Broken Display = Broken Interface? The Impact of Display Damage on Smartphone Interaction

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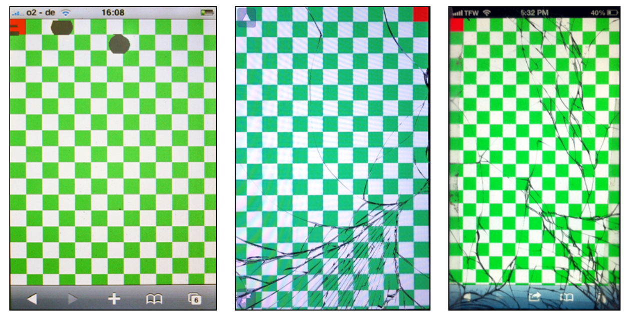
ABSTRACT
This paper is the first to assess the impact of touchscreen damage on smartphone interaction. We gathered a dataset consisting of 95 closeup images of damaged smartphones and extensive information about a device's usage history, damage severity, and impact on use. 88% of our participants continued to use their damaged smartphone for at least three months; 32% plan to use it for another year or more, mainly due to high repair and replacement costs. From the dataset, we identified three categories of damaged smartphone displays. Reading and text input were most affected. Further interviews (n=11) revealed that users adapt to damage with diverse coping strategies, closely tailored to specific interaction issues. In total, we identified 23 different strategies. Based on our results, we proposed guidelines for interaction design in order to provide a positive user experience when display damage occurs.

Author Keywords
Smartphone; mobile interaction; broken display; display damage; user experience.

ACM Classification Keywords
H.5.2 Information Interfaces and Presentation (e.g. HCI): User Interfaces; K.8.2 Personal Computing: Hardware.

INTRODUCTION
Current smartphones are mainly operated via touchscreens that cover a large part of the device's front panel. The large display area of smartphones increases the risk of damage to the display when the phone is dropped. In two recent surveys with UK owners of damaged mobile phones (n=2,579), a mobile insurance company found that 37% of devices suffered damage in the first three months of use [3] and that 23% of iPhone owners (n=2,471) have a smartphone with a broken display, with 31% not planning to get it repaired [4]. Many smartphone owners continue to use their smartphone after it got damaged. We found that the main reason for continued use are high repair and replacement costs. Current smartphones require replacement of the complete display unit, which costs 150–250 USD depending on the model.



(a) minor damage (b) medium damage (c) severe damage

Figure 1. Representative examples of damaged smartphone displays from the identified display damage categories. The checkerboard pattern facilitated image rectification and damage identification.

Considering the combination of visual output and touch input on the display, as well as the visual nature of smartphone software and apps, display damage likely impacts the user's interaction with the smartphone. Scratches, cracks, and screen faults deteriorate the user experience by occluding parts of the displayed content or impairing touch input.

In this work, we assessed the impact of damaged displays on smartphone interaction and how users cope with the damage. Our results can help interaction designers in supporting the growing group of smartphone owners that use a smartphone with a damaged display. Towards this goal, we performed an explorative analysis, resulting in the following contributions.

We conducted an online survey and an Amazon Mechanical Turk (MTurk) study with owners of damaged smartphones. The resulting dataset consists of 95 closeup images of damaged smartphones and extensive information about the devices' usage history, severity and cause of the damage, impact on use, and reasons for continued use. We conducted a structured image analysis, including manual damage annotation. With cluster analysis, we identified three categories of damaged smartphone displays. Figure 1 shows representative

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examples of those categories. The complete damaged display dataset, including analysis data, is made available alongside this paper to foster further research in this area.[1]

In addition, we conducted interviews with owners of damaged smartphones recruited from the online survey (n=11), to gain deeper insights into reasons for continued use and implications of damage on smartphone interaction. Our participants reported 23 different coping strategies, often tailored to individual interaction issues.

Based on our quantitative and qualitative results, we propose interaction design strategies that can support many of those coping strategies already at design time, or facilitate adaptation of interfaces when damage occurs.

RELATED WORK

Not much prior work has considered the implications of hardware damage on user interaction, particularly not the case of users that continue to engage with damaged devices and their interfaces for longer periods of time. However, damage has been studied as a concept. Ikemiya and Rosner [15] define damage as a malfunction or degradation of an artifact, either caused through user engagement or not. Hence, damage is related to *wear*, i.e., the degradation of an artifact over time due to use. Motivations for keeping or discarding personal items can be highly complex [16]. Yet, Huang and Truong present clear insights on when and why people switch to a new mobile phone [14]. The majority of their study participants switched devices when offered a new one with contract renewal or a new contract. About a quarter of their participants switched because their mobile phone broke; another quarter reported they had their phones repaired in the past.

Designing for and Coping with Damage

Damage of artifacts can be addressed with protective measures at design time and during use, as well as reactive measures after damage occurred. One radical approach that embraces the change and transience of artifacts by damage are ephemeral interfaces [9]. Such interfaces are specifically designed for very fast degradation rather than lasting use, e.g., a display created by falling water or interaction handles provided by soap bubbles. Interaction with an ephemeral interface often carries an imminent risk of destroying it [9].

Rosner et al. give examples on how anticipation of potential damage during the design phase of physical artifacts can improve their longevity [18, 15]. For instance, by covering a ceramic plate with a silicon layer, the plate can retain its utility and structure if it shatters. Our proposed interaction design strategies follow a similar goal by considering the impact of potential damage already during app design. Huang and Truong caution to also consider an artifact's expected time of use during its design [14]. For instance, a short-lived artifact may not require durable casing.

The notion of relative obsolescence as discussed by Cooper [7], provides further insights why and when artifacts are being replaced. He distinguishes three types of obsolescence: psychological obsolescence driven by a reduced attractiveness and user satisfaction; technological obsolescence related to changes in functionality, quality, or effectiveness; and economical obsolescence pertaining to value reduction and excess repair costs relative to replacement. Planned obsolescence [6] assumes that manufactures already design products towards obsolescence in order to increase product sales. For instance, designing mobile devices with built-in batteries that cannot be replaced by users on their own. However, our own results indicate that high prices for new smartphones trump perceived obsolescence for many smartphone owners, who continue to use even severely damaged devices.

Accessibility Support and Interaction Alternatives

While little research focused on interaction with damaged devices, a large body of work exists on accessibility support. Such mechanisms could potentially also assist users of damaged smartphones in coping with interaction impairments caused by device damage. Current smartphones offer speech input to control certain features (e.g., Siri [2] or Google Now [11]). Apple's iOS devices further support on-screen emulation of hardware buttons and voice overs for visually impaired users [1]. Recent smartphones, like Samsung's Galaxy S4, support touch-less interaction above the display (*air gestures*) or gaze interaction. Eyes-free interaction without use of the display has also been proposed [22]. Other proposals for alternative mobile device input include scratching [12] or tapping on the phone [13, 17], as well as stomping with the foot [21].

To the best of our knowledge, no work has been conducted that focused on the impact and effects of damaged displays on smartphone interaction or interfaces of mobile devices in general. We are the first to explore and investigate how damage of smartphone displays affects interaction and use.

DISPLAY DAMAGE OF SMARTPHONES

We analyzed smartphone display damage based on a dataset collected through online surveys. In the following, we outline how the data was obtained and analyzed, and discuss respective results.

Survey Methodology

To gain insights on how smartphone displays get damaged, to what degree, and how different types of damage affect interaction, we conducted an online survey with owners of damaged smartphones. Based on the findings of Ross et al. [19], we opted for a MTurk study addressing potential participants from the United States, Europe, and India in order to elicit responses from different cultural and economic backgrounds. In addition, an online version of the survey was widely advertised at multiple schools and universities.

Participants had to provide a photo of their damaged smartphone displaying a given checkerboard pattern, as shown in Figures 1 and 3(a)), in order to ensure high visibility of damage. In initial experiments, the selected green-white pattern proved most suitable for different types of display damage. Each participant also completed multiple questions on phone usage and personal background. The checkerboard pattern

[1]The broken interface dataset is available online under a Creative Commons license: `http://uni-ulm.de/broken-interfaces`

further served as an authenticity check, as bogus pictures not showing the pattern could be removed easily. Furthermore, participants that took the effort of taking and uploading a photo are likely also inclined towards answering the questions accurately. After rigorously rejecting submissions that did not meet our requirements, we are confident that images and data in our dataset are genuine.

Broken Interface Dataset

In total, we received 260 submissions through MTurk and the online survey. 165 of these submissions were discarded as they did not meet the requirements for the photo of the damaged smartphone, e.g., the smartphone display was not turned on or did not show the website with our checkerboard pattern. The resulting dataset includes 95 entries, each consisting of a photo and extensive information on the pictured device's usage history, its damage, and how the damage affects smartphone use. We made our dataset freely available online.[1]

Demographics

Images and information in our dataset were provided by participants from 9 countries, mainly from the United States (50.5%), Germany (32.6%), and India (6%). They were aged 14 to 54 years ($\bar{x}$=M=26, σ=6.7); 39% of them female, 49% male, 12% did not specify a gender. Participants reported a large variety of main occupations, such as students, teachers, or developers. The majority (22.1%) reported a low income (500-1.500 USD/month), 20% a very low income (under 500 USD/month), 15.8% were in the range of 1.500-2.500 USD per month, while 26.3% provided no income information.

Smartphone devices and usage

The dataset contains smartphones from ten manufacturers. The majority were devices from Apple (35.8%), followed by Samsung (30.5%) and HTC (16.8%). A majority of the devices used Android (57.9%), followed by iOS (35.8%). 54.7% of the participants reported that they bought their smartphones without a contract. 17.8% paid a subsidized price or received it free as part of a mobile plan. 22.1% indicated that the smartphone was a gift and 2.1% indicated that it was given to them by their employer. 4.2% obtained a phone through other ways, e.g. using a used phone from a friend.

As to be expected, participants reported to use their smartphones mainly for messaging (e.g., via WhatsApp, SMS, or email), phone calls, and media consumption. Web browsing, personal information management (e.g., calendars, contacts), camera functionalities, as well as gaming were also commonly reported smartphone applications. 83% reported to use their smartphone exclusively for personal use. 16% reported to use it for both, personal and business reasons. Only one participant used the phone only for business. This rather small percentage of business related usage is most likely related to the sample of participants in our online survey.

Results: Reported Degree of Damage

In the online survey, participants rated the damage of different aspects on a five-point scale ranging from *no damage* to *completely broken*. Figure 2 shows the answer frequencies, note that multiple components may be affected per device.

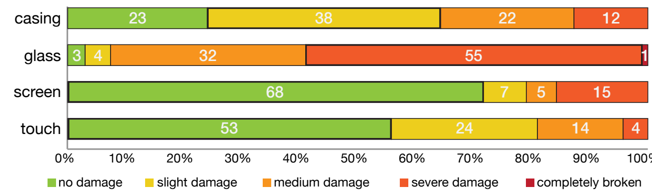


Figure 2. Damage rating frequencies for different components (n=95).

Display *glass* was damaged in most cases, with a median rating of severe damage. For the LCD *screen*, 15.8% reported a severe damage. Concerning *touch*, 4.2% reported severe and 14.7% reported medium damage.

The damage did usually not change after it occurred (72.6%). It deteriorated over time in 24.2% of the cases. Only 3.2% experienced irregular damage of functionality.

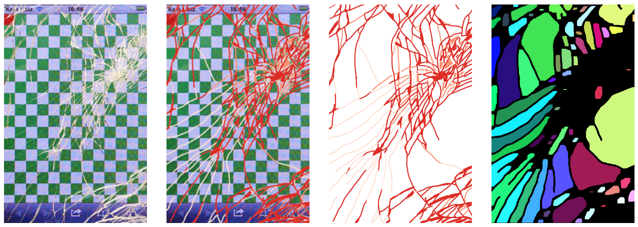
Analysis of Damaged Display Images

As mentioned before, participants not only rated damage, but also provided a photo of the damaged device, displaying a checkerboard pattern we provided as a website. The checkerboard pattern served multiple purposes: it provided a consistent background to make glass and screen damage visible, it provided information about the scale of the damage and a reference for color correction.

We performed a structured analysis of all images in the dataset to objectively quantify the damage of smartphone displays. Hereby, we focused on visible damage to the display (*glass*, *screen*) as we were mainly interested in interaction issues with the smartphone software. *Touch* damage was also not considered in image analysis, as it was not visible.

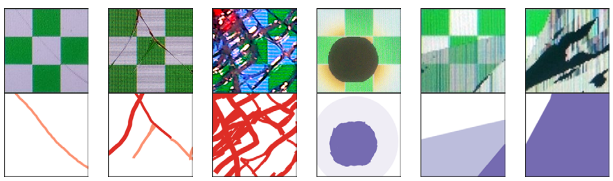
All images were pre-processed to account for differences between submitted photos in terms of illumination, as well as position and size of the damaged smartphone in the image. Images were first de-skewed and rectified based on the checkerboard pattern in order to obtain a rectangular view of the smartphone display. We further normalized colors with an automatic white balancing filter and cropped images to the display area, as shown in Figure 3(a).

In experiments, automated detection of different types of damage showed insufficient reliability. For instance, edge detection would not only detect actual cracks in the glass, but also the web browser address bar, visible on some photos, or reflections on the display. Hence, we employed a manual approach to reliably annotate different types of damage in the pre-processed images. We embedded the image in a Scalable Vector Graphics (SVG) file. Visible damage was then traced by hand with a digital drawing tablet (see Fig. 3(b) & (c)). We followed an iterative approach in the annotation to consistently annotate different types of damage. First, we browsed all original photos to gain an overview of occurring damage types, such as cracks or scratches. Afterwards, we annotated images with the initially identified damage types, extending the set of damage types whenever a new type was encountered. Each damage type was drawn on to a dedicated layer in the SVG to support detailed analysis. Subsequently, annotation results were cross-validated against the original photos.



(a) (b) (c) (d)

Figure 3. The image analysis process included (a) pre-processing the phone image and (b) manual tracing of visible damage. (c) The resulting damage annotation was used for further analysis and (d) to obtain a topology of visible (*colored*) and occluded areas (*black*).



(a) scratch (b) crack (c) spider web (d) color issue (e) grayout (f) blackout

Figure 4. Identified damage types with original photo (*top*) and annotation (*bottom*): (a)–(c) glass issues and (d)–(f) screen issues.

The identified damage types can be categorized as either *glass issues* or *screen issues*. Based on severity, we distinguished glass issues as *scratches*, *cracks*, and *spider webs*, which are marked in shades of red (see Fig. 4(a)–(c)); screen issues as *color issues*, *grayouts*, and *blackouts*, which are marked in shades of blue (see Fig. 4(d)–(f)). Grayouts are areas with partial occlusion, whereas blackouts denote areas with full occlusion, typically caused by screen backlight failure.

Based on the damage annotation, we determined the percentage of visible, intact display areas, as well as damaged and occluded display areas. We further quantified the number of disjunct partitions of a display, separated by cracks or other damage types. In Matlab, we used morphological functions to close small areas and gaps in the damage annotation and sorted resulting areas based on their pixel size. Figure 3(d)) shows an example of the resulting topology of visible (*colored*) and occluded areas (*black*).

Results: Categories of Smartphone Display Damage

Figure 5 shows the distribution of damaged and occluded display areas resulting from the analysis of the damage annotation (cf. Fig. 3(c)). In general, damage (including all damage types shown in Figure 4) covered a low percentage of the display. For 92.6% of the analyzed smartphones, less than 20% of the display was occluded or damaged.

However, displays are partitioned by damage into multiple visible areas, as shown in Figure 3(d). To analyze this data and to assess whether categories can be identified, we employed a two-step approach in cluster analysis. First hierarchical clustering was used to estimate the number of existing clusters. Analyzing the distance between the resulting clusters revealed three main categories and one outlier with a fully damaged display (image 46693-88 in dataset, see also Fig. 6 on the left). Representative examples for the categories are shown in Figure 1. Subsequently, we used k-means clustering to determine cluster members.

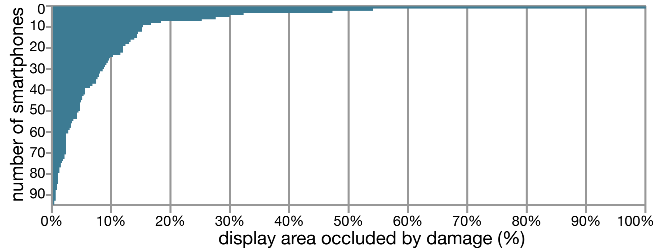


Figure 5. Distribution of damaged and occluded display areas (n=95).

The *minor display damage* category contained 45.3% of the analyzed cases. In this category, the sum of the three largest visible areas covered 93.1% of the overall display area on average (min=77.3%; max=99.9%). The category *medium display damage* contained 15.8% of all cases. Only 62.5% of the display area were included in the three largest visible areas on average (min=45.8%; max=73.9%). The remaining 37.9% were classified as *severe display damage*. In this category, the three largest visible areas contained less than 35.3% of the display on average (M=17.9%; min=7.2%). There is a considerable drop between the medium and severe damage categories in terms of visible area, as shown in Figure 6. Cases in the severe display damage category exhibited extensive spider webs and many scratches and cracks spanning the whole display, with only small unpartitioned areas remaining. The damaged display shown in Figure 3 falls into this category. Devices at the lower end of the medium category also exhibited spider webs but those did not cover the whole display. Thus, the largest visible areas tended to be bigger.

With the visual damage annotation approach, non-visible damages of touch input could not be quantified. Hence, we tested for correlation (using Spearman rank correlation) between visible display damage (percentage of three largest visible display areas) and the subjective rating of touch input damage (cf. Fig. 2). We did not find a correlation between subjectively rated touch input damage (on a five-point scale) and the size of the visible display area (r=-.131; p=.21). Yet, reducing the subjective rating of touch input damage to a binary scale (i.e., touch damage existing or not) revealed a significant correlation (r=-.273; p=.007). This indicates that display damage and touch input issues are likely connected. Although touch input issues of varying severity occur across all three identified display damage categories, as shown in Figure 6. In the severe display damage category, there is a notable concentration of slight and medium self-reported touch damage. However, there are also multiple cases with minor visible display damage but medium to severe touch damage. Thus, while severe display damage appears to co-occur with the presence of touch damage, touch issues may also occur without extensive visible display damage.

LIVING WITH THE DAMAGE

The online survey also inquired about the participants' experiences of living with a damaged smartphone. In addition, we

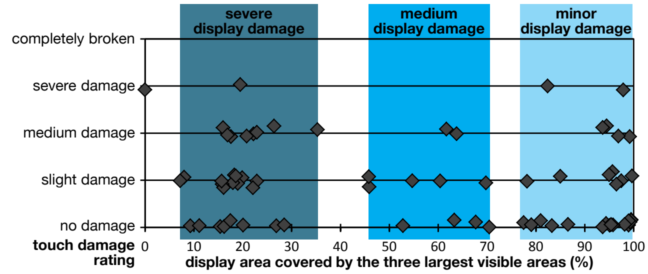


Figure 6. Distribution of touch damage in relation to visible display area and respective display damage categories (n=95).

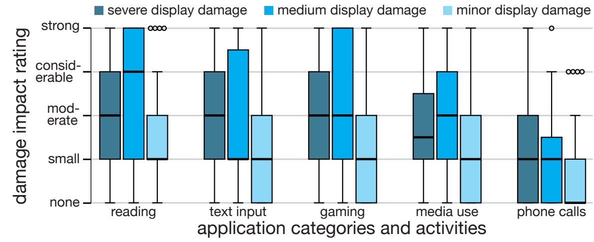


Figure 7. Perceived impact of damage on phone usage (n=94).

conducted interviews with eleven owners of damaged smartphones to gain more differentiated insights.

Results: Survey Responses

Participants of the online survey indicated how damage affected different applications and activities, as well as how long and why they continued to use the damaged phone.

Impact of damage on smartphone use

Participants were asked to rate the impact of their smartphone damage on application categories and activities (same categories as for smartphone use above). Figure 7 shows results for the four most impacted application categories, as well as the least affected category.

Reading was most impacted by damage, particularly in the medium (*mode*=5, M=4) and severe damage categories (*mode*=M=3). The non-parametric Kruskal-Wallis test indicated no significant differences between groups. The effect on *text input*, which was also rated the most important aspect of smartphone use, varied significantly between groups (Kruskal-Wallis: $H(2)$=8.87, p<.05). While minor and medium display damage had a small impact on text input (both *mode*=M=2), severe damage had a higher impact (*mode*=M=3). Post-hoc analysis (Mann-Whitney U with Bonferroni correction) shows that the difference between minor and severe damage was significant (U=485, p<.0167, r=-.33). *Gaming* also exhibited significant differences between groups ($H(2)$=9.68, p<.01). Compared to minor damage (*mode*=1, M=2), damage impact was rated significantly higher in the medium (*mode*=5, M=3; U=518, p<.0167, r=-.29) and severe damage categories (*mode*=4, M=3, U=188.5, p<.0167, r=-.32). The impact on *media use*, i.e., playback of photos, music or videos, was also rated highest in the medium damage category (*mode*=4, M=3), but differences were not significant. Across groups, *phone calls* were least impaired by display damage. The mode for all three groups was a rating of no effect (1), with a marginally higher impact in the medium and severe display damage categories (both M=2), but no significant differences between groups.

Notable in Figure 7 is that the third quartiles are higher in the medium damage group than the severe damage group for the four most affected categories. A potential explanation is that smartphones with medium damage are continued to be used more actively than those with severe damage. This is corroborated by the fact that phones with medium damage were used for longer (*months*) after the damage occurred (*mode*=2, M=4) than severely damaged phones (*mode*=1, M=3).

Continued use of damaged smartphone

Of the 95 participants, 97.9% continued to use their device after it got damaged; 82.1% still used it when completing our survey. On average, a damaged smartphone was used for 5.1 months (σ=5.3, M=4). However, 8 participants (8.4%) were already using their damaged smartphone for 1 year or longer; 3 years in the most extreme case. Furthermore, 85.3% planned to continue using the damaged smartphone. While one third (35.8%) planned to use the damaged phone for 3 months or less, another third (32.1%) planned to use it for at least another year or longer. These numbers align with the frequency of switching phones. The majority (49.5%) switched their smartphone every two years, which corresponds to typical mobile plans in many countries. 18.9% specifically indicated they switched smartphones when offered a new one by their provider, which conforms to Huang and Truong's results [14]. Non-periodic reasons for switching smartphones were damage (24.2%), release of a new model (15.8%), and lack of functionality or performance (3.2%).

67 participants (70.5%) did not plan to get their damaged phone repaired. The main stated reason was high repair costs (n=61), followed by being able to live with the damage (n=48), new phones being too expensive (n=43), and waiting for the release of a new model (n=22). The main stated reasons for abandoning a damaged phone were impaired visibility of display content (n=11), important functionality being broken (n=10), or risk of injury from broken glass (n=8).

Interviews

The survey results indicate that display damage mainly impacts visual output and touch input. Despite that, most displays are not repaired, mainly due to financial reasons, and are continued to be used for prolonged periods of time. We conducted interviews with owners of damaged smartphones to elicit specific interaction issues that arise in daily use and coping strategies that users developed to deal with them.

Interview Methodology

Interviewees were recruited from participants of the online survey (except MTurk workers). The 11 semi-structured interviews consisted of 17 open questions. They were conducted either at our lab (8) or via online video chat (3). Interviews were video-recorded to capture interaction with damaged devices. Participants received 10 Euro as compensation.

	age / gender	*user group*	*importance*	*display damage*
P1	47 / female	mobile utilizer	moderate	severe
P2	25 / female	mobile utilizer	moderate	minor
P3	22 / female	mobile utilizer	important	minor
P4	27 / female	mobile utilizer	important	severe
P5	32 / male	social communicator	moderate	severe
P6	25 / female	social communicator	high	medium
P7	19 / female	social communicator	high	minor
P8	25 / male	social communicator	high	minor
P9	26 / male	social communicator	high	minor
P10	27 / male	social communicator	body extension	minor
P11	26 / male	social communicator	body extension	severe

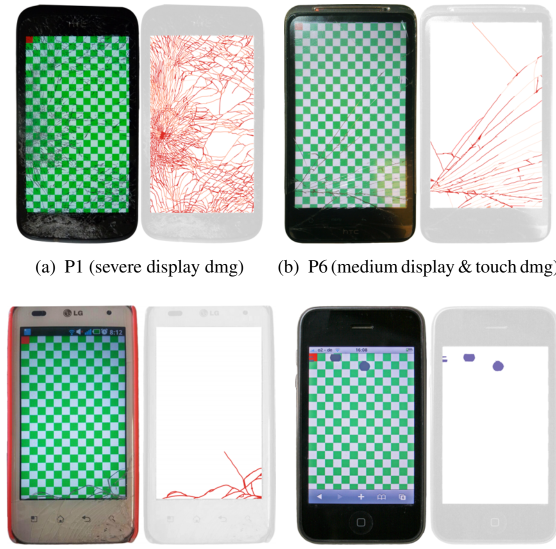
Table 1. Interview participants and their characteristics.

We employed grounded theory [8] with iterative coding for qualitative analysis. First, three of the authors independently coded the same two interviews. Based on these results, a joint consolidated set of coding categories was developed, which was further refined through a second iteration. Inter-rater reliability was verified with a randomly selected interview (P2), before the remaining interviews were coded separately. Fleiss' Kappa [10] showed substantial agreement between the three raters (κ=.64). The coded data was then analyzed with affinity diagramming to identify concepts and insights.

Participant categories and phone damage

The 11 interviewees (6 female, 5 male) came from different German cities, had mainly an academic background (student or researcher), and used smartphones for 1.5–7 years (M=3). We categorized them into two groups, as shown in Table 1, based on the importance of their smartphones to them. *Mobile utilizers* appreciated the mobility and utility of smartphones, but placed less emphasis on social networking or communication with peers. *Social communicators* used their phone primarily to stay in touch via messaging, social networks, and gaming apps. They appreciated mobile Internet access and reachability, but did not talk much on the phone. Almost all rated the importance of their phones higher than mobile utilizers, seeing it as highly important for staying in touch with peers. P10 and P11 described their phone as a *"body extension."* P11 characterized it as a *"permanent social link"* and *"competence extension."* All mobile utilizers were female in our sample; social communicators dominantly male.

Almost all of the participants' phones suffered damage from a fall, either because the phone slipped out of the hand (6) or a pocket (4). P6 and P7 reported that their phones slipped out of their pants' back pocket while in the restroom. P1 dropped the phone in a parking lot without noticing it, and assumed that a car drove over it before she found it (see Fig. 8(a)). P11's phone was damaged while inside a bag. In 9 cases, only the phone's display glass was broken (*minor* to *severe*). P6 also experienced broken glass (*medium*), but the upper part of her display also became unresponsive to touch after a while (see Fig. 8(b)). P10's phone suffered only screen damage (blackouts in two spots, see Fig. 8(d)), with glass and touch being intact (*minor*). The distribution of minor (55%), medium (10%), and severe display damage (36%) in Table 1 roughly corresponds to the display damage distribution in the overall dataset (45.3%, 15.8%, 37.9%).



(a) P1 (severe display dmg) (b) P6 (medium display & touch dmg)

(c) P7 (minor display dmg) (d) P10 (minor display dmg (screen))

Figure 8. Examples of damaged phones from interview participants with photo (*left*) and annotated damage (dmg) (*right*).

Results: Reasons for Continued Use

Many participants continued to use the damaged device because it was still usable with minor constraints (4), or because the damage was deemed too insignificant to justify replacement or repair (5). What degree of damage was perceived as still usable varied considerably, ranging from minor glass (P2, P8) or screen damage (P10) to medium (P6) and severe display damage (P1). However, P1 and P6 planned to replace their phones soon. The threshold for replacing a phone was quite high in both groups. Acceptability of damage was mainly traded off against financial considerations. 5 participants were not willing to pay full price for a new phone. 3 expected to receive a new phone through renewal of their mobile plan. P8 usually bought a new phone every 1.5 years and planned to keep the current phone for another 6 months. P6 continued to use the damaged phone, because she did not like the phones available in her price range.

7 participants thought repairing the phone was too expensive, which corresponds to our online survey results. While 5 participants did not consider repair, others looked into getting it repaired (P1, P2, P5) or self-repair (P8). However, only P4 had the phone repaired at the time of the interview (after 4 months) and P11 had bought a new phone (after 2 months). In general, repair costs were considered too close to the purchase price: *"repair costs 170 Euro, the phone cost 300 Euro. What should I do?"* (P1); *"repair would also cost 200 Euro, I would rather buy a new one then"* (P2). While this suggests economical obsolescence, the high price of a new phone did not lead to replacement [7]. For repair, P6 was also skeptical about placing a new display in the old casing, and P1 feared further malfunction. P2 and P5 knew that high repair costs were caused by combined glass-display units and wished that the glass was easier to replace.

4 participants stated that the damage did not change their perception of the phone manufacturer, and would not influence purchase decisions. However, P11 switched to a different manufacturer after breaking two phones from the same manufacturer. Interestingly, P4, P6, P7, and P9 perceived their phones as more robust, because they were still usable despite the damage. This increased trust in the manufacturer of their phone (P6, P7, P9), but also decreased trust in other manufacturers (P4, P6, P9). For instance, P6 stated *"[...] you see even more broken iPhones. I think those are even easier to break."*

Results: Interaction Issues

Reported interaction issues can be categorized as *viewing/output issues* and *touch/input issues*. Viewing issues are caused by glass and screen damage. Their severity depends on the location, extent, and opacity of the damage. Scratches had a negligible impact on most applications (P2, P3, P7, P8), although reading can be slightly impaired by fine cracks (P2). In line with our survey results, reading was reported to be most affected by damage. P4 stated that reading was *"awkward"*, because the damage was in the display's center. Spider webs made reading particularly difficult, as the display provided only a tessellated view of the text with cracks partially covering words and characters, thus, requiring to *"look between the cracks"* (P1), see Fig. 9(a). Characters are easily confused (P6 mentioned *O/Q* and *r/f* mix ups, cf. Fig. 9(c)) and text passages might have to be guessed (P11). P6 noted that reading issues also impact typing, as typed text can be occluded, resulting in a lack of feedback.

Damage impact can further depend on device orientation. P10 reported hardly any issues in portrait mode (see Fig. 8(d)), but noticeable effects in landscape mode. The dark spots would only cover the browser's address bar in portrait mode, but be in the middle of the text in landscape mode. When using Twitter in landscape mode, the dark spots would either only cover avatars or also be in the middle of text. As a consequence, P10 reported being conscious about the more awkward landscape orientation and having a viewing field reduced to the area between the two spots, with the area below only being used for *"a bit of preview"* (see Fig. 9(d)). Glass and screen damage further impact apps that rely on display content being read by other machines, e.g., displayed barcodes being scanned as entry or bus tickets (P6).

Regarding input, display cracks create a tactile sensation, which is particularly noticeable for swipe gestures (P5). Advanced degradation of the glass surface is also a potential source for injury, as demonstrated by P1 (see Fig. 9(b)), who stated that one *"has to be careful when typing."*

Damage of input-related hardware had the strongest impact on interaction. P3 reported a defect proximity sensor that caused her to accidentally mute calls with her cheek, and a sporadically defective home button (*"it's annoying, if you can't get out of the apps anymore"*). P6 experienced the most severe input issues, after the top part of her display became unresponsive. As a consequence, UI elements located at the top of the screen could not be activated anymore. For instance, the Android notification bar could not be pulled down; the browser address bar and the search field in the app store could also not be activated anymore. Mails could not be sent, and multiple games became unusable, because the buttons to skip ads were placed at the top.

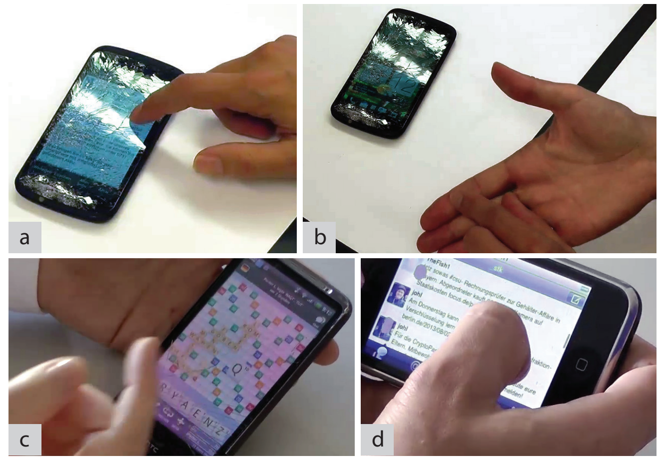


Figure 9. Examples of interaction issues: (a) P1 positioned text between cracks; (b) P1 caught glass splinters on her finger from touching the display; (c) P6 moved characters around in a Scrabble game to enhance readability; and (d) P10 positioned text between two damage spots.

Results: Coping strategies

Participants developed coping strategies to adapt to their phone's damage. In total, our 11 interviewees reported 23 different coping strategies, listed in Table 2.

Preventive strategies aimed to prevent further deterioration (4), e.g., by placing a protective film on the display (S1). P10 considered purchasing an outdoor phone (S2).

Viewing strategies addressed output issues. Most participants (5) used scrolling to move text and UI elements around damaged display areas (S3), cf. Figure 9(a) & (d). 3 participants with severe damage and 1 with minor damage stated that their perception had adapted so that they hardly noticed the damage anymore (S4). P2, P5, and P10 focused on a smaller part of the screen, typically the largest visible area (S5). Rotating the device (S6) and zooming (S7) also helped to position content in intact display areas. P5 noted that cracks were less visible on darker backgrounds, while P10's reflective screen made blackout spots almost see-through in direct sunlight (S8). Hiding or expanding UI elements, such as the virtual keyboard or menu bars, were also used to move content into viewable display areas (S9, S10), e.g., P11 would hide the keyboard to expand the visible area. When viewing a WhatsApp conversation, P6 clicked immediately into the text field in order to show the keyboard and move the message text up into less damaged display parts. P6 would also hold the phone at different angles to recognize text (S11) or just guess based on context (S12). P10 initially massaged the screen to stall spread of blackouts (S13), which eventually grew to their current size (cf. Fig. 8(d)).

Touch and input strategies are concerned with direct contact with the damage. P1, P6, and P7 used or considered protection films to smooth interaction and prevent injury (S14). P1 and P6 also tried to type and click carefully (S15). P11

	Strategy	*Category*	*Freq.*
S1	adding protection film to stall display degradation	preventive	4
S2	possibly buying durable outdoor phone	preventive	1
S3	scrolling	viewing	5
S4	ignoring the damage (perceptual adaptation)	viewing	4
S5	using only reduced viewing field	viewing	3
S6	rotating the device	viewing	3
S7	zooming	viewing	2
S8	adjusting brightness or color theme	viewing	2
S9	hiding UI components (browser bar/keyboard)	viewing	1
S10	expanding UI components (browser bar/keyboard)	viewing	1
S11	adjusting viewing angle	viewing	1
S12	guessing based on context	viewing	1
S13	massaging screen to stall blackouts	viewing	1
S14	adding protection film for smoother interaction	touch	3
S15	touching carefully to avoid injury	touch	2
S16	rotating phone to avoid touching broken glass	touch	1
S17	increased/repeated pressing of hardware buttons	touch	1
S18	using other apps	touch	1
S19	using hands-free telephony	calling	2
S20	using call forwarding to second phone	calling	1
S21	emulating hardware buttons with software	interaction	1
S22	leveraging alternative interaction methods	interaction	1
S23	moving social group to other app(s)	interaction	1

Table 2. Coping strategies employed by interview participants to deal with damage (n=11).

avoided landscape mode as the thumb would rest on broken glass (S16). P3 would press faulty hardware buttons repeatedly or used two fingers to increase pressure (S17). P6 switched to other apps, because certain apps had UI elements only in the touch-damaged area (S18). Surprisingly, no participant rearranged icons on the home screen to make them more accessible. Even P6 did not move icons from the top part of the screen, because *"they can still be activated by clicking them on their very bottom"*. This suggests that customization with widgets and home screen arrangements is rather a tool for personalization [5] than a coping mechanism.

Calling strategies served to make phone calls with minimal phone contact. P1 and P3 made calls in speaker mode to avoid holding the damaged phone against their face (S19). Later on, P1 automatically forwarded calls to an older feature phone in order to take calls more conveniently (S20).

Interaction strategies enabled users to perform activities with alternative means. P6 added the *settings* icon to her home screen to compensate for defective volume controls (S21). P6 also used alternative interaction paths to cope with partially defective touch input (S22). Because the address bar in the browser could not be clicked, she opened a new tab via the context menu, which would directly select the address bar. In the contacts list, the top entry could not be selected, thus she read the number from the contact preview and typed it manually to place a call. Because she could not send emails with her mail app anymore, she used the Web interface of her email provider, which allowed to *"track and scroll the display [in the browser]."* However, this process was perceived as too cumbersome. P6 engaged in multiple social gaming apps to keep in touch with friends. One game became unusable due to a *next* button located at the top of the screen. Another game had a similar setup but allowed to reach the main menu by pressing back. Thus, she actively persuaded her friends to only play the second game (S23): *"I told them all: 'Guys, no more playing WordBlitz, only Razzle."'*

Limitations
Our interview participants all had an academic background, either being students or researchers, coming from different German universities. In our sample population, we only identified mobile utilizers and social communicators as explicit groups. With higher diversity more user categories might emerge that may also exhibit additional or different coping strategies. More users affected by touch damage would be of particular interest, as P3 and P6 exhibited rich and elaborate coping strategies to compensate for partial touch damage. While the list of named coping strategies may not be exhaustive, it highlights the diversity of strategies and the adaptability of users. The interviews also made apparent that seemingly innocuous design decisions, such as the placement of a *next* button to skip ads can have a large impact when interaction is impaired by damage.

SUPPORTING INTERACTION WITH BROKEN DISPLAYS
Our survey and interview results show that the majority of participants continued to use a damaged phone (98%); 88% for at least three months. 32% plan to use it for another year or more. Repair costs are deemed too high by most, regardless of the degree of damage. Yet, new smartphones are also deemed too expensive to justify unplanned purchases. Only if the damage becomes intolerable, e.g., when touch input is strongly affected, damaged phones are actively replaced.

Users adapt to their phone damage with diverse coping strategies, closely tailored to their individual interaction issues. Many of these strategies can already be supported at design time of smartphones and mobile applications. Supporting those strategies would not only provide a positive user experience in the face of display damage, but may also prevent affected users from switching to different apps or platforms, potentially moving their social group with them. Next, we propose respective design guidelines for manufacturers and interaction designers that potentially lessen the impact of display damage on interaction.

Support scrolling and device rotation
The frequently named coping strategies scrolling (S3) and rotating the device (S6) can be actively supported. Scrolling up and down enables users to position screen content and text in less damaged display areas. Inertial scrolling (or rubber-band scrolling) further supports this coping strategy by allowing to move slightly *beyond* the beginning and end of a screen. Allowing to move screen content also slightly to the left or right (2D inertial scrolling) makes it easier to recognize text occluded by damage (S11, S12). The inertia, i.e., how far content can be moved to the sides, should be configurable to enable users to adapt it to the extent of their display's damage. While inertial scrolling is commonly provided by UI widgets, app designers could also integrate it in apps that tend to have non-scrollable screens, such as games.

Switching between portrait and landscape mode changes the perceived visual impact of damage, because different UI elements may be occluded. Apps could also use different layouts for portrait and landscape modes in order to offer the ability to gain access to previously occluded screen content and functionality. Thus, app designers should strive to provide, both, portrait and landscape layouts, whenever possible.

Facilitate layout and theme customization

Coping strategies that rely on expanding and hiding UI elements (S9, S10), such as the keyboard or status bars, indicate a need for flexible UI concepts. Affected users should be able to customize the layout of an app to better suit their needs — damage related or not. For instance, rearranging status bars or soft buttons would have allowed P6 to move essential components to screen areas still responsive to touch. Thus, customization does not only facilitate personalization but can also reduce the impact of potential display damage.

Darker colors make it easier for affected users to ignore glass cracks (S4), because reduction of screen brightness coincides with a reduction of light reflected by cracks. Operating systems and apps could support this by providing different themes to choose from. Some smartphones (e.g., Nokia Lumia 920) already provide sunlight readability modes, which adapt screen contrast and color dynamically. Similar modes could be created to make display damage less noticeable.

Provide alternative interaction paths

By providing multiple alternative interaction paths, utility of an app can be maintained even if the primary intended interaction paths have been rendered unusable by damage (S22). Relying on a single exclusive interaction path may render the whole application unusable, which poses the risk of not only losing the affected users, but their social sphere as well (S23). Alternative interaction paths can often be provided without much additional effort. For P6, the ability to press the *back* button to skip an in-game ad rather than having to use the app's *next* button made all the difference. Similarly, providing redundant options in context menus can suffice as interaction alternatives. Another approach could be to allow to change the function of hardware buttons, such as volume controls, on the system level to sequentially tab through UI elements, e.g., in order to select the browser's address bar for text entry. A short press could mean tab, a long press could act as a trigger. A further option is to provide additional input and output modalities, such as projected UIs [20] or gaze-based interaction [22], to compensate display and touch damage.

Detect and adapt to damage

An avenue for further research is the detection of drops and resulting damage with integrated sensors. Accelerometers could recognize drops as free fall and a sudden stop. A gyroscope could determine whether the device hit the ground with an edge, corner, the front, or the back. Such sensor information could be combined with empirical damage models to estimate whether damage occurred and to what extent, which could also benefit manufacturers to adapt their design.

Accelerometer peaks can also be used to detect taps on the device [17], in oder to determine when intended taps were not sensed properly, e.g., when the display is tapped repeatedly (S17). Over a period of time, this should allow to determine

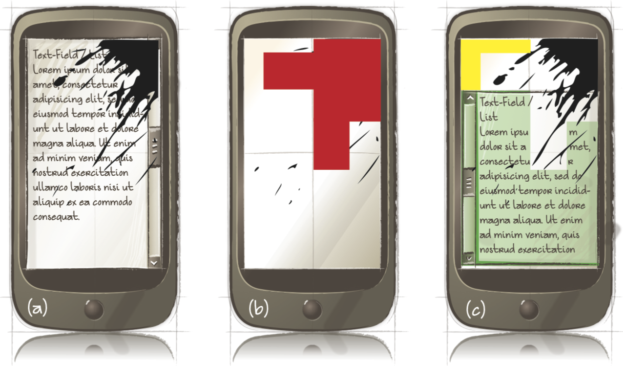


Figure 10. Adaptive content rendering example: (a) A text area is partially occluded by display damage. (b) The user marks the damaged area on a grid (*red*). (c) An adaptive text renderer floats the text around the damaged area (*green*) and moves the scroll indicator to the left. In this scenario, the upper-left corner can also not be used anymore (*yellow*).

in which display areas touch input is impaired. Smartphones could then either adapt system aspects to detected damage or suggest suitable coping strategies to improve continued use.

Provide adaptive content representation

Named interaction issues were dominated by viewing and reading impairments caused by occlusion of content. By offering user control over how content is presented, readability could be enhanced, e.g., by allowing to change font size or family (S11, S12) or by not only supporting zooming for websites, maps, and images, but also for app content (S7).

A potentially useful approach could be adaptive text and content rendering. Display areas highly occluded by damage could either be automatically detected, as proposed before, or manually marked by the user, if touch input is intact. As a result, the phone would be aware of areas with major damage and could adapt content rendering and representation, accordingly, e.g., by excluding parts from rendering or rearranging UI components. Figure 10 shows a simplified example of how this approach might work. Further research is required to assess the potential of such an approach and the impact on readability and user experience, as well as to develop suitable adaptive rendering mechanisms.

CONCLUSIONS

In this work, we have shown that display damage has indeed a large impact on smartphone interaction. Our broken interface dataset is a rich resource on display damage in the wild, including detailed images of damaged phones, information about the damage severity, how damage occurred, as well as the impact of the damage on prolonged use. Participants' damage assessment in combination with image analysis and manual damage annotation showed that three categories of visible display damage can be distinguished (*minor*, *medium*, *severe*), with a considerable gap between the latter two. While touch issues occur across categories, we identified a positive correlation between those categories and the reported presence of touch damage. We provided our damaged display dataset[1] to the CHI community to foster more research on the impact of damage on user interaction.

Our semi-structured interviews revealed that the severity of damage has a stronger impact on interaction than the type of use or assigned importance of the phone. Both survey and interview results indicate that even heavily damaged smartphones are continued to be used for multiple months; phones with less severe damage potentially for years. Main reasons for continued use are high repair or replacement costs, which are balanced against the severity of the damage. Reported interaction issues are dominated by viewing issues due to visible display damage. However, when touch input issues emerged, they were typically more severe. Through our 11 interviews, we collected over 20 coping strategies. Those strategies highlight the adaptability of users, if provided with flexibility in how to interact with their smartphones and apps.

A valuable insight for application developers is the indication that not catering for potential display damage may not only cause affected users but their whole social group to abandon an app, as reported by interviewee P6 (strategy S23). Based on our results, we discussed strategies for interaction designers to cater for potential damage. The proposed strategies support many of the reported coping strategies, and most of them can be readily considered in application design without major effort. Conceptual strategies, such as damage-aware adaptive content rendering and sensor-based damage detection, require further investigation to assess their potential and overcome associated challenges.

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