Abstract
Deformable User Interfaces (DUIs) often require external confirmation of the status of the interface, which is normally provided visually. We propose that tactile cues can also be employed for this end. In a user study that presents both visual and tactile cues in redundancy, we found that both channels can be combined with no loss in user experience or performance. This validates our design for further research on multimodal designs that make use of no redundancy in the supporting cues.

Author Keywords
Deformable User Interface; DUI; Organic User Interface; OUI; dynamic tactile cue; vibrotactile feedback; navigation; scrolling; selection; handheld

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Design, Human Factors

Introduction
In recent years, Organic User Interfaces (OUIs) [14] have emerged as one of the fastest-growing new research areas in HCI. As more research is published,
distinct research-focus areas are shaping out from the common OUI root. Some of the main sub-topics in OUI research include: non-planar displays (NPDs), an area that is looking into the interaction with (rigid) displays that are no longer flat (e.g. [12]); Shape-changing interfaces (SCIs), which focuses on the study of interfaces that change their shape actively as part of the interaction (see [10] for a summary); and Deformable User Interfaces (DUIs), which covers the interaction with interfaces that are made of deformable materials, and in which deformation produced by the user is a key element of the interaction (e.g. [6]).

Each one of these sub-areas of OUI research is motivating investigations that were once conducted for more traditional user interfaces, but which no longer provide all the answers when applied to OUIs. If we consider again the research sub-areas just mentioned, researchers in NPDs are looking into the problems that arise from implementing touch interactions on them [12], and visual ergonomic limitations encountered when reading text on curved displays [9]. Research on SCIs, in turn, is posing new questions about how to communicate information to the users through additional dimensions of the interface, such as its changing shape and volume [15]. Regarding the research around DUIs conducted to date, we find that much of it has concentrated on investigating intuitive vocabularies of deformation gestures (e.g. [8]), and on researching the mechanical properties that such deformable materials should have (e.g. [5]).

This paper introduces a new important topic of research, relevant for the design of DUIs, which has not yet been investigated: the use of dynamic tactile cues (DTCs) to guide interactions with DUIs.

**Dynamic Tactile Cues**

In one form or another, tactile cues are present in all traditional mechanical interfaces. It is likely that, initially, many rudimentary interfaces offered tactile cues as a side effect of the friction forces that were present in their “imperfect” constructions. However, it is well known that such forces fulfill an ancillary function in many use contexts. Notable examples are musical instruments, such as the keys of a piano, where the feeling of the keys supports richness of expression by the performers [2]. The importance of such frictional cues for the enhancement of human motor control is such that researchers have gone to great lengths to understand and reproduce the friction from real systems in virtual environments ([11] is an example of such work).

A similar process has taken place in HCI, for the design of new desktop and mobile interfaces. As mechanical keys have gradually disappeared from many everyday interfaces (e.g., mobile devices with touch displays), such interfaces have lost richness of physicality. In other words, less information about the physical interface and its status is obtained from the interaction with the hardware. As a result, it has become apparent that the lack of mechanical feedback from key presses can hinder performance in many mobile use contexts. In fact, research has shown that adding vibrotactile feedback (even when it is only a gross approximation of the actual mechanical model in real buttons) significantly improves performance during text entry [4]. When more degrees of freedom are present in the interaction, researchers have taken a similar approach to enhancing physicality. For instance, with spatial gestures, it has been proposed that vibrotactile “textures” can help with the non-visual exploration of
the environment when the position of the hand is tracked by motion sensors [1].

**Tactile Cues in Interface Deformation**

One of the main benefits of interacting with DUIs is that they allow for a rich physical interaction with the hardware. The human haptic capabilities are thus put to use in such a way that (i) the continuously-changing shape of the device is perceived with the hands, and (ii) the interface can be dexterously manipulated, allowing a high degree of input precision.

Our previous research showed that minute changes in deformation of an interface (bending with two hands, in that case) can be accurately produced and maintained. While external visual feedback can offer added benefit, high performance was also achieved non-visualy by tracking the forces applied and the deformations caused [7]. Our research also showed that continuous deformation of an interface suits the control of continuous parameters (e.g. speed of scrolling), while also allowing for the performance of discrete actions, such as causing discrete increments in a parameter, or performing a selection [5, 6].

From our experience implementing deformable interactions, we learnt that some threshold deformations have to be defined, even when the interaction occurs over a continuum of deformation. This is particularly true when a neutral deformation status (i.e., no deformation) needs to be defined: it is important for a user to remain aware of such neutral positions, and to know when they are exited (a similar discussion about implementation can be found in [13]).

In several of our studies we employed a **Kinetic Deformable User Interface Research Prototype (Kinetic DUI-RP)**, first described in [6], which could detect bend and twist deformation gestures produced with both hands (Figure 1). In every case, the neutral configuration (interface not deformed) resulted in no action being triggered in the interface. This neutral region was essential in order to provide a way of not executing any action. Figure 2 represents, with dashed lines, the threshold amounts of deformation for bend and twist gestures. Beyond these threshold deformations, interactions were triggered; if continuous parameters were controlled, the amount of deformation beyond the thresholds determined the magnitude of those parameters.

Confirmed by our experience, we postulated that it is important to provide the user with some means of knowing if the device is in its neutral configuration. If visual feedback is present (like in all our previous studies), visual activation of the interface (e.g., displacement of on-screen elements) shows that the neutral region has been left. Since crossing the threshold is a discrete event, we wanted to test if providing additional redundant confirmation of such crossing offered any benefit, such as extra reassurance of improved performance. While such additional confirmation could be auditory, we were interested in providing “tangibility” of such crossing. Thus, as with the vibrotactile burst that offer key press confirmations on touch displays, we decided to create virtual mechanical clicks that emerged from inside the device when the threshold was crossed, as if a mechanical switch had been activated. In this way, and following the discussion in the introduction, we were also testing...
whether enhanced physicality of deformation is an important design parameter for DUlS.

User Study

A software application was implemented in which the task was to scroll through a list of contacts, in order to select a particular one and establish a phone call. The sequence of the interaction is shown in Figure 3, with the following four stages:

i. Each repetition of the task started with the display of the target contact in the list: “James”. There were 120 different names in the list.

ii. The participant then used twist gestures to scroll through the list in either direction, in such a way that a bigger twist deformation (beyond the threshold) resulted in faster scrolling. The threshold deformation to initiate the scrolling was reached when both rigid ends of the device formed an angle of 4.5° with each other. The maximum speed of scrolling was achieved with a relative angle of 24°.

iii. Stopping the cursor on the target name was highlighted visually with a red rectangle.

iv. The selection was done by executing a discrete bend gesture, upwards or downwards, which exceeded the relative angle between the rigid sections around the y axis of the device in 10°.

With this interaction design and task in place, a three condition repeated measures experiment was designed, in which the independent variable was the tactile feedback provided when crossing the deformation threshold around the neutral region, with either type of deformation gesture (twist or bend). For this purpose, two vibrotactile actuators (Minebea LVM8L3FVA) were fitted inside the DUI, one in each rigid section.
The three experimental conditions were:

C1. No tactile cue when crossing thresholds (NoVibra)

C2. Tactile cue when exiting the neutral region, but not when re-entering it (On)

C3. Tactile cue when exiting and also when re-entering the neutral region (On&Off)

Twelve participants took part in the study. Each participant completed 20 repetitions of the task in each condition, the order of which was counterbalanced. The tactile cues generated when twisting were displayed in a directional way: only to the right hand when twisting up and only to the left hand when twisting down (this directional convention was derived from prior extensive pilot testing). In contrast, tactile cues generated when bending (item selection) were provided to both hands simultaneously. Each tactile cue was obtained by exciting the actuators with a 155Hz sinusoidal signal in a square envelope with 30ms duration. The amplitude of the signal was set prior to the experiment, and was determined in a pilot test in which all volunteers could feel the cue in their hands while finding it natural and non-disturbing.

Since the tactile cues were added as redundant to the visual information (which tends to dominate interactions), we did not hypothesize that we would observe any significant benefits from adding tactile cues. Instead, with this setup, we were interested in knowing if both types of cues were compatible within the same interaction, and if the design decisions that we made affected the experience and performance negatively. If we found no negative effect, the next step would be to evaluate the same interaction with visual cues becoming intermittently unavailable, like in mobile interaction contexts. While this approach might appear conservative, we deemed it necessary, as it is, in our experience, common that users deactivate redundant confirmation cues (auditory or tactile) in their mobile devices or desktop computers, unless they are optimally designed. Thus, we formulated the following hypotheses: adding tactile cues does not negatively affect the user experience (H1), neither does it negatively affect performance (H2).

**Results**

The user experience was assessed by measuring the subjective workload using the Raw NASA-TLX questionnaire [3], plus three selected additional subjective categories: Annoyance, Sense of Control and Overall Preference. All these categories were collected in questionnaires by each participant after each condition. Summaries of the results are shown in Figures 4 and 5. Performance was measured by recording the total time to complete the task, and then computing normalized time per unit of distance between the initially-selected item in the list and the target item. In addition, the number of overshoots in which participants incurred when trying to reach the target was also recorded. This was taken as an objective measure of the controllability of the interface. Both metrics are summarized in Figures 6 and 7.

The results, as shown in Figures 4 to 7, hint the emergence of a common pattern: the average values tended to improve slightly when feedback was added at the gesture activations points only (On condition), but the benefits disappeared when feedback was also added at the gesture deactivation points (On&Off).
condition). However, ANOVA analysis found no significant differences between conditions for any of the metrics (see a summary of the test results in Table 1).

### Discussion and Next Steps

Since none of the differences observed was significant, we concluded that both hypotheses formulated for this study could be accepted: adding tactile cues did not negatively affect either the user experience (H1), or the performance obtained (H2). These results serve as proof of concept that the approach and design decisions taken are acceptable and valid to be taken forward to the next stage in our research agenda.

A complementary perspective of these same results is that no significant positive effects were measured either, after adding tactile cues to the interaction. As discussed, we did expect this from a setup in which the tactile cues were redundant with the visual feedback. However, we are intrigued by the possibility that the non-significant improvements hinted in our results might become significant and more prominent once the interface is used with less visual feedback. For instance, we propose a follow up study with a scenario in which visual attention is intermittently diverted from the task, and where other versions of the tactile feedback can also be evaluated.

### References