Twisting Touch: Combining Deformation and Touch as Input within the Same Interaction Cycle on Handheld Devices

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ABSTRACT
We present a study that investigates the potential of combining, within the same interaction cycle, deformation and touch input in a handheld device. Using a flexible, input-only device connected to an external display, we compared a multitouch input technique and two hybrid deformation-plus-touch input techniques (bending and twisting the device, plus either front- or back-touch), in an image-docking task. We compared and analyzed the performance (completion time) and user experience (UX) obtained in each case, using multiple assessment metrics. We found that combining device deformation with front-touch produced the best UX. All the interaction techniques showed the same efficiency in task completion. This was a surprising finding, since multitouch (an integral input technique) was expected to be the most efficient technique in an image docking task (an interaction in an integral perceptual space). We discuss these findings in relation to self-reported qualitative data and observed interaction-procedure metrics. We found that the interaction procedures with the hybrid techniques were more sequential but also more paced. These findings suggest that the benefits of deformation input can still be observed when deformation and touch are combined in an input device.

Author Keywords
Deformable UI; organic UI; user interface; bend; twist.

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

General Terms
Design; Human Factors; Measurement.

INTRODUCTION
As a subset of Organic User Interfaces (OUIs) [31], Deformable User Interfaces (DUIs) are characterized by the use of deformation gestures as input in interaction cycles. To perform common deformation gestures on handheld DUIs (e.g., bending, twisting, stretching, etc.), people need to apply pairs of forces or torques in opposite directions, which is usually achieved by operating DUIs symmetrically with both hands. While existing DUIs have shown the potential of deformation as input in isolation (e.g., [19; 21; 29], it is still unclear how deformation will coexist with other input techniques.

Currently, touch is the dominant input technique for the design of interactions with rigid handheld devices. It is reasonable to predict that future flexible devices will also have touch sensitive surfaces. In this context, the following question arises: can interface deformation and touch co-exist in the same interaction cycle? This is a complex question when considering the many different devices, interaction cycles and gesture-to-action mappings that can be studied.

In this paper we investigate the combination of deformation gestures and touch as input within the same interaction cycle. We do so by reporting an in-depth study in which deformation and touch gestures are used in combination to complete an image-docking task. We measured pragmatic (i.e., usability) and hedonic (i.e., UX) aspects of the interaction with three different interaction designs implemented on the same handheld device: two hybrid designs integrating deformation and touch, and one design in which only multitouch was used. We identify various factors that are relevant for the optimal design of hybrid deformation-plus-touch interactions, and we reflect on the benefits that the transition from touch-only to hybrid interfaces can bring.

The rest of this paper is structured as follows. First, we review relevant related work. Then, we describe our experimental study and discuss the decisions that we made in its design. Finally, we report the results of the study, followed by a discussion and conclusions.

RELATED WORK
Along with notable benefits that multitouch interaction has brought about in terms of direct manipulation, it has also contributed to impoverishing the tangible physicality of many handheld interfaces. With some eloquence, touch interfaces have been described as "images behind glass" [32], meaning that direct manipulation stops when the finger gets in contact with the touch surface, unable to reach the actual objects. In reaction to this, the HCI community has proposed radically new approaches to UI

design, such as Tangible User Interfaces (TUIs) [14] and the already-mentioned OUIs [31]. These new approaches share the view that current interactive technologies dramatically underuse the capacity that human hands have to extract rich information from the physical world.

In some of the OUI examples that have been proposed, users interact directly with the material the interface is made of, by physically deforming it. This subset of OUIs has also been called DUIs [19], so as to highlight the fact that the user deforms the interface actively during the interaction. Much of the work conducted in this area has been inspired by interacting with flexible materials that can offer paper-like affordances [6; 22; 29]. Within this theme, the use case of the electronic book and document manipulation has received particular attention [30; 34; 35]. Mobile use scenarios (e.g., phone functionality and street navigation with maps) have also been central to research, with form factors that resembled flexible versions of mobile devices [19; 21; 29]. Other proposed areas of use included controlling home appliances [23] and videogames [38].

Much of the research has resulted in proposing catalogues of deformation gestures, which applied not only to the flexible bending of semi-rigid material [6; 21], but also to rollable displays [16], foldable form factors [13; 17], and even crumpling of the device [22]. Of all the gestures proposed, bending and twisting of the whole device with two hands are among the most studied [2; 7; 10; 18-20]. These are also the gestures that we included in our study.

Once OUIs were proposed, researchers started revising our current knowledge regarding touch for the cases in which the touch surfaces are not planar and/or rigid [1; 27]. The question about integrating input deformation gestures with other input techniques, and in particular with touch, also came up naturally. Other hybrid input techniques have previously been proposed around touch, such as motion sensing plus touch [4; 11] and pressure (i.e., normal force) plus touch [24; 26]. Burstyn *et al*. [5] recently investigated the combination of deformation and touch on a handheld thin flexible display, in a three-dimensional navigation scenario. One of the hybrid designs investigated (one-handed squeeze with the non-dominant hand, plus touch with the dominant hand) offered performance that was superior to one-handed multitouch. Another technique in which the deformation was two handed did not offer any performance benefit.

EXPERIMENTAL STUDY

Our main research goal was to conduct an in-depth investigation about the potential of combining deformation and touch in a single interaction cycle, using a handheld interface. For this goal, we selected: (i) a functional handheld interface that could sense deformation as well as touch on its surface; (ii) an interaction task with enough degrees of freedom (DOFs); (iii) interaction techniques that mapped input deformation and touch to the task; (iv) a set of research methods, both quantitative and qualitative.

Hardware Interface

We built a handheld deformable input device that could be bent and twisted for interaction (Figure 1). It also included a multitouch panel on one side (Figure 3). The device consisted of a rectangular casing, with dimensions W·H·D=139·78·10 (mm), designed to be held with both hands on landscape position. The casing could be deformed by hand, and it behaved elastically (i.e., it *returned* to a flat configuration when forces were released). Deformation sensors inside the device (i.e., strain gauges) detected bend and twist gestures with 10-bit precision in a range of 15 degrees in each direction, both for bend and for twist input actions. Further deformation was mechanically impossible. The rotational stiffness of the device (the torque required to cause rotational deformation when bending or twisting) was approximately 1.5 N·m/rad (similar to the medium-stiffness devices used in [18; 20]). A multi-finger capacitive touch panel with dimensions W·H=78·45 (mm) was installed centered on one side of the device, thus framed by a non-sensitive area that allowed holding and deforming the device without triggering accidental touch input actions. The touch panel, made of thin flexible material, bent and twisted together with the device. We very deliberately designed the interface with this form factor, mechanical properties and range of deformation, thus departing from paper-thin form factors already being broadly studied by the OUI research community (see section on related work). When designing this interface, we were building on our earlier *Kinetic Device* [19] prototype, and on the user research that we conducted to inform its design [18; 20].

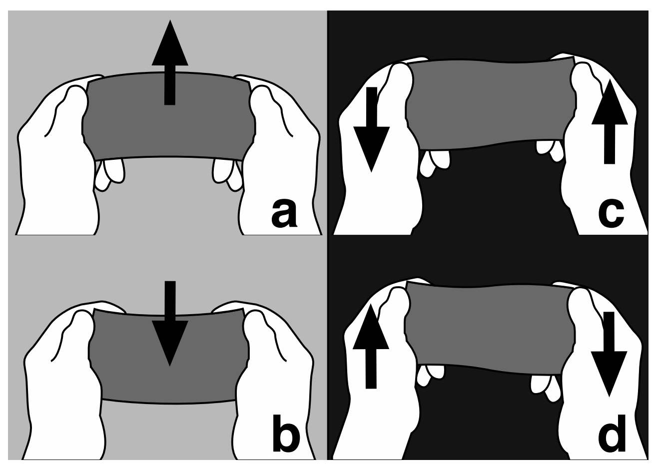

Figure 1. Deformation gestures consist of: bending the device up (a) or down (b), and/or twisting the device in (c) or out (d).

The device was connected to a laptop that collected readings from all the sensors at a rate of 33Hz. The device did not include a visual display on its main body. Instead, an external display connected to the same laptop was used to present visual feedback (Figure 4). Using indirect touch on an external display may not best represent the majority of touch devices currently in use (e.g., touch smartphones). However, we chose this solution to provide a similar level of indirectness for touch and for deformation gestures, since the latter could not currently be applied directly on the objects displayed on screen. In addition, as interactions took place with one visual object at a time, there was no need to touch the precise location of the object, but rather its relative position within the panel. Since the hands remained at a fixed distance from each other, proprioception allowed the user to look at the display only, and not at the hands (like in [37]). This is fundamentally different from large surfaces with which direct and indirect touch have been compared [28].

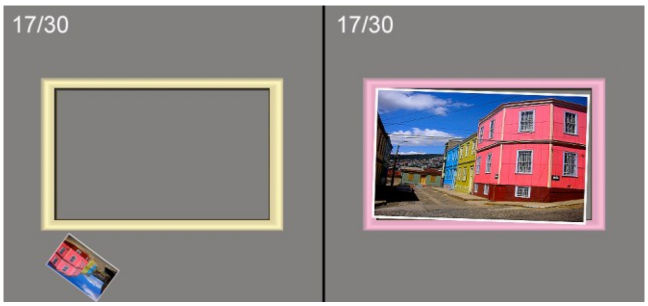

Figure 2. The photo manipulation UI. *Left*: a new photo appears outside the yellow frame. *Right*: the user has put the photo inside the frame by panning, rotating and scaling the photo. The frame blinks in pink to provide feedback.

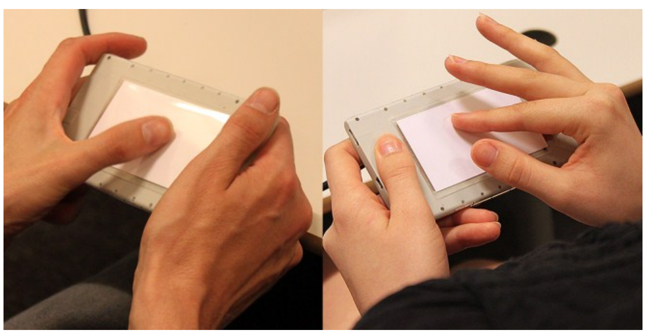

Figure 3. Different interaction techniques. Left: *DeformTouch* consists of deforming and touching on the front (*DeformBackTouch* is similar but participants had to touch on the back). Right: *Touch* used multitouch capabilities.

Application

We implemented a photo manipulation (image docking) application with which to perform interactions in the study ([25] includes a review of studies employing similar tasks). The task was to use three different interaction techniques to make a photo fit within a frame by panning, scaling and rotating it. This task was four-dimensional (one more than in [5]): the x and y coordinates of the center of the photo, its angle of rotation and its level of scale (big/small). Such a task has an *integral* perceptual structure[1] [15; 33], which makes it a good candidate for *parallel* manipulations of all the DOFs, rather than modifying them serially.

The user interface consisted of a yellow photo frame shown on top of a grey background. At the start of each trial (Figure 2, left), a new photo appeared on the screen, randomly picked from a pool of 30 color photos showing landscapes, buildings, faces, animals, and objects. The initial position, size and rotation of the photo were also randomly defined, always fulfilling all of the following conditions, in order to avoid repetition and predictability of the initial configuration, while also avoiding short-distance manipulations: (i) the center of the image was outside the target frame, (ii) the image was scaled down to 0.5, 0.25 or 0.16 times the size of the frame, and (iii) the image was rotated at least 100 degrees away from the target orientation. We allowed for a maximum error of 5% in position, size and rotation of the photo to consider it "on target". When intersecting with the frame, the photo was always shown above the frame. Once a photo was correctly placed inside the frame, the yellow photo frame blinked twice in pink to provide feedback to the participant (Figure 2, right), after which a new trial could start.

Interaction Techniques

As mentioned, the docking task we devised has an integral perceptual structure. In such cases, using an interaction technique that is also integral can offer superior performance since it permits following a route to the target that is closer to the Euclidean distance (i.e., a "direct line", by manipulating concurrently or simultaneously all the dimensions) [15; 33]. Multitouch is one such integral technique [25]. Therefore, we included a multitouch-only technique as a comparison condition that could offer, in principle, optimum efficiency (*Touch*, Figure 3).

As second and third experimental conditions, we implemented two variations of the same hybrid combination of deformation and touch: *DeformTouch* (using front-touch) and *DeformBackTouch* (similar, except using back-touch). These hybrid interaction techniques are *separable* except for the two dimensions controlled with touch (x and y coordinates, while panning). For this reason, the efficiency attainable with the hybrid techniques should be inferior than with *Touch*: the route in the interaction space would follow more of a "city-block" trajectory, with less simultaneity in the manipulations of the four dimensions of the interaction task. However, facilitating some separability (like in [25]) could be desirable to implement certain task-completion strategies, such as first aligning the orientation with the frame, then matching its scale and finally centering it. Thus, we decided to compare all three techniques and observe if the advantage of using the integral technique (*Touch*) was indeed significant.

In *DeformTouch* and *DeformBackTouch,* after extensive piloting, we defined that photo rotation was achieved by twisting the device *in*/*out* (Figure 1 c,d), resulting in the

[1] Attributes that combine perceptually are said to be *integral*; those that remain distinct are *separable* [15].

photo rotating clockwise/counterclockwise respectively. Also in both hybrid techniques, we defined that the photo was scaled up/down by bending the device *up*/*down* (Figure 1 a,b) respectively (as in [19; 21; 22]). With both bend and twist, the amount of deformation was proportional to the speed of the resulting displacement (first order controls). Finally, by placing the touch panel on the front (*DeformTouch)* or on the back of the device (*DeformBackTouch*), users could pan the image using one finger (zero order). We included these two variants of the hybrid technique in order to observe if the natural position of the fingers on the back of the device conduced to a good combination of deformation and touch. Unlike with previous work on back-of-device touch (e.g., [3]), we did not provide any means of seeing the contact position of the fingers on the back of the device. Instead, as mentioned, we relayed on the proprioception of the user's hands placed around a fixed frame, for the manipulation of one objet at a time (no need to aim at absolute positions).

The *Touch* technique was implemented following common multitouch interaction designs: a two-finger circular gesture to rotate an image (e.g., by using both thumbs or the index and thumb of the same hand), a pinch gesture to scale the image up or down, and swiping the photo with one finger to pan it around the screen (all of them zero-order controls with 1:1 mapping of angles and distances).

In all three techniques, the surface of the touch panel was mapped to the total display area, meaning that the center of the photo could be displaced to any position and, in *Touch*, also scaled to full screen and rotated to any angle in a single stroke. As mentioned, the user did not need to initiate the manipulation by placing the fingers on the location of the photo. Rather, the displacements were calculated relative to the first point of contact with the panel. This feature allowed users to constantly look at the display and achieve visuomotor coordination by relying on proprioception, both when using front- and back-touch.

Participants

The experiment was conducted with 24 participants that varied in gender (12 male, 12 female), age (20-48 y/o), handedness (18 right, 6 left), and background (14 technical, 10 non-technical). All participants had previous experience with graphical user interfaces and owned a mobile phone. Regarding their familiarity with multi touch input devices, most participants had touch-enabled mobile phones (20/24), some owned tablets (10/24), trackpads (8/24) or used graphics tablets (e.g., Wacom) (4/24). Most participants used their cameraphone to take photos (23/24) and browsed the resulting pictures directly from their mobile phone (20/24). All participants were tested individually.

Experiment Design and Procedure

We compared the three interaction techniques in the task just described, by using a combination of quantitative and qualitative research methods. With this, we intended to obtain a complete picture of the differences between the techniques that we were comparing, in terms of the performance they offered, the strategies followed by the participants, and the effects of our design decisions on the whole UX. We used the following research methods: quantitative analysis of objective metrics (time efficiency and procedure metrics), quantitative analysis of subjective metrics (extended Raw NASA-TLX and AttrakDiff), and qualitative analysis of subjective data (interviews and observation data via Affinity Diagrams).

Each 70-minute session with a participant consisted of three parts: introduction, completion of task (including evaluation in questionnaires), and a semi-structured interview. First, we explained the purpose of our experiment (10 min). Then, participants performed 10 training trials followed by 30 test trials in each condition, in counterbalanced order (30 min). Each session was conducted in a meeting room. The prototype was set on a table and the participant sat at the table in front of a computer monitor (Figure 4). One researcher (the facilitator) sat next to the participant, while another researcher made notes and took pictures from a distance. All experiments, including the semi-structured interviews, were recorded on video. After the interviews, participants were given two movie tickets each, to compensate them for their time.

Trial completion time was used as the main quantitative measure of efficiency to compare the different techniques. In order to understand the interaction styles and procedures employed, we also monitored these metrics:

- *Concurrency.* The extent to which different input actions (pan, rotate, scale) were performed in parallel. The ceiling value of 3 meant full overlap: all three separable input channels (bend, twist, touch) used simultaneously.
- *Density*. Fraction of the total trial-completion time in which actual interaction happened (at least one input channel being used). This took into account the total idle time in the interaction cycle.
- *Fragmentation*. Number of distinct interaction segments that were performed to complete the task. This quantified the number of idle periods in the interaction cycle, with no input channel being used.

At the end of each experimental condition, we asked participants to fill-out two validated questionnaires: Raw NASA-TLX[2] [8] and AttrakDiff[3] [9]. Finally, we conducted semi-structured interviews in which we asked a consistent set of open-ended questions, prompting participants to reflect back on their experience while performing the tasks (30 min).

[2] http://humansystems.arc.nasa.gov/groups/TLX
[3] http://www.attrakdiff.de/en/Home/

During the data analysis stage, Affinity Diagramming [12] was used to analyze the data collected through observation and the data from the semi-structured interviews. Two researchers independently made notes as they watched the videos of each participant's experimental session. The same two researchers collaboratively analyzed the qualitative data through several interpretation rounds. The affinity diagram supported categorization and visualization of the main themes emerging from the data. These themes form the heart of the qualitative part of our results section.

Based on prior knowledge about the strengths and weaknesses of the techniques compared in the study, we had expectations about what the findings for some of our metrics might be. First, we predicted that the UX would be superior with hybrid techniques, as they would benefit from the superior tangibility of malleable OUIs, as well as the reported good controllability of continuous parameters [19]. In the comparison between hybrid techniques, we predicted that, due to familiarity, UX would be superior with front than with back-touch. However, we expected that the natural positioning of the fingers on the back when holding the device could result in matching task completion time for both hybrid techniques. Also about performance, we hypothesized that *Touch* would be the most efficient technique of all three (shortest time for completion), since it was the only fully-integral input technique in the study, and our task also had an integral perceptual structure [15; 33]. For the same reasons, we also hypothesized that we would observe a higher degree of concurrency of processes with *Touch* than with the hybrid techniques.

Below, the *Results* section reports the outcomes from our analysis of all the data collected. Later, under *Discussion*, we discuss all the results together and devise conclusions.

RESULTS

Quantitative

We analyzed the quantitative data collected in log files, using standard ANOVA analysis (one-way, three-conditions, within-subjects design). We found no significant differences between interaction techniques in task completion time [F(2,46)=2.527; p=0.091] (Figure 5a). Thus, the time required to complete the task with *Touch* (M=8,892s; SD=3,105) was not significantly different from the time required in *DeformTouch* (M=8.588s; SD=2.247) and *DeformBackTouch* (M=9.848s; SD=2.728).

Regarding the style of the interaction, we found that the interaction technique significantly affected the observed levels of *Concurrency* (Figure 5c) and *Density* (Figure 5d), but not on *Fragmentation* (Figure 5b). The strongest of these effects was on *Concurrency* [F(2,46)=1049.757; p≈0; FLSD[4]$_{95\%}$ = 0.0599], where the average level was much higher with *Touch* (M=2.375; SD=0.13) than with *DeformTouch* (M=1.172; SD=0.093) and *DeformBackTouch* (M=1.218; SD=0.097). The significant effect on *Density* [F(2,46)=3.412; p=0.042; FLSD$_{95\%}$ = 0.039] was again higher in *Touch* (M=0.694; SD=0.049) than in *DeformTouch* (M=0,644; SD=0.088) and *DeformBackTouch* (M=0.664; SD=0.088). As just mentioned, there was no statistically significant difference between conditions in the levels of *Fragmentation* observed in *DeformTouch* (M=9.418; SD=2.279), in *DeformBackTouch* (M=10.05; SD=2.362), and in *Touch* (M=9.519; SD=3.939), [F(2,46)=0.426; p=0.614].

Figure 4. Experiment setup with one participant manipulating images while seated in front of the computer monitor as the facilitator takes notes in the back.

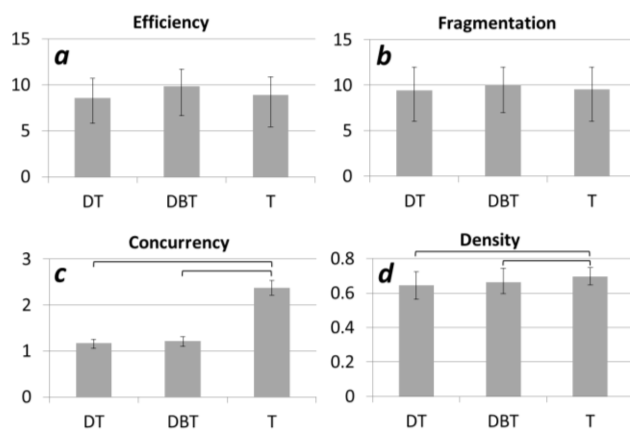

Figure 5. Effect of the interaction technique on (*a*) Efficiency (completion time, secs.), (*b*) Fragmentation, (*c*) Concurrency, (*d*) Density. Error bars show interquartile distance. Braces indicate significant differences (p<0.05 FLSD). DT: DeformTouch; DBT: DeformBackTouch; T: Touch

Subjective Workload and Extension Categories

The results from the extended Raw NASA-TLX questionnaire are presented graphically in Figure 6. The *Task Load Index* itself (the main measure derived from this questionnaire) showed that, overall, the level of subjective workload was lower when interacting in the *DeformTouch* condition (M=6.701; SD=2.771) than when interacting in either the *DeformBackTouch* condition (M=8.389; SD=3.429) or the *Touch* condition (M=7.958; SD=2.673), [F(2,46)=4.066; p=0.027; FLSD$_{95\%}$ = 1.238]. We then inspected the data collected in the sub-categories, in order

[4] Fischer's Least Significant Difference *post-hoc* test

to have a better indication of the origin of this significant difference. We found that *Physical Demand* and *Performance* presented statistically significant differences when comparing interaction conditions. *Performance* (i.e., the perception that the participant had of his/her own level of performance) was significantly better when interacting with *DeformTouch* (M=14.5; SD=4.086) than when interacting with *DeformBackTouch* (M=12.042; SD=4.554) or with *Touch* (M=11.875; SD=4.456), [F(2,46)=6.744; p=0.003; $FLSD_{95\%}$ = 1.611]. With *Physical Demand*, the lowest levels of were observed with *DeformTouch* (M=6.458; SD=3.349) and *Touch* (M=6.875; SD=3.167), with comparable levels. These levels were both statistically significantly lower than in *DeformBackTouch* (M=8.5; SD=4.17), [F(2,46)=4.768; p=0.013; $FLSD_{95\%}$ = 1.406].

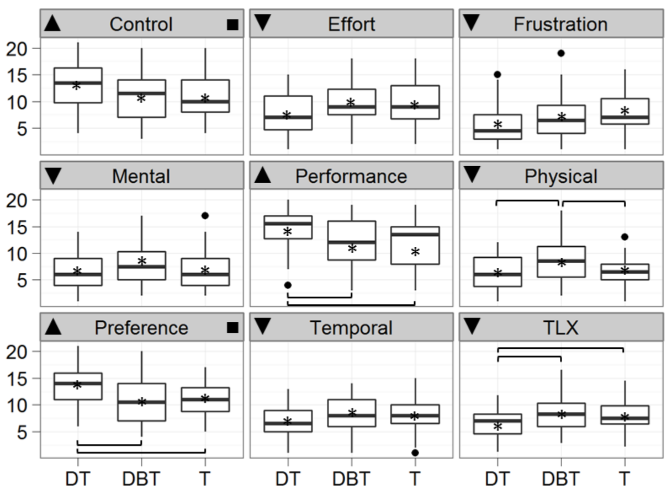

Figure 6. Extended Raw NASA-TLX index and categories. DT: *DeformTouch*; DBT: *DeformBackTouch*; T: *Touch*; braces indicate significant differences (p<0.05 FLSD); ▲: higher ratings are better; ▼: lower ratings are better; ■: metrics that do not belong to NASA TLX; *: mean value

Of the two extension categories to the NASA-TLX questionnaire (not used to calculate the *TLX* index itself), *Sense of Control* did not show any significant differences, with the average levels (M=13; SD=4.737), (M=11.125; SD=4.739), and (M=11.208; SD=4.597) respectively for *DeformTouch*, *DeformBackTouch* and *Touch* [F(2,46)=2.595; p=0.086; $FLSD_{95\%}$ = 1.872]. In contrast, we found statistically highly significant differences on *Preference* [F(2,46)=6.259; p=0.004; $FLSD_{95\%}$ = 1.824]. The highest reported *Preference* was with *DeformTouch* (M=13.75; SD=3.97), a level that was significantly higher than the levels for both *DeformBackTouch* (M=10.875; SD=4.675) and *Touch* (M=11.083; SD=3.682).

Qualitative

Combined Deformation and Touch Provides New Interaction Possibilities

Participants (16/24) were generally positive about combining deformation and touch, and about the extra possibilities it provides for interaction. Participants saw the potential behind deformation and touch, describing it as an attractive and interesting way to interact: "It's quite attractive and very fast to rotate and manage [photos]." (P23) "It's good to have more ways of controlling [mobile devices], so not just fingers." (P15) A few participants (3/24) specifically mentioned back-touch and how it could play a role when interacting with deformable devices: "It was interesting, (…) having something to do with my other fingers than just thumbs." (P21) On the AttrakDiff questionnaire (Figure 7), both hybrid techniques are located above *Touch* on the attractiveness (ATT) dimension. These ratings indicate that the participants perceive the interaction using both deformation techniques as motivating and appealing. In particular, the difference between *DeformTouch* and *Touch* is statistically significant.

Most participants (18/24) described deformation as fun, partly due to the fact that they had never experienced it before: "This is fun! (…) It felt like a game. I was really enjoying it and into it!" (P5) However, a few participants explicitly mentioned that deformation was fun in its own right and not only because it was novel: "[It was fun despite that] the novelty wore off after a while." (P18) On stimulation (HQ-S), one of the two hedonic quality dimensions of AttrakDiff (Figure 7), both deformation techniques are clearly in the above-average region, implying that people think the interaction with the prototype is creative and inventive. In terms of the stimulation aspect, the difference between deformation and *Touch* is statistically significant.

Combined Deformation and Touch Requires Learning

Most participants saw the potential behind combining deformation and touch. However, a good number of participants (9/24) generally preferred touch only over deformation. They often mentioned familiarity with touch as the main reason to find it easier than combined deformation and touch to perform the tasks: "Touch was the easiest because it is similar to what I am used to." (P7) However, almost half of the participants (10/24), including some of those that said they preferred touch, also said that it takes time to get used to deformation. "After I got the idea of [deformation], it was easy to do." (P18) They said if they would use combined deformation and touch for a longer period of time, then they might perform better with it: "It's the first time I am doing [deformation] so of course it's harder to use, but I think the learning curve is fast." (P16)

Especially at the start of each technique, half of the participants (12/24) encountered sporadic problems and would accidentally trigger one function while trying to perform another (e.g., rotation while scaling up): "When bending to [scale], the picture was rotating as well. Maybe I have to get used to it." (P11) A few participants (4/24) requested to be able to customize the sensitivity of deformation: "It requires a bit of calibration for me. (…) The speed and sensitivity should be customizable." (P17)

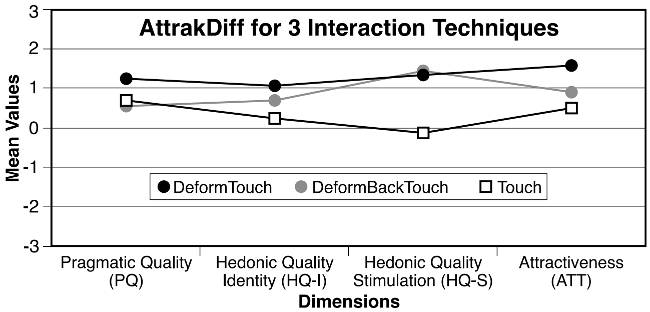

Figure 7. Mean values along the four AttrakDiff dimensions.

Combined Deformation and Touch Feels More Accurate and Efficient than Touch Only

When comparing the overall accuracy between touch and combined deformation and touch, almost all participants (22/24) said the latter provided more precision than touch: "I'm impressed with the accuracy." (P13) "With fingers it was harder to get it exactly to the size that I wanted it to be." (P12) In particular, most participants (15/24) felt an increased sense of control while twisting to rotate the photos compared to touch: "It was a lot easier with twisting because it moved faster and you could stop it when you wanted to." (P8) "With twisting I could feel the gradient, I knew how much to twist." (P5)

Almost half of the participants (11/24) indicated that combined deformations and touch made their actions more efficient than with touch, mostly because with deformation they were able to perform continuous gestures: "My actions are more elegant when I am trying to rotate pictures." (P8) "Rotation you can almost achieve with one [deformation] gesture." (P15) Most participants (9/11) mentioned twisting as being faster and less tiring than touch for rotation. One often mentioned reason for this was the increased number of rotation hand gestures that were sometimes needed to complete the task: "It went faster with twisting [because] with fingers you had to do many more movements." (P9) "Twisting with fingers is an unnatural movement." (P8) "Rotating with fingers over and over feels stupid." (P2)

Combined Deformation and Touch Feels More Intuitive and Tangible than Touch Only

In general, participants were able to perform the tasks and figure out how a certain deformation (and touch) gesture would allow them to execute a given action. Almost half of them (11/24) explicitly referred to the interaction using deformation gestures as natural and intuitive: "I'm used to touch from mobile phones, but my physical impression is that [deformation] is more natural." (P11) "The [deformation] it is quite obvious how it works." (P16) "I really liked the [deforming] ones because they require less concentration. (…) It's natural, it feels like paper." (P5)

Another aspect mentioned by participants was tangibility. For some, (9/24), using the prototype to interact with images gave them a physical feeling of holding something in their hands: "It was much better [with deformation] when I had something physical to handle. (…) Twisting was more human as I had something physical in my hand." (P12) "[Deformation] is fun because it was a physical thing to do." (P6) Despite the action and perception spaces being decoupled (i.e., the photo was presented on a separate screen), participants got the feeling that they were touching the images directly with their hands: "You really get the feeling that you are in the picture while [deforming]." (P20) "[Deformation] feels like I'm working with the images." (P22) On the other hedonic quality dimension of AttrakDiff, identity (HQ-I), both deformation techniques were located above *Touch*, which means people thought the interaction was integrating and connective. The difference between *DeformTouch* and *Touch* was statistically significant. Finally, a couple of participants reflected on how, with combined deformation and touch gestures, it was both the hands and the arms that are involved in the interaction: "With touch you use your fingers only, but with [deformation] you use your arms." (P13)

Front-touch is Easier than Back-touch

A vast majority of the participants (19/24) found front-touch to be easier than back-touch. During their interaction with the deformable device in combination with front-touch, participants knew exactly where to press as they could quickly glance down to see their fingers, if needed: "I know where to touch, where the finger should be." (P7) "I don't sense and feel what I am actually doing [with touch at the back]." (P5) Another reason mentioned by participants was that with front-touch they could use their thumbs to interact, while with back-touch they would resort to using their index or middle finger: "[With front-touch] it was somewhat easier [to interact], I have more control on my thumb than on my index finger." (P18) "Front-touch was easier mainly because I could use my thumb." (P4) Finally, we observed during the interaction that a few participants (7/24) had to make a slight posture change to hold the device in order to reach the back-touch panel. On the AttrakDiff questionnaire (Figure 7), *DeformBackTouch* had the lowest mean value on the pragmatic quality (PQ) dimensions after *DeformTouch* and *Touch*, which means there is room for improvement in terms of usability.

Bending Down is More Difficult than Bending Up

More than a third of the participants (9/24) reported some difficulties when performing an inward bend to scale down compared to an outward bend to scale up. Participants said bending inwards was an unnatural movement that requires more force than bending outwards: "The [scale up] movement is more natural than the [scale down]." (P17) "[Scaling up] is easier than [down]. I need more force." (P3) A few participants said bending inwards requires a slight posture change to hold the device, especially when the touch panel is located at the front: "It seems twisting and bending can be done while holding the device the same way, but [scaling down] is pretty hard." (P21) The most natural movement to perform an inward bend requires people to firmly hold the device with two hands and simultaneously press with both fingers in the center of the device. When the touch panel was located at the front of the device, participants found it hard to perform all the necessary force solely with their wrists by applying force on the edges of the device. Inversely, when the touch panel was located at the back, participants did not complain about the scale up movement as most of the force can be performed on the edges and the thumbs are therefore not needed. This quote illustrates that participants in general were aware and sometimes concerned about accidentally touching the touchscreen: "I like the borders [of the device] to hold so that I don't touch the screen." (P11)

Different Strategies to Complete the Task

Participants provided us with different insights on how the techniques supported their strategies to complete the tasks. Some participants (7/24) explicitly said they liked that with deformation they could rotate and scale photos simultaneously: "When I figured out I could rotate and [scale] at the same time, it was quite easy." (P3) However, participants felt that panning had to be done separately for the two deformation techniques, and thus rotation-scale had to be done sequentially with pan: "I could only do two things [rotate and scale]." (P24) "It's really hard to use your fingers for panning while [deforming]." (P18) Indeed, certain combinations where people try to twist, bend and use back-touch at the same time were quite cumbersome to achieve. Due to this, one quarter of the participants (6/24) explicitly told us that with touch they could perform all three actions (i.e., rotate, scale, pan) simultaneously: "I notice I do things in sequence with [deformation], but with the touch pad I do it simultaneously." (P18) "Panning and [scaling] at the same time is easier with touch." (P4).

DISCUSSION

As explained, we observed and analyzed our data from different quantitative and qualitative perspectives, in order to gain a full-picture of the use of our hybrid input device and interaction techniques. In this section, we discuss the results and extract our main findings.

Combining Deformation and Front Touch Offered a Superior UX than Using Touch Alone

From our qualitative data, we learnt that the hybrid input techniques offered superior UX than touch alone. In fact, the majority of participants found the hybrid techniques more intuitive and enjoyable to use, and also easier in the case of *DeformTouch*. Several participants reported that they experienced an enhanced sense of control when interacting by deforming the interface, although the *Control* sub-category from NASA-TLX failed to capture this difference. The superior UX was particularly strong when deformation was combined with front-touch: the subjective workload (TLX index) was significantly lower with *DeformTouch*. In addition, both hedonic qualities and the attractiveness measured in AttrakDiff were significantly higher for *DeformTouch* than for *Touch*. What's more, in the overall preference scale, *DeformTouch* was significantly preferred over the other two techniques. In summary, the hybrid techniques offered improved UX when compared to touch alone, in particular when deformation was combined with front-touch.

UX Was Superior When Combining Deformation with Front Rather than With Back Touch

This finding also confirms our prediction. The subjective workload (TLX index) using back-touch was significantly higher than using front-touch. The origin for this difference may be in the significantly-higher physical demand that interacting with back-touch posed on the participants (as seen in the *Physical* sub-category of TLX and reported in the interviews). All participants reported that they were much more familiar with using front-touch than back-touch. Thus, it is possible that extended use of the back-touch technique might reduce these differences. However, not being able to see the fingers on the rear touch panel while deforming and touching was also reported to be a problem for some, although, according to the literature, seeing the fingers would have not made a big difference [37].

All Three Input Techniques Provided Equivalent Performance, Measured as Task-Completion Time

The analysis of our data did not show significant differences in time to complete task between any of the three input techniques. This result agrees with what Burstyn *et al.* [5] reported for their hybrid design with two-handed deformation. It was surprising that efficiency with *Touch* was not better than with the hybrid techniques. As discussed, *Touch* was the only integral input technique that we tested, and according to the literature [15; 33] this should have resulted in shorter navigation times (more straight-line routes) when navigating an integral perceptual space, as was the case in our study. Furthermore, from a UX perspective, the subjective judgment of the performance achieved (*Performance* sub-category in NASA-TLX) was significantly higher with *DeformTouch,* a separable input technique.

We observed in the results that *Concurrency* was significantly higher with *Touch* than with hybrid techniques, as predicted by its integral structure. Thus, with the hybrid techniques, the interaction was more serial. However, *Touch* did not result in more efficient navigations, To gain more insight into this apparent paradox (shorter route but not shorter completion time), we also measured that the *Density* of interaction was significantly higher in the *Touch* condition. In other words, interacting with the hybrid techniques was more "paced", since more idle time was allowed in interaction cycles that, in total, had the same duration. Looking once more at the qualitative data, some participants felt that it was faster to interact by deforming the interface (i.e., by steering the deformation throughout a continuous displacement), than by repeatedly performing actions with two fingers in the

Touch condition (we did not detect higher *Fragmentation* of *Touch* in our measurements, though). According to these comments, *Touch* would result in an overall slower advancement of each action. Thus, the slower execution of the input actions in *Touch* would be compensated by a denser and more concurrent style of interaction (i.e., with less idle time altogether). The result of all this was that efficiency was comparable in all three conditions. It is possible that this more intensive interaction style observed with *Touch* also contributed to the higher levels of subjected workload (TLX) that were recorded for that condition, when compared with *DeformTouch*.

In any case, it is also possible that *DeformTouch* and *DeformBackTouch* are not that much “less integral” input techniques than *Touch*. In the hybrid techniques, the x and y coordinates remain integral (operated with touch), and various participants said that they did not have difficulties performing bend and twist gestures in parallel. Thus, there would only be one strong separation point in this four dimensional interaction space.

It is likely that ergonomic aspects of the interaction also played a relevant role in shaping these results. Rotating and scaling by twisting and bending can each be performed in a single stroke, since they are first order controls. The same actions with the zero order rotation and pinch touch gestures, however, may sometimes be difficult to perform in a single stroke (although it was theoretically possible in our implementation). In fact, finger articulations dictate movement restrictions, particularly when rotating with two fingers over large angles. This was already reported in the interviews.. It is reasonable to expect that other ergonomic factors (such as the asymmetry of bend up and bend down gestures) will also be common to other implementations of two-handed deformable input devices.

In the comparison between both hybrid techniques, the subjective metrics favoring front-touch did not reflect in better performance. This suggests that our assumption that proprioception would be enough to support the interaction was correct. However, we believe that if absolute touch had been required (e.g., for the manipulation of several images at the same time), some visualization of the fingers on the back (such as *LucidTouch* [3]) might have been necessary.

CONCLUSIONS

In this paper, we set ourselves the goal of investigating in depth the potential of combining deformation and touch in a single interaction cycle, using a handheld interface. The main conclusion that we can extract from our study is that deformation gestures and touch can be combined successfully as input techniques. In fact, we found that the benefits in UX typically offered by DUIs (such as an improved tangibility and even more direct manipulation of computational objects) are transferred to hybrid interaction techniques that combine deformation and touch. Additionally, we found that the hybrid techniques, although not fully integral as multitouch is, allowed for efficiencies of interaction with multidimensional integral tasks that were comparable with the efficiency offered by multitouch (which, *a priori*, we considered optimum and expected to be more efficient).

In our study, we also conducted an initial first exploration of a hybrid input technique that combined deformation with touch on the back of the device. We are fully aware of the complexity of back-of-device interaction design, and our contribution to this area of HCI research is minor. Still, we fulfilled our goal of observing the potential of the fingers for back-touch, since in a two-handed DUI they naturally fall on that area to support the device. Our results showed that touch on the front and on the back offered similar efficiency to complete the task. However, the users clearly preferred the option with front-touch, possibly for reasons of familiarity and because of the reassurance of seeing the fingers. Encouraged by these results, we believe that there is still room to include back-touch in future research with hybrid deformation-plus-touch input devices and interfaces.

Our study has clear limitations of scope, and for that reason our findings cannot be immediately extrapolated to other setups. One main defining factor of our setup is that we conducted our study using an input device with no visual display integrated in it. Thus, in principle, our results are only relevant for other setups that also use indirect touch. We believe that symmetric two-handed deformation input on a handheld device, is also very different from two-handed indirect input on larger surfaces. For this reason, new research is needed to know the differences that direct or indirect touch impose on the user when using input devices with form factors similar to the one we used. In any case, our results can be useful for the design of input devices that are used to control information and media in external displays. Everyday examples can be found in any home, where information on displays such as television sets is managed using remote controls and two-handed game controllers.

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