Evaluating Deformable Devices with Emergent Users

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Figure 1. A sensel-based slider control, as used in the studies reported here. As the user tilts the sensel and moves their grasp from one raised rod to the next, adjacent components rise and fall on-demand to give the impression—and feeling—of moving a tangible slider thumb along a static guide rail.

ABSTRACT
This research forms part of a wider body of work focused around involving emergent users—those just beginning to get access to mobile devices—in the development and refinement of far-future technologies. In this paper we present an evaluation of a new type of deformable slider with emergent users, designed to investigate whether shape-changing interfaces provide any benefit over touchscreens for this type of user. Our trials, which took place in two contexts and three disparate regions, revealed that while there was a clear correlation between performance and technology exposure, emergent users had similar ability with both touchscreen and deformable controls.

Author Keywords
Deformable devices; emergent users; tangibility; sensels.

ACM Classification Keywords
H.5.2 User Interfaces: Input devices and strategies.

INTRODUCTION
Emergent users, as defined by Devanuj and Joshi [2], are the millions of people, often residing in developing regions, who are just beginning to get access to the sorts of advanced mobile devices and services that many users in developed regions are familiar with. These new mobile natives are also used to dealing with a range of everyday challenges, including economic, geographic, technological and educational constraints. In response to this, the ICTD research community has long focused on innovating mobile solutions using current or older technology, adapting or appropriating existing devices for better use in resource-constrained situations (e.g., [16, 23]).

At the opposite end of the technology spectrum, it is common to see intense excitement about far-future mobile concepts – consider, for example, the current hype around virtual reality, machine learning or chatbot assistants. It is often assumed that, when developed to consumer level, these technologies will eventually "trickle down" to emergent users [6]. While this may or may not ultimately be the case, our view is that emergent users have a unique perspective on mobile and interaction design, and that far-future interactions should be developed focusing on and directly involving them from the beginning.

One technology we are particularly interested in within this context is tangible interaction – in particular, deformable devices. Research activity in this area over recent years has increasingly demonstrated the benefits of devices that can change their shape to support interaction. From augmented keyboards [1] to shape-changing buttons [8] or rod-based table displays [4], there are copious examples of using deformation to increase usability, illustrating a natural progression from digital to tangible devices, and often while mobile (e.g., [9, 11]).

In developing a new technology, such as a future deformable device, it is of course tempting to assume that problems from one user group will transfer directly to another, and that those with similar levels of technology experience might have comparable reactions to its use. However, this is not necessarily the case. Consider, for example, studies with older mobile users (in developed regions), which have shown that difficulties are often due to age-related health or mobility issues [5, 30]. Compare this to studies of emergent users, where challenges—putting aside those related to resource constraint—have included conceptual models [17] or community structures [15] that simply do not fit with users' experiences. People from different backgrounds, then, often have very different experiences with technology. As a result, we argue that there is value in involving diverse user populations early in the process of designing and developing a new technology approach.

In previous work we have involved emergent users in ideation and design sessions around future mobiles, including deformable devices [14]. In the work presented here, we were interested in whether deformable device themselves are of direct value to emergent users. In particular, we wanted to explore whether people who are more familiar with physical than

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digital interaction might find deformable devices of value; and, whether these would be easier to use or more accurate than their digital equivalents. In order to answer this question, we constructed a prototype deformable device based on the sensel rod approach used in [22]. This previous work compared different fidelities of slider and dial widgets, testing the concept extensively with mainstream, affluent users, and showing its promise. We developed a higher-fidelity deformable slider using the same rod-based interaction technique, and tested it against a graphical equivalent in a controlled study with two groups of emergent users in India and South Africa, and a comparison group in the UK. Our evaluation was structured to measure the effect of the different presentation of a slider (e.g., GUI vs. physical) over the three study sites. In the rest of this paper we situate our work, then discuss the prototype, study, results, and implications for future deformable devices.

BACKGROUND

The use of tangible controls as a preferred method of interaction has been demonstrated for many years [3, 27]. It is clear that there are benefits in creating devices that can combine the versatility of graphical interfaces with the interaction advantages of tactile feedback. Research in this area has often focused on output or data visualisation, however, aiming to bring a third dimension to visual displays. For example, Follmer et al. [4] provided a wide array of dynamic effects on a tabletop rod-based surface, while others have used a variety of physical forms to consider a broader set of deformation and visualisation possibilities (e.g., [13, 25]).

In contrast, in this work we are interested in developing deformable physical widgets for direct interaction, creating elements that can rise up from the display and be manipulated by the user before returning to appear flat. This type of dynamic deformation of control elements, first introduced by Poupyrev et al. [21] using the Lumen display [20], has previously been demonstrated to be effective for static buttons [1, 8], dials [18], and continuous controls such sliders [22] or a variety of pneumatically-actuated variably-resistive inputs [29].

A common theme throughout previous work in this area is evaluation from a developed world, "WEIRD"-focused perspective [10]. In the work reported here, we constructed a rod-based deformable slider based on that described in [22], and trialled it with diverse groups of users in three regions. There are a small number of examples of previous work that has explored the use of deformable interfaces outside the traditional lab setting. For example, experiments have included field studies in public places [7], with professional musicians [28], or with the general public in a town centre [26]. All of these studies took place with affluent, developed-world users, however. To our knowledge, so far there has been no research that has explored the use of deformable, shape-changing devices or controls with emergent mobile users.

PROTOTYPE

We constructed a prototype deformable slider device to be used in our evaluation, as illustrated in Figs. 1 and 2. The device consists of a row of nine independently actuated 'sensel' (see [24]) rods that are able to rise and fall to give

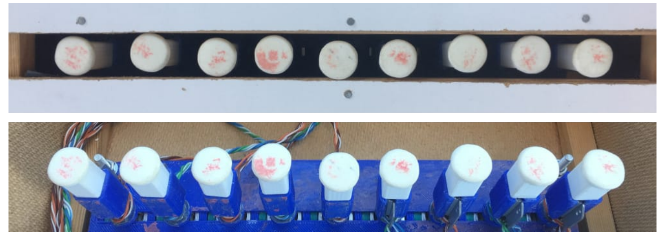

Figure 2. The prototype constructed for our cross-site study. Top: the sensel rods that rise and fall to simulate a slider, as illustrated in Fig. 1. Bottom: the internal construction of the prototype – each rod is vertically actuated by a linear stepper motor mounted on a micro joystick (cf. [22]).

the illusion of lateral movement. That is, as demonstrated in Fig. 1, grasping a raised sensel and tilting it to either side will cause the adjacent rod to rise and the held rod to fall. In this way, a user moving their grasp along the row of sensels is given the impression that they are holding a tangible slider thumb, moved along a static guide rail.

Figure 2 shows the prototype from above, and its internal construction. The system was created using a similar approach to the low-fidelity prototype described by Robinson et al. [22]. This previous work suggested that a greater sensel resolution might increase the usability of the rod-based slider technique. Our prototype improves slider resolution in two ways. Firstly, we increased the number of sensel rods that are used for a slider (from four to nine), and refined the design of the sensel components, reducing the spacing between them. In our prototype each sensel is 12 mm in diameter, compared to 15 mm in [22]. Combined with a more compact design, this means that our prototype slider is 20 cm in length for nine sensel elements (0.45 sensels per cm), in comparison to 12 cm for four sensel elements (0.3 sensels per cm) in [22]. We also increased the fidelity of interaction that is supported by the device. While Robinson et al. used simple navigation switches to support directional movement (i.e., tilting left or right produced a single value only), our prototype used micro joysticks to allow continuous movement from side to side. As a result, our design is able to continuously move focus from sensel to sensel, supporting far more nuanced slider interactions than previous designs.

EVALUATIONS

As discussed earlier, the overall goal in our work is to involve emergent users in shaping future technology. To this end, we conducted a study to compare the deformable slider prototype against a touchscreen equivalent, aiming to explore the potential value and benefits of a deformable device in this context. Our main research questions were:

RQ1: Does technology exposure affect the accuracy of deformable or touchscreen sliders?

RQ2: For users with limited technology exposure, does a deformable slider offer benefits over a touchscreen slider in terms of ease of use or accuracy?

To answer these questions, we conducted a cross-site trial with two emergent user groups from India and South Africa and a control group from the UK. In order to be able to evaluate our

Site	Highest educational attainment			Touchscreen experience				Mobile phone ownership			
	Primary	Secondary	University	None	<1 year	1–2 years	3+ years	None	Basic	Featurephone	Smartphone
UK	0	5	11	0	1	0	15	0	0	0	16
SA	10	6	0	14	1	1	0	5	5	6	0
India	11	5	0	8	6	2	0	0	6	7	3

Table 1. Participant demographics in the three sites used for our evaluation. UK participants were primarily smartphone owners with extensive touchscreen experience, and educated to secondary or university level. Participants in South Africa and India owned either basic or featurephones (or did not own a phone), with little to no touchscreen experience, and had education to primary or secondary level.

deformable slider prototype against a touchscreen slider, we also constructed a GUI-based control system for comparison. The control, developed using an Android tablet, was designed to mimic the deformable slider as far as possible. That is, its slider track was 20 cm in length, with a thumb of 12 mm in diameter. The control system was equivalent in the rest of its appearance, and was mounted on top of the deformable prototype when in use, in order to appear the same physical size.

Participants

We recruited a total of 48 participants from three regions to take part in the experiment. Table 1 details the education level and technology exposure of the participants in each region.

Emergent users: South Africa and India

Thirty-two participants from emergent user communities in and around Langa, a township near Cape Town, South Africa (16 total, 10M, 6F, aged 24–55) and Dharavi, a large slum in Mumbai, India (16 total, 8M, 8F, aged 18–60) were recruited to take part in the study. Participants were typically blue-collar workers (14 people) such as gardeners, cleaners or decorators, or unemployed (12), but there were also three professionals (teachers, technician) and three homemakers. There were a range of technical abilities (see Table 1) but participants had predominantly lower educational attainment or technology exposure than the group of UK-based experienced users.

Experienced users: UK

We also recruited 16 participants (9M, 7F, aged 21–55) from Swansea, UK. These users were generally professionals (6 people) such as educators and managers, or graduate students (6), but there were also several blue-collar and service workers (4) such as personal assistants or warehouse operatives. This cohort was recruited to represent the type of user we would typically expect to make use of cutting-edge technology – that is, affluent, mobile-savvy users with high educational attainment and prolonged experience with the latest mobile devices.

Tasks

In keeping with previous work on continuous parameter evaluations (e.g., [3, 12, 22]), we opted to use pursuit tasks as a method of evaluating participants' ability to use and control a slider. The tasks in our study required participants to use either the deformable or touchscreen system to follow a target along a linear track. In all cases, users were standing up using the interface with one hand (of their choice), in front of a 40 cm display that showed the task at hand. Figure 3 shows examples of the pursuit tasks. In both cases, the solid black line is the user's cursor and the red shaded area is the target region. Following [3], the target moved at a constant speed but darted off at random intervals of 2 s to 4 s. Each pursuit task lasted 60 s, and participants were instructed to keep their cursor within the target region as much as possible. Each participant performed three sets of pursuit tasks per system.

Figure 3. Examples of the pursuit tasks used in the study. Top: the participant's cursor (vertical black line) outside the target region (red area). Bottom: the target has moved and darted off randomly (as described below), and the participant has moved their cursor to track its position.

Procedure

We followed the same study format at each location. Participants took part individually, and the study began with an IRB-approved consent process. Following this, we demonstrated one of the two interfaces (the deformable or the GUI control) to the participant, and gave them time to get acquainted with the system before beginning the pursuit tasks. After completing three tasks on the first interface, we then demonstrated the second interface to the participant and, again, gave them the opportunity to familiarise themselves before starting the second set of three pursuit tasks. The session ended with a short post-study interview which gathered general participant demographics, ease of use ratings (on a Likert-like scale of 1 (low) to 10 (high)), and ideas for future use of deformables.

To reduce bias, we counterbalanced the order in which the systems were presented to participants, with half of the participants in each study site using the deformable prototype first, and half using the GUI control first. Each session took around 20 min on average, and participants were compensated for their time with monetary incentives of £5 (UK), R150 (South Africa) and ₹200 (India). Study sessions were video recorded (with participants' consent), and the systems automatically logged all usage data, which allowed us to measure participants' pursuit accuracy throughout each task, in addition to subjective scoring and touchscreen experience metrics.

Results

Subjective ratings

Overall, across all three sites, participants found the GUI control system easier to use than the deformable interface, giving

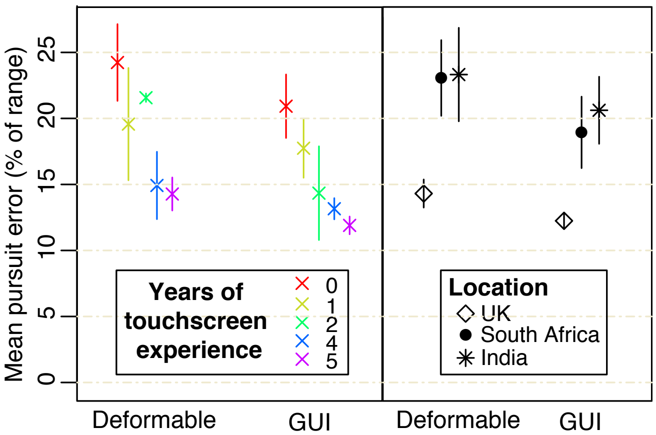

Figure 4. Pursuit error according to touchscreen experience (left) and location (right). Accuracy with both systems increases in line with touchscreen experience over all locations. Overall, participants in SA and India were less accurate with both the deformable and GUI systems.

the systems average ratings of 7.1 and 5.3 out of 10, respectively. This result proved to be significant in a Wilcoxon signed rank test ($p < 0.01, Z- = -3.78, W- = 182.5$). When we consider individual locations, however, it should be noted that the only *significant* difference in opinion between the deformable and GUI interfaces was seen in the UK study, where the ratings were 5.0 for the deformable and 6.8 for the GUI ($p < 0.01, Z- = -2.7, W- = 15.5$). While the ratings in both the Cape Town and Mumbai studies follow the same trend of rating the GUI as slightly easier to use, these results did not prove to be statistically significant.

This result suggests that emergent users found little difference in difficulty between deformable and GUI sliders. This result could perhaps be due to a general lack of experience with touchscreen sliders. Separating these results based on touchscreen experience reveals a slightly larger split in opinion – emergent users who *did* have touchscreen experience (10 of 32 participants), rated the GUI slider 3 points higher than the deformable slider on average, whereas those with no such experience (22 of 32) rated it 1.3 points higher.

Pursuit accuracy

A Kolmogorov-Smirnov test on the pursuit error data showed that we can assume its normality ($D = 0.108, p = 0.202$). We performed a two-way ANOVA on the pursuit error, with the interface as a within-subject variable, location as a between-subject variable and participant as a random factor. We found significant main effects of the interface ($F(1,45) = 15.85, p < 0.001$, generalised $\eta^2 = 0.086$) and location ($F(2,45) = 19.78, p < 0.0001$, generalised $\eta^2 = 0.39$) on the pursuit error. However, we found no significant interaction between the interface and location themselves ($F(2,45) = 0.66, p = 0.52$, generalised $\eta^2 = 0.0078$).

Turning first to the interface as a factor. A post-hoc pairwise t-test with Bonferroni correction shows that the difference between GUI and deformable sliders is significant ($p < 0.001$). However, the effect size is limited: the deformable slider is only a little less accurate than the GUI slider (20.2 % vs. 17.3 % of the slider's range on average, respectively).

When we consider location as a factor, consistently with the subjective ratings, pursuit error is much lower in the UK (13.3 %) than in South Africa (21.0 %) or India (22.0 %). Accordingly, a post-hoc pairwise t-test with Bonferroni correction shows the difference between UK and South Africa ($p < 0.0001$), and UK and India ($p < 0.0001$), to be significant, whereas the difference between South Africa and India is not significant. See Fig. 4 (right) for a visual representation of these differences.

We also analysed the results to identify any trends between technology exposure and pursuit accuracy (see Fig. 4). The results here show a clear pattern for both interfaces; that is, the greater the number of years of touchscreen experience, the lower the pursuit error for both the deformable and GUI sliders. This result suggests that prolonged exposure to these devices may result in higher accuracy over time.

Finally, we investigated the impact of additional variables on pursuit accuracy, in particular that of gender. The gender ability gap is smallest in the UK, with men approximately 1 % more accurate with both GUI and deformable sliders than women. In South Africa the gap is larger: men are 4.3 % more accurate with deformable sliders than women, and 1.6 % more accurate with GUI sliders. The gender gap is largest in India: men are 7.5 % more accurate with deformable sliders than women, and 5.6 % more accurate with GUI sliders. We believe this gap is likely a consequence of unequal exposure to technology. In the UK, where the gap is smallest, all participants owned a smartphone. South African participants owned fewer phones, or less advanced ones, but this exposure to technology was similar between men and women. Although all Indian participants owned a phone, in general, women owned phones that were less advanced than those owned by men.

Observations and participants' feedback

Participants used various strategies to interact with the deformable slider, with the most common being to consistently use the same hand in the pinch-like orientation shown in Fig. 1. Several participants (over all three sites) chose to use two hands, however, switching as the target moved so that they were always 'pulling' the slider thumb towards the marker.

In terms of future uses for the deformable technology, UK participants suggested possibilities that primarily revolved around gaming controllers or disability (e.g., visually-impaired users). Those in India and South Africa suggested several additional uses, including, for example, improving touchscreen keyboards: *"when I want to type something my finger goes to the wrong letter – with this it's more convenient,"* and, *"it'd be easier to type – [my] phone sometimes doesn't work"*. Others suggested using deformable controls to augment existing touchscreen inputs: *"I'm so used to a button phone, so if I want to transfer to a touch screen that would be convenient if the buttons came out of the screen,"* and, *"especially with zoom and slide [. . .] I can feel it with my fingers where they are"*. There were also further suggestions for non-mobile scenarios: *"somewhere in the car as an indicator,"* and, *"a toy [. . .] for babies"*.

DISCUSSION

Turning now to the results of our studies in relation to the two research questions proposed at the start of this paper:

RQ1: *Does technology exposure affect slider accuracy?*

As Fig. 4 (right) illustrates, there are clear differences in pursuit accuracy performance with both the deformable and GUI interfaces between emergent users (South Africa and India) and the control group (UK). Post-hoc tests show the differences between the UK and emergent user participants' results to be highly significant. In contrast, no significant differences were found between the two emergent user groups.

This result is, of course, relatively predictable – it is natural that those people with less experience using a particular interface will perform worse at related interactions than experienced users. However, as discussed in the introduction to this paper, it is certainly not necessarily the case that all inexperienced technology users will have the same reaction to new mobile experiences. The emergent users who took part in this study had little exposure to both touchscreens and deformables, but the ratings they gave for ease of use were not significantly different between the two interfaces. UK participants with previous touchscreen experience rated the GUI interface as significantly easier to use than the deformable.

As Fig. 4 (left) illustrates, overall, there is a correlation between low touchscreen experience and increased errors on both GUI and deformable slider controls. This suggests that perhaps longer exposure to deformable controls should be tested to assess whether accuracy improves with experience. Further work is needed to quantify the aspects of interaction that caused this particular result.

RQ2: *Does a deformable slider offer benefits over a touchscreen slider for users with limited technology exposure?*

When considering the results from the 32 emergent user participants, we found no statistically significant differences between the GUI and deformable systems for either pursuit accuracy or ease of use ratings. Although these findings are not conclusive, they do suggest that the emergent users who participated had similar ability with both interfaces, finding them of comparable difficulty.

Turning to a more general view, although overall our results favour the GUI system over the deformable prototype for ease of use, it is promising that—at least from the perspective of those who have no experience with either interface—the deformable was as easy to use as its touchscreen alternative. With no significant difference between the two approaches, it is possible that the deformable device will provide additional benefits as it naturally supports eyes-free usage. It should also be noted that emergent users often tend to rate aspirationally, ranking technologies that seem advanced higher than those perceived to be lower-end, regardless of what tasks are being performed [19]. It is possible, then, that our deformable prototype was perceived as low-tech by these participants, which could explain why deformable sliders were not rated higher, regardless of performance.

Finally, although the results presented here cannot be rigorously compared to previous work (as the experiments are different), it is interesting to see that our findings are consistent with those of Robinson et al. [22]. The 4-sensel deformable slider used in [22] resulted in 12.6 % pursuit error, in comparison to a GUI slider with 9.5 % error (e.g., ~3 % difference). In this experiment, when comparing results from non-emergent users only, the 9-sensel deformable slider resulted in 14.3 % pursuit error, which is ~2 % away from the 12.2 % pursuit error of the GUI slider. This result suggests that the higher resolution of sensel rods of this size does not significantly increase pursuit accuracy, and therefore a resolution of four sensels is currently accurate enough for this type of task.

CONCLUSIONS

We believe there are several conclusions that can be drawn from these results. Evaluations of cutting-edge technologies with emergent users are not currently widely undertaken, perhaps under the assumption that these groups will never perform as well as the more mainstream "average" user. However, we disagree with this approach. It is our view that instead of ignoring this user group, and relying on the trickle-down of Western-designed, second-hand technology, emergent users should have the opportunity to shape and refine new and innovative ideas right from the start. The alternative, perhaps, is an ever-widening digital divide between users with access to the latest technology, and those without. Indeed, given the lack of emergent user performance difference between the two systems tested here, one approach could be to deploy far-future technologies immediately – after all, why not?

Finally there is also evidence to suggest that involving communities with such unique perspectives in these types of evaluations can often lead to fresh and original design solutions. Emergent users were involved in the work that originally led to the deformable innovations described here (cf. [14, 22]), and have provided valuable insights when evaluating deformable devices in our studies. The next step in our work in this area, then, is to conduct a more in-depth investigation of our deformable slider and other deformable components and widgets with emergent users to assess if further experience improves accuracy; and, to work with these participants in driving innovation of future deformable and shape-changing controls.

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