 and the program chair for ACM UIST 2012. He is currently on the ACM UIST steering committee and on the advisory board for SmartHaptics. He is also the Information Director and Associate Editor for ACM TOCHI journal.

Gheorghita Ghinea (M02) received the B.Sc. and B.Sc. (Hons.) degrees in computer science and mathematics and the M.Sc. degree in computer science from the University of the Witwatersrand, Johannesburg, South Africa, in 1993, 1994, and 1996, respectively, and the Ph.D. degree in computer science from the University of Reading, Reading, U.K., in 2000.

He is a Reader with the Department of Computer Science, Brunel University, London, U.K. He has more than 250 publications in leading international conferences and journals. He has co-edited two books entitled Digital Multimedia Perception and Design (IGI Global, 2006) and Multiple Sensorial Media Advance and Applications (IGI Global, 2011). His research interests include the confluence of computer science, media, and psychology. In particular, his work focuses on the area of perceptual multimedia quality and building end-to-end communication systems incorporating user perceptual requirements. Dr. Ghinea is a Member of the British Computer Society.