Pulling, Pressing, and Sensing with *In-Flat*: Transparent Touch Overlay for Smartphones

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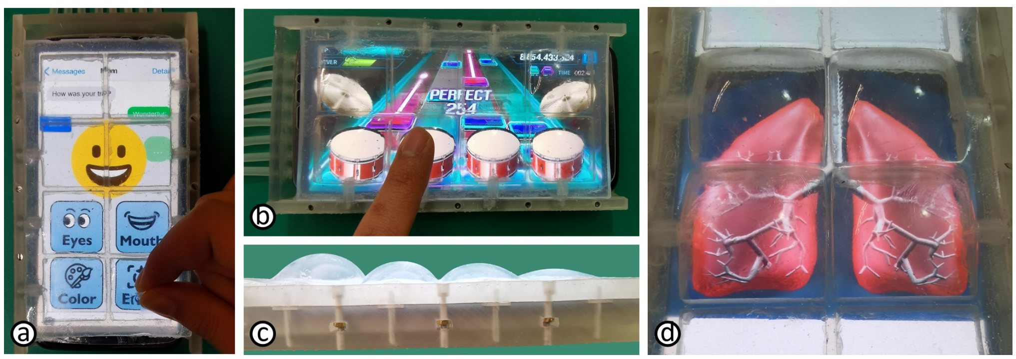

Figure 1: *In-Flat* is a pressure-sensitive silicon overlay on smartphones that enables coupling between visual display and touch I/O. *In-Flat* can be used to enhance GUI interactions (a) on buttons to parameterize dynamic emojis; or (b) in games. (c) Each airbag can have different inflation levels, (d) e.g., enabling dynamic tangible affordances to visualize a breathing lung.

ABSTRACT

Smartphones' screens are touch-sensitive and offer rich visual output capabilities, but do not allow users to control a wide range of pressure input nor provide rich pressure sensations. We propose *In-Flat*, an input/output pressure-sensitive overlay for smartphones. *In-Flat* consists of a transparent inflatable skin-like silicon layer that can be placed on the top or the back of a smartphone. As an output device, *In-Flat* offers tangible affordances and dynamic pressure feedback coupled with visual display. As an input device, *In-Flat* enables users to continuously perform a wide range of input gestures, notably *press* and *pinch-and-pull* gestures. Thus, *In-Flat* can be used to finely manipulate visual objects in mobile interaction or mediate interpersonal touch communications. In contrast to previous studies that mostly focus on press, we investigated the performance of pinch-and-pull and compared it with press. Our experiment (N=12) showed that participants could perform pinch-and-pull (83.8%) as well as press (84.7%), but felt having more control when performing pinch-and-pull. We explored the use of *In-Flat* to enable multimodal interaction that couples visual display and touch input/output. Participants appreciated this coupling as well as the touch sensation supplied by the *In-Flat* device.

CCS CONCEPTS

• **Human-centered computing → Haptic devices**.

KEYWORDS

Transparent Pneumatic Smartphone Overlay, Visual/Touch I/O Interface, Press and Pinch-and-Pull Gestures

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1 INTRODUCTION

Touchscreens on smartphones offer high-resolution visual display, yet lack of the capabilities to generate tactile sensations that are often present in physical objects. While tactile illusions can be induced through visual cues [39], they can only influence the expectation of how the physical objects should feel [4]. More accurate and richer tactile perceptions still require touch interactions with the objects. Notably, perceiving physical properties like compliance requires dynamic pressure on the object [5]. Soft materials deform under the finger's pressure and the surface wraps around the fingertip, inducing more tactile innervation [17]. Given that smartphones' screens are often flat, rigid, and made of glass, the pressure sensations on smartphone interactions are limited [10].

Our goal is to augment smartphones' visual display with rich touch input and output (I/O) capabilities. As an input device, the touch overlay should not only enable touch input gestures to interact with the visual objects displayed on the screen, but also provide *bi-directional* touch sensations: the users feel the resistance from the surface as the surface deforms according to the pressure level they apply onto it. As an output device, the users should be able not only to see the visual display, but at the same time also perceive tangible affordances and sense dynamic touch outputs. Additionally, users should be able to have controls over the touch surface behaviour, including setting up the compliance levels (i.e., how soft or stiff the touch stimuli should feel when pressured).

While research in HCI has proposed different touch devices, many of them are designed to provide either input capabilities only [8, 14, 38], or output capabilities only [19, 43]. Some touch devices provide both I/O capabilities, but also have some limitations that we attempt to address in this paper. In particular, touch I/O devices like [13, 27] enable coupling between touch I/O and visual displays, however they rely on projectors to display the visual cues, hence reducing the mobility aspect of the device. Touch I/O devices that can potentially be combined with visual displays on mobile devices [9, 11, 22] often do not allow in-place touch interactions that dynamically match the visual objects displayed on the screen.

We propose *In-Flat*, a pressure-sensitive overlay on smartphones that couples pressure-based touch I/O with visual display. *In-Flat* offers tangible affordances on the visual objects, enabling users to perceive visual and temporal changes and/or surface compliance levels. *In-Flat* also enables a variety of touch input gestures – not only *press* but also *pinch-and-pull* gestures. We built a prototype of *In-Flat* in the form of a detachable phone case with an inflatable silicon layer (Fig. 1c). Both the silicon layer (front part) and the phone case (back part) are made of transparent materials, preserving access to visual display. The touch I/O on each airbag can be controlled and captured independently, enabling dynamic multi-finger pressure interactions on the touch overlay.

Our contributions are three folds. First, we propose the design and prototype of *In-Flat*, a novel touch I/O device that couples touch interactions with visual display on smartphones. Second, we contribute a fabricating approach of highly transparent and stretchable overlays for smartphones, enabling rich I/O interactions and skin-like touch sensation. Our explorations on different silicone materials and fluid options offer technical insights for researchers in touch interactions. Third, we provided empirical evidence that users can perform *pinch-and-pull* as well as *press* gestures on inflatable silicon layers with *In-Flat*. We compared the performance of the two gestures, complementing past studies on touch devices that mainly focused on press only [10, 13] or pinch only [31]. We discuss future directions and implementations for supporting the coupling between touch I/O and visual displays on smartphones.

2 RELATED WORK

2.1 Capturing pressure input gestures

Force input (i.e., pressure) is a powerful alternative to mobile interactions as it only requires a finger and fingertip-sized interactive surfaces (i.e., space-efficient) [8, 10]. Past works have demonstrated the benefits of force input, including supporting rich and efficient GUI interactions such as picking values from long ordered list [8] or selecting parametric commands [6]. Some smartphones enables force input on touchscreens, for example with iPhone 6s, users can perform light, medium, or firm press on the screen with a pressure ranging from 0 to 3.3 Newtons [3]. Other smartphones without pressure sensors capture simulated force input values by calculating the contact area size between the screen and the fingertip. Nevertheless, applying pressures on a flat, rigid surface limits the pressure sensation and the perception of complicity, as the users can hardly feel the surface bends according to the pressure [10].

Past works have also explored the use of Force Sensing Resistor (FSR) to capture pressure input on smartphones. Wilson et al. showed that users can choose up to ten items with their fingers at 85% accuracy with continuous visual feedback [38]. Similarly, Heo and Lee embedded several FSRs on the back of a smartphone to enable force gesture inputs like slides or drags [14]. In this case, the gesture recognition process considers the combination of several touch dimensions, including spatial movements, pressure levels, and the change of pressure levels over time. Elastic fabrics can also be used to capture force input [12, 31]. For example, Han et al. created an elastic touch interface with fabric and magnet field sensors, enabling users perform various gestures including pinch-and-pull [12]. Han et al. also conducted a short pilot study to better design the pinch-and-pull recognition process. The use of FSR and elastic fabrics is often limited to support touch input capabilities only.

Another alternative is using silicons with pneumatic activations and air pressure sensors, as they can be inflated dynamically to generate touch output as well [11, 13, 22]. Fruchard et al. [10] showed that controlling high-pressure inputs on soft surfaces (i.e., high complicity) takes more time and is more prone to errors compared to on hard surfaces, but more comfortable to perform. Silicons with pneumatic actuations support continuous pressure input with controllable levels of complicity (i.e., how stiff or soft the material feels when pressured) [13]. A longitudinal study on the use of inflatable silicons as a communication medium showed that users could create personalized touch patterns using the silicons, combining different pressure levels, the number of press, and temporal variations [22].

With *In-Flat*, we demonstrated that inflatable silicons can be used to capture not only *press* but also *pinch-and-pull* gestures (Fig. 2). Our evaluation study complements but differs from past studies, in that: 1) in contrast to a short pilot done in [31], we conducted a systematic experiment to evaluate the performance of *pinch-and-pull* gestures; and 2) in contrast to previous evaluation studies that mostly focused on press gestures only [10, 11, 13], we compared the performance of the *press* gestures to that of the *pinch-and-pull*, and showed that the participants can perform both gestures well.

2.2 Generating touch feedback

Most smartphones already include vibration motors, hence can generate various tactile feedback [37, 41].Past works have also explored the possibility of embedding vibrotactile grids on the back of the smartphone to enable rich vibrotactile feedback for GUI interactions (e.g., [40]) or notifications (e.g., [2]). However, the expressiveness of vibrotactile sensations is limited [22, 43]. Alternatively, Maiero et al. [19] explored the use of actuated pins on the back of the smartphone to provide tactile guidance on visual objects on the screen. Jang et al. [15] embedded an array of actuated pins on the edge of the smartphone. Aside from enabling tangible notifications and tactile guidance, the device can also be used as an input channel by creating buttons or sliders with the pins.

To enhance touch perceptions such as sensing surface complicity, Feng et al. proposed a fabrication method of inflatable smalls silicon using full-range speakers [9]. The silicons can be attached to physical objects such as statues to provide tactile feedback on fingertips. Similarly, Gohlke et al. proposed an inflatable silicon button that can both generate touch feedback and capture touch input when inflated [11]. Their study showed that users can reliably perceive and recognize touch patterns of different *inflation levels* and *total activations*. Past works have also shown that inflatable silicons can also induce human-like touch sensations that can support interpersonal touch communications [22, 42]. Complementary but different from these works, *In-Flat* can be used to generate dynamic touch output patterns that augments smartphones' visual display, enabling in-place tangible affordances on smartphones.

2.3 Augmenting visual display with touch

Augmenting touchscreens with touch feedback can increase interaction speed, reduce operating errors, and minimize visual and cognitive load, for example when scrolling [24], typing [6], and interacting with virtual buttons [40], due to enhanced spatial and temporal perceptions. Beyond enhancing GUI interactions, touch feedback has also been used to generate pressure sensations to graphical objects or images [19] and to enhance mobile communications, for example accompanying emojis with vibrotactile patterns [37]. These tactile systems often spatially decouple the touch feedback from the virtual objects displayed on the screen to avoid occlusions and enable full access to the touchscreen capacities.

Meanwhile, past works highlighted the benefits of spatially coupling visual and tactile feedback [13, 43], notable to generate direct physical feel on virtual objects. The dynamic physical buttons in [13] uses rear projections to couple touch I/O and visual display, which not only make them tangible and easier to find, but also provide bi-directional pressure feedback as the users physically interact with the buttons. Sahoo et al. also used projectors on an elastic fabric surface to form a tabletop display with touch I/O capabilities [27]. However, using projectors to generate the visual display may limit the mobility of the touch device. Instead of projectors, *In-Flat* uses the smartphone's screen as the visual display. Few papers explored this approach and we tried to address their limitations: [20] uses a transparent gel overlay that turns opaque when activated, thus occluding the visual cues; [26] uses transparent silicon, but only with limited shapes and size (i.e., small buttons).

3 *IN-FLAT*

We propose *In-Flat*, a novel visual+touch display with inflatable silicon layers in the form of a phone case. *In-Flat* uses transparent and translucent materials to accommodate visual display. The silicon layers can be installed on the back of the smartphone to preserve the screen's touch input and visual output capabilities; or as an overlay to enhance the visual output displayed on the screen with in-place pressure input/output capabilities. A silicon layer consists of one or more airbags (e.g., 2x4 grid). Each airbag can capture continuous pressure input independently. As such, a silicon layer with multiple airbags can enable multi-finger pressure interactions. Each airbag can also be inflated with different amount of air (Fig. 1c), enabling dynamic controls over the complicity levels of the surface. Altogether, it creates a general-purpose visual+touch display with dynamic pressure I/O capabilities on smartphones.

3.1 Rich touch input patterns

When an airbag is inflated, the surface of the silicon stretches outwards and enables direct manipulations of the surface. When the user presses or pulls the silicon surface, the required force to deform the elastic silicon layer has a positive correlation to its deformation and has a negative correlation to the volume change. Thus, by measuring the air pressure change of the airbag, we can measure different touch forces from users and enable continuous pressure control. The users can then *press* the convex silicon surface with different *pressure levels* and *temporal variations* by manipulating the duration and the gap between presses (Fig. 2). When pressed, the silicon surface is stretched and the volume of the airbag decreases. As such, we can combine these touch input dimensions to generate rich touch patterns on *In-Flat*. Users can also *pinch and pull* the silicon surface with two fingers and have different touch patterns.

3.2 Tangible dynamic touch output

As the overlay is transparent, *In-Flat* enables visual+touch display with tangible feedback. When inflated, the silicon surface deforms according to the amount of air injected into the airbag (Fig. 1c). By dynamically parameterizing the *inflation levels* and the *temporal variations*, we can create in-place dynamic inflation effects like breathing (slowly inflating and deflating the airbag) or vibrating (inflating to a certain level first, and then switching to a series of inflations and deflations in a high frequency). *In-Flat* also enables skin-like touch sensations with different complicity levels. When

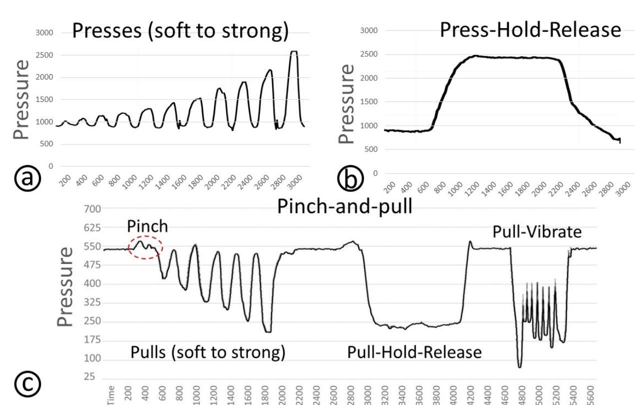

Figure 2: Examples of touch input patterns with different pressure levels and temporal variations. (a) Pressing with different pressure levels. (b) A long press. (c) A combinations of *pinch-and-pull* input patterns.

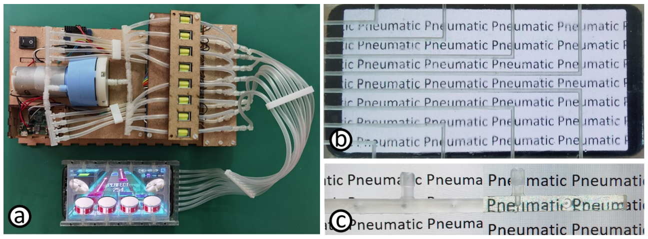

Figure 3: (a) The structure of *In-Flat*. (b) Transparent case. (c) Comparing resin before and after nitrocellulose coating.

the user presses its surface, a pressure is exerted to the airbag and the air inside the touched airbag gets compressed. Thus, the tension of the silicon and the pressure difference between the airbag and the atmospheric pressure give a force feedback to the fingertip. Thus, we can control the compliance level dynamically (i.e., how soft or stiff the surface is when pressured), and the users can perceive different sensations. Altogether, *In-Flat* enhances both visual and touch perceptions of a visual object displayed on the screen.

4 IMPLEMENTATION AND DESIGN CHOICES

In-Flat consists of two parts: 1) the transparent screen overlay + transparent resin case; and 2) the inflation and pressure control. In this section, we describe our design and fabrication approach.

4.1 Fabrication approach

4.1.1 Soft and transparent overlay. Material choice. As an overlay, *In-Flat* requires materials that are easy-to-get, transparent, stretchable, robust, soft, and skin-contact friendly. Different materials have been explored in the literature: latex [13, 22, 31], silicon [42], PE sheets [32], or spandix [12, 31]. Latex is robust and highly stretchable, but the transparency is not high enough to allow visibility when placed on top of the screen. PE sheet is highly transparent, but non-elastic. We saw the potential of using silicons thanks to its stretchability, robust, diversity and bio-capability. Spandix is also robust and highly stretchable, and spandix fabrics can also be seen through. But its transparency is still limited, and the mesh structure of spandix fabrics does not support inflatable applications.

Silicons are often used to induce skin-like sensations [22, 42]. Thus, we explored different types of silicon to make the inflatable layer. *Ecoflex* series are highly stretchable (elongation at break: 845% [29]) and durable, but the transparency cannot support screen overlay interactions (Fig. 5e). *SORTA-Clear* series have a high transparency (Fig. 5a), even though they are not as stretchable (elongation at break: 425% [30]) as *Ecoflex* series, its stretchability can already meet the requirements for screen overlay interaction. Additionally, it can also provide a skin-like touch sensation to the users. We chose skin-safe *SORTA-Clear 18* (100% Modulus: 35psi [30]) as the material of the inflatable layer. We set the thickness of the inflation layer to 1.5mm (Fig. 4b) after exploring the elastic modulus of different thickness of SORTA-Clear 18 silicon.

Composite structure. When *In-Flat* is placed on the smartphone, the deformation of the airbag should only face outwards. Thus, we designed a two-layer composite structure. First, we created the inflatable silicon layer with a 3D-printed mold. The silicon layer is created using a mold that printed by a PLA 3D printer. To increase the smoothness of the silicon airbag with current laboratory

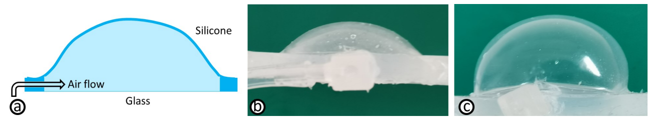

Figure 4: Composite structure of the airbags. (a) Two-layer structure. (b) Uni-directional inflation with 1.5mm thick silicone layer. (a) Inflation with 0.8mm thick silicone layer.

equipment, we pasted a layer of plastic tape to the surface of the printed PLA mold (Fig. 5a). After that, we glued the silicon layer to a screen-protection glass with silicon rubber adhesive (*ref: Sil-Poxy*). As such, when the air volume changes, the airbag's deformation only happens on the silicon side (i.e., outwards) (Fig. 4).

4.1.2 Transparent case. *In-Flat* can also be placed on the back of the smartphone to enable back-of-device interactions. With this setting, the screen of smartphone is faced towards the rigid phone case. Similar to the selection of silicons, the transparency is crucial to ensure visibility. Thus, we fabricated a phone case using a resin 3D printer, with built-in air channels in the case to avoid tubes (Fig. 3c). We then applied a thin layer of transparent nitrocellulose coat on the surface of resin case to increase the transparency (Fig. 3d).

4.1.3 Inflation medium. We can potentially inflate the grid with different fluids. Previous research explored different fluids for inflatable touch devices, including air [13, 22, 42], water [18], and other specialty fluids [35]. *In-Flat* requires a high transparency level and high response speed, so we explored the use of water and air to actuate the device. Comparing these two fluids, water can be considered as non-compressible liquid in *In-Flat* pressure range, which lead to a high response speed. However, due to the high refractive index of water, the water-inflated silicon bag works as a plano-convex lens and deforms the content on the screen (Fig. 5c). Finally, we chose air as the inflation medium in our design (Fig. 5b).

4.2 Pneumatic control

4.2.1 Actuators. To ensure accurate inflation levels and pressure input recognition, we implemented a closed-loop inflation/deflation system for each airbag. For example, for a silicon layer with 2x4 grid, the 8 airbags of *In-Flat* are actuated with a 12V DC vacuum pump (*ref: WP36C*). The inflation and deflation air flow are equally distributed into 2x8 flows and controlled separately by 2x8 DC solenoid valves (*ref: CJAV08-2B05A*). The solenoid valves are powered by two 8-channel relay boards and controlled by a 16-channel PWM motor driver (*ref: PCA9685*).

4.2.2 Pressure detection and inflation control. To enable continuous input, the accuracy and speed of touch input detection is crucial. Different technologies have been explored to detect touch [10, 33],

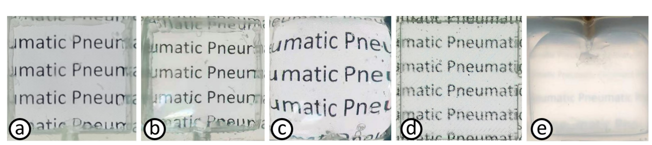

Figure 5: Different fabrication methods of silicon airbags: (a) using *SORTA-Clear 18* and fabricated with tape-covered PLA mold; (b) inflated with air; (c) filled with water; (d) fabricated with 3D printed PLA mold directly; (e) using *Ecoflex 20*.

but none of these can be used in our case considering the high requirement of transparency of the screen overlay. To this end, we used air pressure to detect the touch forces (as done in previous works [22, 32]) and built a force-detection system with 8 air pressure sensors (*ref: XGZP6847A*) with a sample rate of 40Hz. The sensors are directly connected to the silicon tubes that transport the air to the phone case. When the user touches the airbags, they are deformed and the pressure changes accordingly. As the sensors and the airbags are communicating vessels, the air pressure stays the same all the time. Thus, by detecting the pressure value in the airbags, we can get the equivalent touch pressure indirectly. When a airbag is inflated to a certain level, the inflation and deflation valves are closed to ensure air impermeability. Furthermore, we added close-loop pressure control. When the current pressure is outside the desired value range, the inflate or deflate valve is activated until the targeted pressure value is obtained. The real-time pressure value is sent to the interface and used for pressure-related control.

5 APPLICATION AND USE CASES

We illustrate potential use cases that leverage *In-Flat*'s capabilities to generate in-place dynamic output, to capture rich touch input patterns, and to support skin-like touch perception on smartphones.

Enhancing GUI interaction. *In-Flat* enables continuous pressure input, which can be mapped to GUI elements on smartphones, adding one additional dimension to the input channel. For example, *In-Flat* can be used for controlling the scroll bar: a *pinch-and-pull* would scroll up the page while a *press* would scroll it down. We can then map the pressure level to the speed of scrolling: the harder the user presses/pulls the airbag, the faster the page scrolls.

Enhancing bimanual interaction. *In-Flat* can support bimanual interactions when the silicon layer is put on the back of the device. This can be particularly useful when the users use an application that requires a full screen real estate. For example, productivity apps like Google Doc display the content (i.e., the text) and the keyboard, but the users also need to access the menu from time to time. Instead of making them go back and forth between typing and accessing the menu, with *In-Flat*, some airbags can be inflated to signify the available pop-up menus or widgets. As the users presses an airbag on the back of the smartphone, a pop-up/widget menu appears, and she selects the desired menu item. The pop-up menu disappears as soon as she releases her finger from the airbag.

Expressive interpersonal communication. As one of the most important non-verbal communication channels, touch plays an essential role in interpersonal affective communication. In addition to the commonly-used visual and audio channels, *In-Flat* allows users to generate and send touch input patterns to each other with expressive skin-like sensation, as opposed to vibrations in current smartphones that do not resemble human-like touch [22, 42]. As an example, when the user is having a phone conversation by holding the phone against the face, *In-Flat* can generate pressure patterns such as a caress, a poke, or a vibration on the cheek to express different emotions, as demonstrated in POKE [22]. If *In-Flat*'s silicon layer is placed on the back of device, when the users are having a video chat by holding the phone with one hand and contact the palm with the overlay, they can also send touch gestures like stroke, hit, pat, caress to each other's palm (Fig. 6a). This functionality can also be used when there is no verbal communication going on.

Parametric and tangible emojis. Past work has proposed tools that parameterize dynamic emojis through typing input variations [1]. Similarly, *In-Flat*'s continuous pressure input can be used to parameterize dynamic emojis (Fig. 1a). The emoji can be sent along with its pressure values (i.e., visual emoji enriched with inflated airbags). As such, the receivers can also dynamically interact with the emoji by pressing or pinching the corresponding inflated airbags, which will animate the visual emoji.

Expressive tangible notifications. *In-Flat* can support tangible notification systems. The tangibility increases the expressivity of the notification, for example *In-Flat* displays a breathing inflation pattern to notify the arrival of a message, with the inflation level changes depending on the importance of the message. The users can perceive the expressive notifications from afar without reading what is written on the screen. Conversely, a user receiving a call notification can press the airbag to hang up, or pinch-and-pull to send a preset quick reply to the caller.

Supporting visually-impaired users. Thanks to its tangible feedback, *In-Flat* can support eyes-free interactions, offering an alternative interaction channel for the visually-impaired users. Similar to the approach proposed by Rantala et al. [25], *In-Flat* can be used to display Braille outputs and to input Braille characters.

Interactive games. The gaming experience could be enhanced by combining visual, audio, and touch feedback. For example, in the *"catch-a-cat"* game (similar to the "whack-a-mole" game), a cat appears at a random place and the corresponding airbag inflates accordingly (Fig. 6b). Users can perform *press* and *pinch-and-pull* gesture on the corresponding airbag. The cat will emit a pleasant sound on a gentle press, a scream on a pinch-and-pull, a loud sound and run away on a strong press. The airbags inflates or deflates accordingly. *In-Flat* can also enhance musical gaming experience such as drumming (Fig. 1b). The pressure level and temporal variations can be mapped to the drum's percussion and rhythm. *In-Flat*'s overlay can also be used as gaming console buttons (Fig.6c).

Displaying objects with tangible properties. *In-Flat* provides tangible feedback that lets the user perceive the physical and the temporal property of a visual object (e.g., compliance, rhythm). For example, in the case of a remote medical consultation, the user can communicate his lung breathing via *In-Flat*, while the doctor can see the lung movement and touch the overlay to perceive the breathing remotely and directly with their finger (Fig. 1d).

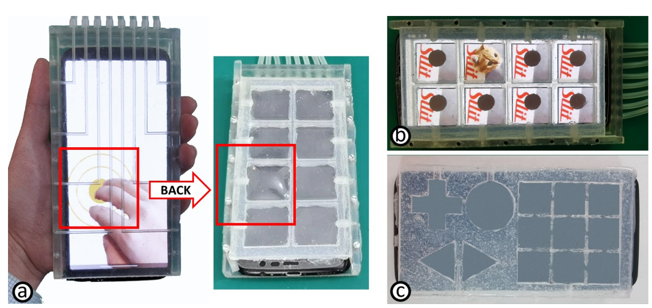

Figure 6: (a) Users can send each other social touch gestures like a pat in the palm, and the airbag of *In-Flat* will inflate accordingly. (b) Interactive game "catch-a-cat". (c) *In-Flat*'s overlay can include different shapes of airbags.

6 EVALUATION

Considering our goal to augment smartphones' touchscreens with rich touch input and output (I/O) capabilities via *In-Flat* interface, it is important to evaluate if users can perform continuous pressure input with *In-Flat* and the visual+touch output can enhance mobile interactions. Our goals were 1) to assess *quantitatively* if users can perform both *pinch-and-pull* and *press* input gestures with *In-Flat*; 2) to probe on user perception on the coupling between touch I/O and visual display *qualitatively*. To this end, we conducted a two-stage study: 1) an experiment on continuous input control where participants played a game similar to "Flappy bird" [36]; 2) a semi-structured interview where participants explored four pre-designed demo applications of *In-Flat* and then shared their perceptions.

6.1 Evaluation Design

6.1.1 Stage 1: Controlled experiment on continuous input control. The experiment was a [2x6] within-participant design with one primary factor *InputTechnique* (*pinch-and-pull* and *press*) and one secondary factor *PressureLevel* (Level 1 to 6). The game was inspired by "Flappy bird" [36], in which the players need to control the movement of a bird so that it flies through a small gap between pipes (Fig. 7). We chose game tasks as opposed to more abstract tasks to highlight the visual+touch coupling and increase the ecological validity of the study. In our game, the bird always flies on the left side of the screen while the pairs of pipes move towards the bird with a uniform speed (80 pixels per second). The participants only needed to position the bird on the correct height (i.e., movement on y-axis): *press* the airbag to fly down, *pinch-and-pull* to fly up.

Past studies showed that users can accurately control pressure input with 10±2 different levels [7, 21, 38]. Similarly, we tested 13 pressure levels: Level 1 to 6 of *press*; Level 1 to 6 of *pinch-and-pull*; and Level 0 when no input gesture was captured (i.e., baseline). The experiment consisted of three blocks of 12 trials: *BLOCK-1* of 6 *PressureLevel* x 2 replications of *pinch-and-pull*; *BLOCK-2* of 6x2 trials of *press*; and *BLOCK-3* of 12 mixed trials of *pinch-and-pull* and *press*. The order of *PressureLevel* was counter balanced using Latin Square across participants. *BLOCK-3* was always the last block. Half of the participants started with *BLOCK-1* and the other half with *BLOCK-2*. Each participant completed 36 trials.

6.1.2 Stage 2: Semi-structured interview on user perception. We designed and presented 3 demo applications described in Section 5 to participants: 1) the "*catch-a-cat*" game (Fig. 6b); 2) touch communication with the silicon layer placed on the back of the smartphone (Fig. 6a); and 3) dynamic visual and tangible feedback presented as an animated breathing lung (Fig. 1d). Finally, we prompted on the generalizability of *In-Flat* where other shapes of airbags were presented to the participants, and they were asked to reflect what kind of interaction they might have with these different shapes of airbags, and what other shapes of airbags they might needed in interaction. The shapes presented in the study were 9-button keyboard layout, a cross, a circle and two opposite triangles (Fig. 6c).

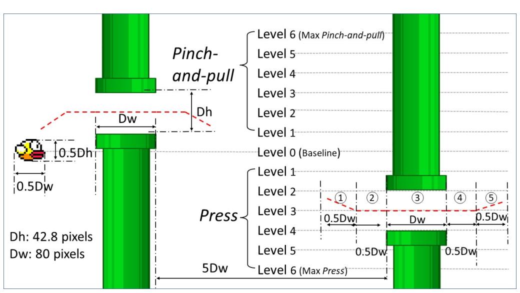

Figure 7: The parameters of the experiment interface and the illustration of the targets in Stage 1.

6.2 Participants and Apparatus

We recruited twelve participants (3 women, 9 men, 24-43 years old, median age 28.5). All participants used their right hand to interact with their smartphones in daily life. We used a OnePlus 5T smartphone with the interface displayed full screen (on 300 x 600 pixels). The game and the demos were web-based apps, connected with *In-Flat* through WiFi. For each participant, the calibrated pressure value for maximum *press*, maximum *pinch-and-pull*, and the baseline pressure were recorded and used throughout the session. The game also logged the distance between the bird and the target red line. The data were measured and recorded every 25ms.

6.3 Procedure

Following the health protocol, participants sat behind a desk in a wide meeting room with opened windows, with *In-Flat* placed on the desk. We disinfected the surface of *In-Flat* device before each session. All the participants read and signed the informed consent.

Stage 1 started with the calibration session: the participants were asked to perform the press and pull gesture with the maximum strength they will likely use in mobile interaction with the hand they used in their daily mobile interaction. For each gesture, we mapped the maximum pressure value to Level 6. The pressure value when no input was performed was mapped to Level 0. The mapping of the other levels (Level 1 to 5) was equally distributed in between the pressure values of Level 0 and 6. We then divided the screen's height into 13 rows and mapped each pressure level to each row (the middle point of a row was illustrated as a grey line in Fig. 7). We also drew a dotted red line to give a visual guideline on the path the participants needed to follow (Fig. 7). After passing through the pair of pipes, the participants can lift their finger to rest.

We included a training session where they could practice playing the game (5 minutes). In the testing session, the participants were asked to perform all three blocks of trials as accurately and stably as possible. After performing all the trials, we asked them to share their experience of using *In-Flat* as input device in this game. Stage 1 took around 25 minutes. In Stage 2, the participants were asked to play around each of the demo while thinking aloud and to share their perception after each demo. Stage 2 took around 25 minutes.

6.4 Measurement

To better evaluate the user performance of each input gesture, we divided the target path (i.e. the dashed red line in Fig. 7) into 3 parts: the *preparation phase* (part 1), the *test phase* (part 2, 3 and 4) and the *exit phase* (part 5). We measured: 1) *success rate*, the percentage of successfully completed trials (i.e., the distance between the bird's position and the red line is always lower than half of the bird size); 2) *accuracy*, the average distance between the location of the center of the bird and the red line; and 3) *stability*, the standard deviation of the distance between the center of the bird and the red line. We then performed the statistical analysis using JMP [16] with REML method followed by a post-hoc analysis with Tukey HSD.

6.5 Quantitative Results

6.5.1 Participants performed pinch-and-pull gestures as well as press gestures. The *success rate* for *press* and *pinch-and-pull* were 84.7% and 83.8% respectively. Given that the *pinch-and-pull* gestures were a relatively new interaction technique, we were surprised to find that there was no significant effect of *InputTechnique* ($F_{1,11}$=0.05, p=0.82) on *success rate*. *PressureLevel* ($F_{5,55}$=1.36, p=0.23) and *BlockID* ($F_{2,22}$=0.84, p=0.43) also did not have any significant effect on *success rate*. We also did not find any significant effect of *InputTechnique* on the input *accuracy* (i.e., the average distance between the bird and the target path), neither during the *preparation phase* ($F_{1,11}$=1.44, p=0.23), the *test phase* ($F_{1,11}$=2.59, p=0.11), nor the *exit phase* ($F_{1,11}$=2.43, p=0.12). Similarly, there was no significant effect of *InputTechnique* on the input *stability* (i.e., the standard deviation of the distance) during the *preparing phase* ($F_{1,11}$=1.32, p=0.25), *test phase* ($F_{1,11}$=2.93, p=0.09) and *exit phase* ($F_{1,11}$=1.88, p=0.17). This suggested that the participants could perform *pinch-and-pull* gestures as accurately and as stably as *press* gestures.

We suspected there was a possibility that this result was impacted by some failed trials in which the participant gave up right away and released their finger(s) once the bird hit the pipe. Hence, we performed another analysis with the successful trials only (84% of total trials). The statistical analysis yielded similar results for *success rate* and *accuracy*. The only difference was a significant effect of *InputTechnique* on the *stability* during the *test phase* ($F_{1,11}$=21.7, p<0.0001). That said, the difference between the two standard deviations was rather small (only 0.25 pixels: $SD_{PINCH-AND-PULL}$=1.82 pixels and SD_{PRESS}=1.57 pixels), so we can still conclude that the participants performed *pinch-and-pull* as well as *press* gestures.

6.5.2 Performing the highest level of pinch-and-pull gestures was more challenging. Although *PressureLevel* did not have a significant effect on *success rate* ($F_{5,55}$=1.36, p=0.24), the success rates for *PressureLevel*=6 for both *InputTechnique* were lower than the other five levels: 76% for overall success rate, 72.2% and 80.6% for *pinch-and-pull* and *press* respectively. We also found a significant effect of *PressureLevel* on both the *average distance* and the *standard deviation of distance* during all three phases (all p<0.05). A post-hoc analysis with Tukey HSD revealed that Level 6 had significantly higher *average distance* (i.e., *accuracy*) and *standard deviation of distance* (i.e., *stability*) in all three phases. There might be two possible explanations for this result: 1) As the distance the bird needs to travel from the baseline to the target location in Level 6 was the largest (Fig. 7), it required more physical preparations to perform the gestures, resulting in lower performance; 2) The participants might have performed the input gesture as intensely as possible to reach the top or the bottom of the screen for Level 6 as they knew that these trials required the largest amount of force, hence, reducing the *accuracy* and the *stability*.

To summarize, given that we calibrated the maximum pressures (i.e., Level 6) for each gesture based on each participant's maximum "comfortable" pressures, the data suggested that while they were

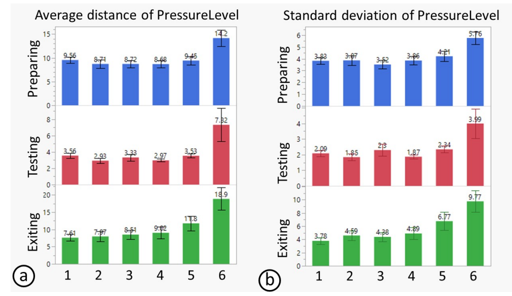

Figure 8: (a) The average distance and (b) the standard deviation for all *PressureLevel* in all three phases.

still able to perform successfully, the accuracy and the stability might be slightly compromised. This can be potentially reduced by imposing a better calibration session: instead of performing just one pressure input and record its value as the maximum pressure level (as done in our current experiment design), we can ask the participants to perform several pressure inputs and record their average or median value as the maximum pressure level. Their perception of maximum "comfortable" pressure might also change over time as they get more used to the interaction.

6.5.3 More preparation was needed when the participants switched between pinch-and-pull and press gestures. BLOCK-1 only consisted of *pinch-and-pull*, BLOCK-2 only *press*, while BLOCK-3 consisted of both gestures in a mixed order. We found that *BlockID* had a significant effect on the *average distance* ($F_{2,22}$=24.6, p<0.0001) and the *standard deviation of distance* ($F_{2,22}$=33.6, p<0.0001) during the *preparation phase*, as well as on the *standard deviation of distance* during the *exit phase* ($F_{2,22}$=6.32, p=0.002). A post-hoc analysis on the three conditions revealed that the performance was significantly lower for BLOCK-3 than for the other blocks. There might be two possible explanations. First, given that in BLOCK-3 the *pinch-and-pull* and *press* gestures were mixed, some participants might constantly switch their finger position between *pinch-and-pull* with two fingers and *press* with one finger, making performing the gesture more challenging. Second, with 12 different pressure levels (i.e., 6 levels each for *pinch-and-pull* and *press*) mixed within one block, the target level's heights in one trial to another had a larger difference than BLOCK-2 and BLOCK-1 that only included 6 levels. This implied more travelling distance when switching between trials. Thus, the challenge to prepare the gesture was higher in BLOCK-3, which might lead some participants to exit the area earlier to prepare for the next trial.

6.6 Qualitative Results

6.6.1 Participants felt having more control when performing the pinch-and-pull gestures. Surprisingly, although the performances of *pinch-and-pull* and *press* were quite similar, half of the participants (6/12) reported that they felt that they had a better sense of control for *pinch-and-pull*. Only 2 participants felt that they could control the *press* gestures more accurately. Some participants (4/12) explained that it was because they had more rooms to pull the airbag upwards with, in contrast with pressing the airbag towards the screen which at some point blocked their finger movement. Half of the participants (6/12) also mentioned that, with *pinch-and-pull*, the silicon's elasticity provided additional sense of resistance onto their finger, and this resistance kept increasing as they pulled harder. In contrast, when pressing harder, the silicon surface eventually touched the rigid screen, so the perception became somewhat similar to just touching the screen. That said, most participants (8/12) still reported that pressing the airbag increased the sense of control compared to touching the rigid screen directly, because the soft airbag deformed under pressure, consequently providing additional sensory cues and enabling more freedom of finger movement.

6.6.2 Participants appreciated the coupling between visual display and touch I/O interactions. All 12 participants appreciated the sensation of touching the *In-Flat*'s overlay. They perceived the silicon's texture as "*comfortable*" (8/12) and the "*bouncy feeling*" of the airbag was "*interactive*" and "*fun*" (5/12). Most participants (10/12) thought the transparent silicon layer allowed them to see the visual display with no issues. More than half of participants (7/12) highly appreciated the visual effect of dynamic movement of the airbag in the animated breathing lung demo, and found that it "*follows well the movement of the GIF*" (6/12) and "*[looks] vivid and natural*" (3/12). Thanks to the combination of two modalities (visual+touch), they "*can feel what [they] see*" (P2) and it was "*dynamic and playful*" (P5) and "*makes the phone alive*" (P1,P10). The participants also appreciated the possibility of using different shapes of silicon layer including grids, buttons, and console controllers. They expressed willingness to use *In-Flat* in their daily life and proposed different ways of using it, for example as landmarks on the screen and help guiding the movement of the finger (P4) and providing full tactile experience when watching a movie (P7).

7 DISCUSSION, LIMITATIONS, FUTURE WORK

Improving pressure control on smartphones. Thanks to the high stretchability of the *In-Flat*'s silicon layer, users can perform not only *press* but also *pinch-and-pull* input gestures. To the best of our knowledge, previously proposed touch devices did not specifically discuss nor compare user performance of *pinch-and-pull* and *press* gestures. Our evaluation with *In-Flat* indicated that the participants were able to perform *pinch-and-pull* gestures as accurately as *press* gestures, despite the fact that they mentioned of never using *pinch-and-pull* gestures to interact with digital devices in their daily lives. This shows a promising opportunity to leverage inflatable silicon layers for rich pressure-based input capabilities.

Reflecting on the results of our evaluation, we see different ways to improve pressure-based controls on inflatable silicons. We only tested six levels of *pinch-and-pull* and six levels of *press.* The participants could perform both gestures with high success rate and high accuracy. Fruchard et al. [10] suggested that pressure-based input like *press* on a soft surface was underestimated. Similarly, the performance of the *pinch-and-pull* gestures with *In-Flat* might also be underestimated. A future study on *pinch-and-pull* is needed to better determine its full potentials, i.e., how many levels of *pinch-and-pull* gestures can the users control reliably.

Although statistically not different, some participants in our evaluation study mentioned that performing the *pinch-and-pull* gestures required more physical demands than *press* gestures because the silicon's surface was too smooth to pinch. To make the surface easier to pinch, we can consider using different materials that can induce larger frictions or fabricate the silicone to include a small handle that is easier to pull. However, this might compromise the transparency that is needed to enable clear visual display when put on top of the screen.

Improving the technical implementation. The current prototype, which was conceived as a probe to experiment on the *press* and *pinch-and-pull* gestures and to explore applications and use cases, still has some limitations. First, due to the electrical insulation property of the silicon we used, the current *In-Flat* prototype does not support touchscreen interactions when the overlay is placed on top of the screen. However, researchers in material science proposed new materials that are not only stretchable and transparent, but also conductive [44, 44]. Combining *In-Flat* with these new materials would thus solve this limitation. Second, pneumatic technology limits the mobility because of the relatively important size of the actuation device. This problem could be solved by adopting a new, more compact, pneumatic technology such as FlowIO [28]. Moreover, because of its reduced size, this new technology may allow using more cells than in the current prototype.

Exploring different inflation medium. Another interesting research direction would be to use other media than air to inflate the silicon bags. For example, we explored water-inflated silicon bags in Section 4. The observed plano-convex lens effect then affects the visual display on the screen, a feature that may be interesting for certain tasks, such as showing details on the screen [34] or performing fish-eye effects [23]. As participants mentioned, the tactile feeling (e.g. complicity/stiffness, density, temperature) could change with different medium, and fluids with different colors could be used to make the airbags work as physical filters.

Beyond augmenting smartphones. The current design of *In-Flat* focused on smartphone interactions, but it can potentially be adapted to larger devices, by increasing the number of airbags. As some participants mentioned in the evaluation, *In-Flat*'s overlay can be designed to be detach-and-play on any device such as a smartwatch or a tabletop. One factor to be considered is the trade-off between size and mobility: the bigger the overlay is, the more complex pneumatic control it needs, hence, limiting its mobility. This may not be an issue for fixed devices like tabletops, but future work should address this issue for bigger mobile devices like tablets.

8 CONCLUSION

This paper aims to augment smartphones with touch I/O capabilities. With our fabrication approach, we produce pressure-sensitive silicon layers with high transparency level, enabling users to 1) see the visual display; 2) perceive tangible affordances when *In-Flat*'s overlay is inflated; and 3) perform continuous pressure input gestures. As such, we enable in-place coupling between visual objects displayed on the smartphone and touch I/O interactions. The participants in our evaluation study were able to perform both *pinch-and-pull* and *press* gestures on *In-Flat* with similar performance. They also appreciated the fact that they could still see the visual display, and at the same time, perceive the dynamic tangible affordance that enriched their visual perceptions. Our work demonstrates the potentials of supporting rich tangible interactions on smartphones, in particular the potential of adding in-place pressure-based I/O capabilities on touchscreens.

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