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Focus: A Usable & Effective Approach to OLED Display Power Management

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ABSTRACT
In this paper, we present the design and implementation of *Focus*, a system for effectively and efficiently reducing power consumption of OLED displays on smartphones. These displays, while becoming exceedingly common still consume significant power. The key idea of *Focus* is that we use the notion of saliency to save display power by dimming portions of the applications that are less important to the user. We envision *Focus* being especially useful during low battery situations when usability is less important than power savings. We tested *Focus* using 15 applications running on a Samsung Galaxy S III and show that it saves, on average, between 23 to 34% of the OLED display power with little impact on task completion times. Finally, we present the results of a user study, involving 30 participants that shows that *Focus*, even with its dimming behaviour, is still quite usable.

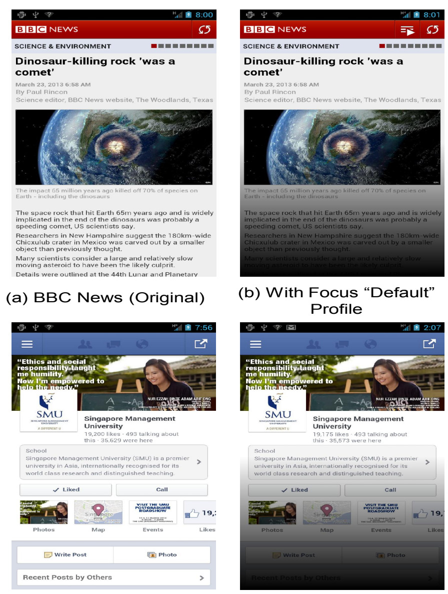
ACM Classification Keywords
I.4.3 Image Processing & Computer Vision: Enhancement; I.3.3 Computer Graphics: Picture / Image Generation—*Display Algorithms*

General Terms
Algorithms, Design, Human Factors, Experimentation

Author Keywords
Power Management, Tone Mapping, Mobile Games

INTRODUCTION
Prolonging the battery lifetime of phones under continuous application usage is a very active area of research. In this paper, we contribute to this goal by presenting a technique for reducing the power consumption of Organic Light Emitting Diode (OLED) displays on smartphones — especially during critical low battery situations or extended outdoor use, when prolonging the battery lifetime may be just as important as preserving usability. In such situations, users are far more likely to willingly sacrifice the visible screen real estate, so as to prolong their battery life (by 20% longer or more).

OLED displays are becoming ever more popular due to their more vibrant colour palette and lower average power consumption (40% less on average [1]) (relative to traditional Liquid Crystal Displays (LCD)). However, prior work has shown that, even with OLED's typical power efficiency, OLED-based smartphone displays still impose the dominant energy overhead, consuming up to 67% [3] of the total device power consumption. Clearly, reducing the display's power consumption will have significant practical impact, especially as smartphones with larger displays such as the 4 inch iPhone 5, 4.8 inch Galaxy S III, 5 inch Galaxy S IV, and the 5.3 inch Galaxy Note II gain wider consumer adoption.



(a) BBC News (Original) (b) With Focus "Default" Profile
(c) Facebook (Original) (d) With Focus "Default" Profile

Figure 1. Two Apps where Focus Saves Power By Screen Dimming

In general, there are two ways to save power for OLED displays: *1)* convert the displayed colours into colours that consume less energy [8, 9, 20] (in OLED displays, the red, green, and blue diodes consume different amounts of power), and *2)* darken or turn off portions of the displayed contents that are less interesting to the user [20, 24]. Unfortunately, both of these approaches are very visible to the end user. The challenge thus lies in reducing the power consumption, while still preserving the user experience.

In this paper, we focus on option 2, *darkening of the display*, and present a solution, called *Focus*, that *a)* is a generic technique that can be applied to many applications, *b)* significantly reduces display power consumption, *c)* can prove effective even without requiring any user-specific personalisation, and most importantly, *d)* does not noticeably degrade either the user's satisfaction or her effective use of the application. *Focus* is complementary to colour-remapping techniques for OLED display power management.

∗Research performed by author as a Research Engineer at Singapore Management University.

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Focus works by darkening portions of the screen that contain content that is less important to the user. Figure 1 shows the effect of applying *Focus* to two popular applications (the exact mechanisms used will be detailed in the implementation section). To systematically identify the portions of the screen that can be dimmed or darkened, we carefully analysed a broad range of popular smartphone applications and established that they could be grouped into a few distinct categories, based on certain properties of how users interact with each application. We then utilised the the concept of *saliency* to identify the appropriate *Regions of Interest* (ROI) for each of these categories. In particular, we discovered that most (but not all) applications require the user to focus on just one half of the screen, with the the other half usually containing older content (e.g., *Facebook*, *Gmail*, *Twitter*, *WhatsApp Messenger* etc.). Using such insight, we were able to design *Focus* to be simple-to-use and understand, while satisfying the desired goals of *a)* saving power, while preserving usability, and *b)* being generically applicable to almost all applications.

To evaluate *Focus*, we conducted two different studies:

1. In the first study, we measured the actual power savings of *Focus*, with the Monsoon hardware-based power monitor [18], using 15 different popular applications (that cover a wide range of application types) running on a 4.8 inch OLED display Galaxy S III smartphone. The results show that *Focus* saves up to 45% of the OLED display power (average savings of 34%) when optimised on a per-application basis and up to 31% of the OLED display power (average savings of 23%) when using a standard application-agnostic "One Size Fits All" approach. In addition, our results show that that *Focus* has little impact on task completion times. These power savings numbers suggest that *Focus* could be a good approach for prolonging battery life in low-power situations – e.g., when the battery has 15% or less charge, as long as the user experience is acceptable.
2. The second study then helped establish that *Focus* could indeed be acceptable to users. In this user study, we focused on 6 representative applications and asked 30 participants to each evaluate the usability of 4 of these 6 applications, with and without *Focus*. Our results show that *Focus* remained quite usable, and acceptable to users, when compared to the original unmodified application.

Key Contributions: This paper's major contributions are

1. A detailed study of 520 Android applications, across 26 categories, to understand the distinct *saliency* characteristics across applications.
2. The design and implementation of a general technique, called *Focus*, that saves up to 45% of the OLED display power consumption of applications by smartly darkening the display. *Focus* requires the creation of a profile only once (either for all Apps or once per-App).
3. Validation of the display power savings achievable with *Focus* and the impact on task completion times through extensive evaluations with 15 applications running on a 4.8 inch display Samsung Galaxy S III OLED-based smartphone.
4. Validation of the usability of *Focus* through a large user study, with 30 participants, involving 6 key applications, and using the Galaxy S III.

BACKGROUND

In this section, we cover some of the background material that influenced the design and implementation of *Focus*.

OLED displays

Unlike LCDs, OLED displays do not use a backlight for illumination. Instead, they use an organic semiconducting compound where each pixel contains red, green, and blue (RGB) diodes [22]. To achieve the desired colour, each pixel independently lights up the corresponding RGB diodes with a variable intensity, that directly correlates to the OLED display's power consumption.

As a result, LCD power conservation techniques that reduce the backlight intensity (e.g., Anand et. al [1]) will not work on OLED displays. Instead, as described earlier, OLED displays will require either *colour remapping* (each coloured diode consumes different amounts of power) or *display darkening* so that diodes can be either turned off or reduced in intensity. We use the display darkening technique in our solution.

Are OLED-based Smartphones Common?

A key early question we asked was "Are OLED-based smartphones here to stay?" — i.e., is this a real problem? We discovered that OLED-based smartphones are extremely popular, with Samsung leading the way and other manufacturers soon to follow [17]. Samsung, according to Gartner [12], has become the world's most popular smartphone manufacturer — with their OLED-based Galaxy Series smartphones (S II, III & IV, Note I & II, etc.). In addition, due to market and technology issues, larger OLED displays (e.g., tablets, laptops, or TVs) [17] will not become common anytime soon. Indeed, searching the tablet market revealed only 2 OLED-based tablets (the Samsung Galaxy Tab 7.7 and the Toshiba Excite 7.7). Hence, we focused our research effort on reducing the power consumption of smartphone OLED displays.

How flexibly can users control OLED brightness?

Our work is motivated by the belief that, under low battery conditions, users will trade off their display's brightness intensity for longer usage duration. However, at present, OLED-based smartphones do not offer users the flexibility to apply application-specific or non-uniform dimming patterns — e.g., Samsung S III users can only apply brightness adjustments uniformly to the entire screen. *Focus* is predicated on the hypothesis that better tradeoffs between usability and energy savings can be achieved by applying non-uniform dimming strategies that are tuned to the typical ways in which a user interacts with each individual application.

Saliency and Regions of Interest

To effectively dim the screen image (instead of just uniformly darkening the whole screen), we must identify the parts of the screen that are of less importance to the user. We use the concept of *saliency* (similar to prior work [10, 11, 15, 25]), which captures the fact that a human typically pays attention to only specific parts of the entire display. As we describe later, we found that almost all applications, with a few exceptions, are designed for either bottom-up or top-down visual attention. With this insight, we can create *Regions of Interest* (ROI) that work across multiple application types.

In this paper, we use a simple ROI model (guided by our application survey shown next) that assumes that user attention, when using an application, is directed mostly towards the *top* or *bottom* portions of the screen. The user is then able, if they so desire, to toggle the ROI between the top and bottom halves of the screen with a simple button press. We chose this approach, for implementing *Focus*, over more precise ROI detection mechanisms, such as eye-tracking (that was introduced in the latest Samsung Galaxy S IV) for the following reasons: 1) more advanced methods require either more hardware (specialised eye tracking devices) or are not that accurate (eye tracking using a phone camera is still imperfect), 2) they tend to require user effort (to train the system etc.), and most importantly, 3) as we show in the evaluation section, our simpler approach works across a large range of application types, saves significant power, and is quite usable with no additional effort, devices, or training required by users.

DESIGNING FOCUS

In this section, we describe the design objectives of *Focus* and how our specific design choice for screen darkening is driven by our detailed study of 520 Android applications.

Design Requirements

We identified four main design requirements for *Focus*:

1 **User Friendly**. *Focus* must not affect the end user experience in unacceptable ways. This was the highest design consideration and was validated via a user study.

2 **Significant Power Savings**. In addition to being user friendly, *Focus* must also save significant amounts of OLED display power. Our results show that *Focus* saves, on average, between 23 and 34% of the OLED display power, translating into an overall power savings of 15-20%.

3 **Generalisable**. *Focus* must support all application types and not require application-specific code modifications. We describe how we achieved this (in particular, *Focus* leaves the application binaries unchanged) and present results from multiple applications in later sections.

4 **Low Computational Requirements**. *Focus* must be computationally efficient, i.e., *Focus* cannot save OLED display power at the expense of incurring a significant CPU or other resource energy cost. Our results show that *Focus*, even with its additional overhead, saves significant power without any significant latency impact.

Understanding Android Application Characteristics

To understand the dimming methods that are likely to prove successful, we first carefully surveyed the top 20 applications in each of the 26 Google Play application categories (520 apps in total). Our analysis revealed the following:

- A majority of applications (64%) place their new content either at the top or bottom portions of the screen. For a reasonably large set of applications (29%) (e.g. book readers), the new content was on the entire screen. There were also a few applications (7%) (e.g. wallpapers) that were meant to be run in the background and could be safely dimmed or even turned off when power conservation becomes crucial.
- In addition, most applications (69%) used scrolling to access new content, while a few applications (30%) (book readers again) used page flips (where you swipe across the screen and the whole page refreshes with new content). An even smaller set (1%) (*Ebay*) used a combination of both scrolling and page flips.
- Finally, a significant majority of applications were principally focused on digital consumption and are thus *read-only* (77%), with very little user input (beyond navigation controls). However, a few applications (23%) (e.g. *WhatsApp* and *Twitter*) required the user to provide a lot of input.

IMPLEMENTING FOCUS IN ANDROID

In this section, we explain the implementation of *Focus*.

Implementing Focus Inside The Android Framework

Focus is implemented in the Android Application Framework as it allows access to both user keypresses (to detect swipes, etc.) and the display framebuffer. This was a careful architectural choice and offers advantages over the two likely alternatives: *a)* Implementing *Focus* in the lower levels of the stack (such as the kernel video drivers): This would have provided more direct access to the image framebuffer at the expense of semantically meaningful keypresses (which would now be reported as raw pressure values), making it difficult to adjust the dimming function in response to user interactions; *b)* Implementing *Focus* in user space: This would have incurred a significant performance penalty (and limited its generalisability by requiring application recompiling).

We implemented *Focus* by extending the Android drawing process that draws application content onto the screen. Standard Android applications that use widgets to draw content on the screen are arranged internally in a parent-child relationship with each widget being a child of the master "View object" [13]. At runtime, Android draws all the widgets onto the screen, in a recursive way, starting from the parent. Once all the children for the entire rendering tree have been added to the framebuffer, Android goes ahead and renders the entire framebuffer to the display. *Focus* extends the drawing routines of the master root object, as this root activates only after all the application widgets have been processed.

Focus applies a *dimming profile* to the final root display object using the well-known alpha blending technique, which uses a special colour channel to gradually adjust the opacity and translucency of the individual pixels of the screen image, so as to achieve a smooth dimming gradient. The overall process for *Focus* is illustrated in Figure 4.

Default vs. App-Specific Profiles

In *Focus*, the dimming profile determines the pattern of darkening that is applied to the display. To provide both flexibility and runtime execution efficiency, profiles in *Focus* can manipulate three different portions of the screen: 1) a dimming region at the top, 2) a clear region in the middle, and 3) a dimming region at the bottom. For the two dimming regions, two values can be specified; i) the size of the region (ranging from 0% to 100% of the screen), and ii) the intensity level at the end of the dimming region, i.e., the alpha blending should blend from 100% intensity to x% intensity (where x is the value specified) at the end of the dimming region. By default, this value is set to 10%. For the bottom dimming region (which is much larger than the top dimming region in all the applications used for this paper), a "plateau point" could also be specified. This is the point where the gradual dimming should be stopped and the remaining portion of the screen from the plateau point downwards should become completely black (i.e., 100% dimmed).

We consider two different alternatives for such profiles.

Default Profile: *Focus's* default profile is *application independent* and leaves the top half of the screen clear while gradually dimming the bottom half of the screen (as shown in Figure 1). The settings for the "Default" profile are thus as follows: the top dimming region size was set to 0% (i.e., turned off). The size of the bottom dimming region was set to 50% (i.e., half of the screen) and the plateau region was set to the bottom of the screen (i.e., there was no area of the visible screen that was turned off). Finally, the gradient of the bottom dimming region was set to 10%. This profile leaves the top 50% of the screen unmodified while dimming the bottom 50% gradually from 100% intensity to 10% intensity at the very bottom of the screen. The effect of this conservative profile is shown in Figure 1.

In addition, by pressing a hardware button, the dimming "flips", i.e., the bottom portion is clear and the top portion is dimmed. (The topmost status bar dimming never flips). This approach handles the majority of applications that have new content on either the top or bottom portions of the screen. In addition, the flip button makes it possible to view content anywhere on the screen — albeit with more effort and usability impact. To ensure that scrolling is still easy, *Focus* removes all dimming the moment the screen is touched (so that all content and scrollbars become instantly visible). Moreover, to allow easy entering of user input, *Focus* does not dim any of the virtual keyboards.

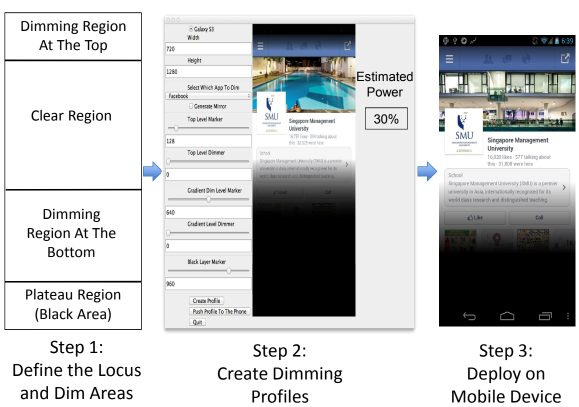


Figure 2. Applying Application-specific Profiles In Focus

Application-Specific "Customised" Profiles: In situations where *Focus's* default profile is not appropriate or sufficiently optimised, *Focus* allows either the Application developer or the user to specify per-application dimming profiles. Such per-application dimming profiles are creating by altering the default values of the *top dimming region*, the *middle clear region*, and the *bottom dimming region*, in terms of both the region size and the final intensity level.

Creating and Deploying the 'Customised" Profiles: Each such customised dimming profile allows the characteristics of each of three portions of the screen (i.e., the dimming region at the top, the clear region in the middle and the dimming region at the bottom) to be explicitly manipulated, in terms of both the size of the region and the intensity value (i.e., the x% intensity at the end of the dimming region), as explained previously.

We created a simple Java-based tool to allow users to create "Customised" profiles for any application they choose. The interface of this tool is shown in Figure 2. Currently, the tool works on a laptop (as we needed this for our user study); the resulting profiles created are then transferred to the phone. When *Focus* is deployed, we will allow users to easily create profiles for any application on their phones themselves. The tool allows users to easily specify the three portions stated above for any application. For every dimming setting, the tool shows the expected effect on the application and the expected power savings achievable (by interpolating a-priori power measurements of various settings for that applications). When the user is comfortable with their profile, they can click a button to deploy the profile to their phone. Figure 3 illustrates the resulting application profiles that we (as researchers) created, for 3 out of the total set of 6 applications that we investigated.

Putting it all Together

Figure 4 shows how *Focus* works with all the pieces connected. When an application starts, *Focus* checks if it has a profile for that application (either a "Customised" or "Default" profile). If it does, *Focus* applies the profile using the process described above. If not, *Focus* leaves the application unmodified. *Focus* intentionally requires each application to have an explicit profile first, as this allows users and device manufacturers to selectively target applications for dimming (even with the "Default" dimming scheme).

In future versions, *Focus* could query a web service for an appropriate profile (the profile could also be downloaded when installing the application). We also envision *Focus* being eventually integrated into the OS so that it is activated automatically when battery levels reach fairly low levels (15% or less for example).

PERFORMANCE EVALUATION

In this section, we evaluate the detailed power performance of *Focus* using a Samsung Galaxy S III OLED-based smartphone with 15 popular applications. The applications, shown in Table 1, were chosen to be both popular and to cover the entire application space described earlier.

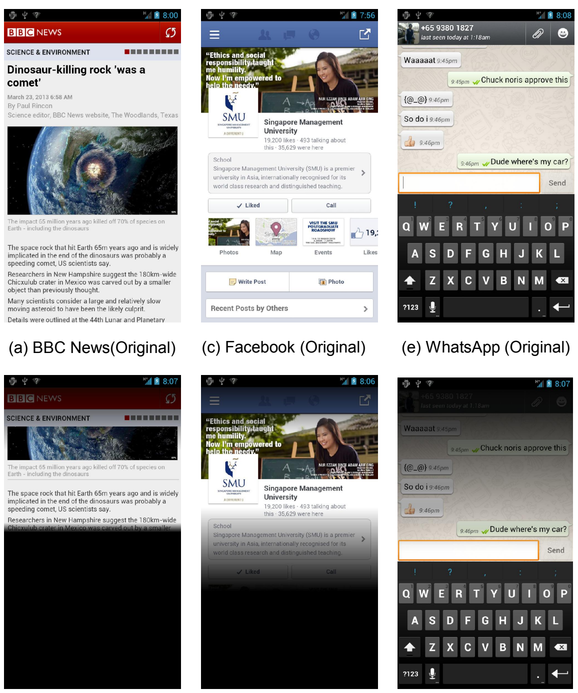
Detailed Measurement Results

The first evaluation was to identify how much OLED display power *Focus* could save. We used the Monsoon external hardware power monitor [18] to collect accurate power measurements. We conducted two main sets of experiments. In the first set of experiments, we used the generic "Default" profile

Name	Category	One Minute Continuous Usage Scenario	Completing A Specific Task Scenario
Aldiko Book Reader	Books	Page 14 of a eBook ("Oliver Twist")	Flip to 1st page and read the 1st page
Documents To Go 3.0	Business	Viewing 4 sample files provided by the app (2 Excel, 1 Word, 1 Powerpoint)	Open a specific word document and read to specified point
Gmail	Communication	Inbox listing	Browse content of a selected email
Firefox Browser	Communication	Main pages of Google, Yahoo SG, Wikipedia, Amazon US, and Endgadget	Use Google, search: cnn and browse to www.cnn.com
WhatsApp Messenger	Communication	Chat screen with keyboard active	Browse to specific thread and post "test" reply
OCBC Bank	Finance	Current balance screen	Browse and read transaction history
YouTube	Media and Video	Portrait mode playback of "Gangnam Style" video	Portrait mode playback of "Gangnam Style" video
BBC News	News	Article view page of 5 long lived articles	Read top three news articles completely
Adobe Reader	Productivity	Page 10 of a pdf file ("Java Cryptography")	Read default document to specified point
Dropbox	Productivity	File listing page	Browse contents of specific folder
ES File Explorer	Productivity	File listing page	Browse folder contents of directory on sdcard
Calendar	Productivity	Weekly schedule page	Browse event calendar for a specific day
eBay	Shopping	Individual Item description page	Browse printer section to a particular printer sale
Facebook	Social	Timeline of the 5 most popular Facebook pages	Read top 15 postings of a specific user
Twitter	Social	Timeline screen	Browse top 15 tweets of a specific user

For each application, we conducted our continuous power measurements using the scenario(s) in the "One Minute Continuous Usage Scenario" column and our task completion measurements using the scenario(s) in the "Specific Task Scenario" column

Table 1. Applications Used For This Evaluation



(a) BBC News(Original) (c) Facebook (Original) (e) WhatsApp (Original)

(b) BBC News(Custom) (d) Facebook (Custom) (f) WhatsApp (Custom)

Figure 3. Examples Of Customised Profiles

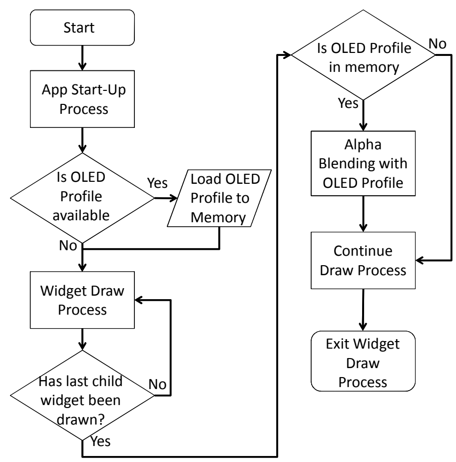


Figure 4. Focus Flowchart When Used With Applications

(that gradually dimmed only the bottom half of the screen) for all the applications listed in Table 1. For each application, we ran the application without *Focus* for one minute and with *Focus* for one minute. In both cases, we ensured that no other applications or processes were running (the phone was rooted and we manually killed all background processes etc.).

To ensure repeatability across experiments, we did the following: for each application, we left the application on the "main" page. In particular, this was the page which was the most frequently accessed page when the application was used normally. For example, for the *Aldiko Book Reader* and *Adobe Reader*, this was the page that showed the contents of the book or pdf being read (and not the main menu page).

Table 1 lists the "One Minute Continuous Usage Scenario" we used for each application. Note: for four applications, *Documents to Go 3.0*, *Firefox Browser*, *BBC News*, and *Facebook*, the content displayed could change dramatically and this affected the power savings. Hence, for these four applications, we used multiple compelling test scenarios as described in Table 1. The measurement results shown for these four applications are the average values across all the different test scenarios for that application. We did not use different test scenarios for the other dynamic-content applications applications such as *eBay*, *Adobe Reader*, and *Twitter* as our testing showed no significant power variation even across different pages containing fairly standard amounts of text.

In the second set of experiments, we used a per-application "Customised" profile, which we created to save as much power as possible while still preserving (from our perceptual standpoint) application usability. These profiles could thus be thought off as a form of usable "upper bound" to demonstrate the potential of *Focus*.

Results: Focus Saves Significant Display Power

Table 2 shows the average power consumption when running each application without *Focus* ("Unmodified"), with the

Application	One Minute Continuous Usage Scenario						Specific Task Scenario			
	Power Consumption (mW)			% Improvement			% Improvement			
	Base	"Default"	"Customised"	(2) over	(3) over	(3) over (2)	"Default"		"Customised"	
	(1)	(2)	(3)	(1)	(1)	(% & Diff.)	Time	Energy	Time	Energy
Aldiko Book Reader	1952.30	1337.65	1236.27	31.48	36.68	16.52 (5.20)	-0.37	23.21	0.49	29.06
Documents To Go 3.0	1620.04	1357.11	1267.67	16.23	21.75	34.01 (5.52)	-0.17	11.79	0.18	7.23
Gmail	1707.48	1243.77	1006.59	27.16	41.05	51.14 (13.89)	0.90	19.34	-10.09	16.62
Firefox Browser	1703.89	1255.24	1047.32	26.33	38.53	46.33 (12.20)	1.09	10.22	-12.75	3.39
WhatsApp Messenger	1237.10	1218.18	952.98	1.53	22.97	1401.31 (21.44)	-1.10	21.82	-1.45	15.99
OCBC Banking	1696.96	1249.17	1036.19	26.39	38.94	47.56 (12.55)	-0.59	20.98	-0.75	29.31
YouTube	1452.80	1113.60	787.30	23.35	45.81	96.18 (22.46)	0.01	27.88	0.02	36.81
BBC News	1550.99	1118.97	881.51	27.85	43.11	54.79 (15.26)	4.77	27.36	5.09	42.37
Adobe Reader	1923.19	1437.42	1261.15	25.26	34.42	36.26 (9.16)	2.58	5.31	4.95	7.82
Dropbox	1921.80	1358.99	1284.40	29.29	33.17	13.25 (3.88)	-1.57	15.79	0.46	14.23
ES File Explorer	889.71	790.46	768.43	11.16	13.63	22.13 (2.47)	-0.07	2.78	0.44	12.10
Calendar	1520.55	1149.23	1092.58	24.42	28.15	15.27 (3.73)	-0.16	22.02	0.68	24.71
eBay	1766.78	1259.86	1238.60	28.69	29.90	4.22 (1.21)	0.26	8.02	-0.14	4.62
Facebook	1557.35	1288.49	1041.78	17.26	33.11	91.83 (15.85)	0.28	14.47	-1.01	8.93
Twitter	1823.38	1230.84	1020.18	32.50	44.05	35.54 (11.55)	0.73	31.57	-0.33	38.71
Average	—	—	—	23.26	33.68	—	0.44	17.50	-0.95	19.46

The table shows the average values across all test scenarios for each application (Table 1). The bracket values for the "(% & Diff.)" column are the % savings difference between the "Customised" and "Default" profiles for the continuous measurement scenario. For the task scenario, all values are the % improvement over the base case (without *Focus* running) — negative values indicating an increase in the time or power consumption.

Table 2. Measurement Results

"Default" profile, and with the "Customised" profile. The table also shows the % improvement in power consumption between the "Default" profile and the unmodified version ("(2) over (1)" in the table), between the "Customised" profile and the unmodified version ("(3) over (1)" in the table), and between the "Customised" and "Default" profiles ("(3) over (2)" in the table). We show both the % improvement and the absolute difference in % savings (in brackets) for this last case.

The results show that the "Default" profile's power savings ranged from 1.5% (*WhatsApp*) to 32.5% (*Twitter*). The poor performance of *WhatsApp* arose because the "Default" profile only dims the bottom half of the screen. However, the *WhatsApp* test scenario has the virtual keyboard active on most of the bottom half of the screen, rendering *Focus* (which does not dim the keyboard) largely ineffective. However, even with *WhatsApp*'s poor performance, on average, the "Default" profile saves about 23% of the OLED display power. This translates to savings of anywhere between 15% to 20% or more of the total power consumption of the phone when the screen is on (depending on which other components are also active).

The "Customised" profiles obtained higher power savings. In particular, *WhatsApp* increased from 1.5% to almost 23% as the *WhatsApp* "Customised" profile, shown in Figure 3, darkens areas of less interest to the user that are not covered by the virtual keyboard. On average, the "Customised" profile saved about 34% of the OLED display power (with a maximum savings of about 45% for *YouTube*). This translates to saving 20% to 30% of the phone's total power consumption.

Results: But What About The Time To Finish Tasks?

For the results shown above, the applications were used continuously for 1 minute each. It is, however, important to ascertain if such dimming impacts *task effectiveness*, i.e., will the partial dimming of the screen result in a much higher task-completion time (as the user has to scroll unnecessarily to find things), thereby increasing the overall *energy* consumption?

To evaluate this, we tested all 15 applications with a series of realistic tasks (described in the "Completing a Specific Task Scenario" column in Table 1) without *Focus* and with both the "Default" and "Customised" profiles. For each application, we measured the energy consumption (in mJ) as well as the time to completion of each task.

The 'Specific Task Scenario" column of Table 2 shows the results of this experiment as a % improvement over the same task being run for the same application without *Focus* active. (negative numbers indicate the time or energy consumed increased by that % value).

Our experiment revealed that the task completion time increased by 0.44% and -0.95%, on average, when using the "Default" and "Customised" profiles respectively. Even in the cases when *Focus* increased or decreased task completion times (e.g., an increase of 12.75% for *Firefox* and 10% for *Gmail*, a decrease of 4.77% for *BBC News*), the absolute time increase was at most 1 to 2 seconds only and within the error margin. This suggests that *Focus* has minimal impact on task completion times. However, even with this minimal impact, the "Default" and "Customised" profiles still saved, on average, 17.50% and 19.52% of the overall display energy consumption respectively. Coupled with the higher energy savings achievable when using applications continuously, we posit that using *Focus* regularly will achieve significant energy savings with minimal impact on task completion times.

USER STUDY

Having established that *Focus* is indeed effective in saving display power, we now present the results of a user study designed to evaluate if *Focus* is acceptable to end users. The user study was designed to answer two questions:

1 **Are the "Default" and "Customised" profiles usable?**: We compared both profiles against the base application.
2 **Are Supplied Profiles Good Enough?**: The most useful systems tend to be the ones that require no user intervention. As such, the second experiment investigated if the "Default" and "Customised" profiles created by the research team (and which could, in theory, be created easily by application developers) are good enough for end users.

User's demographic profile

Table 3 shows the demographics of the participants of the user study. In total, we had 30 undergraduate participants (18 males and 12 females) from SMU's Information Systems school. From the pre-test demographics survey, 96% of the participants recharged their phones at least once a day, 66% of the participants agreed or strongly agreed that they reduced their application usage to save power, and 63% of the participants agreed or strongly agreed that their phones did not have sufficient battery capacity for their daily usage patterns.

Methodology

For the user study, we reduced the set of applications tested to just 6. This allowed us to obtain enough participant data points per application without requiring an extremely large user base. We chose 6 popular applications that collectively covered a very broad application range: *WhatsApp Messenger*, *Facebook*, *BBC News*, *Gmail*, *Adobe Reader*, and *Firefox Browser*. To avoid fatigue, each participant tested just 4 applications. In total, each of the 6 applications was tested by 15 participants. The user study procedure was as follows: Each user was asked to answer a small pre-test demographics questionnaire and then perform two experiments. Each participant was paid SGD $10 (≈USD $8) for taking part in the study.

Experiment 1: Is Focus Usable?

This first experiment was designed to evaluate the usability of *Focus*, with both the "Default" and a research team-supplied "Customised" profile. We asked each participant to first use the unmodified version of the application for 30-50 seconds to re-familiarise themselves with these popular applications. Each participant then used both modified versions of the application (running *Focus* with either the "Default" or "Customised" profile) for a short period of time (about 2 to 3 minutes per modified application). To minimise bias, we counterbalanced the order of using the modified versions among the participants, i.e., half the participants used the applications in the order {Unmodified, "Default", "Customised"}, whereas the other half used the order {Unmodified, "Customised", "Default"}.

Right after completing the use of each modified version, they had to answer the following two questions using a 5-point Likert scale (5—Strongly Agree, 4—Somewhat Agree, 3—Neutral, 2—Somewhat Disagree, 1—Strongly Disagree). Question 1 was *"This version of the application is as usable as the original version"* while Question 2 was *"The most important portions of the application are still visible"*.

We understand that the positive phrasing of the questions, coupled with a direct comparison instead of an objective score, could lead to experimental bias. However, because

Total Number	30
Gender	Male (18), Female (12)
Smartphone proficiency level	novice (1), average (24), expert (5)
Which smart phones have you used?	iPhone (18), Android (23), Blackberry (4), Windows Phone 7 or 8 (3), Other (1)
How often do you recharge your phone during the day?	Multiple times every day (8), Once a day (21), A few times per week (1)
I intentionally reduce my app usage to save battery power.	Strongly agree (9), Agree (11), Neutral (3), Disagree (3), Strongly disagree (4)
My phone has insufficient battery power for my usage.	Strongly agree (11), Agree (8), Neutral (5), Disagree (5), Strongly disagree (1)

Table 3. Demographic Statistics

each participant was already very familiar with every test application (all 6 are very popular mobile applications) and because of our intentional bias against *Focus* (see below), we believe that the results collected are still quite meaningful.

No specific training was provided to the participant for any part of this experiment. Note: to avoid further bias, we did not tell participants either that *Focus* was for saving display power or the amount of power savings achieved. As such, even the participants who guessed that *Focus* was power-related did not know the actual gains for either the "Default" or the "Customised" profiles. This was an intentional bias to avoid making the users more receptive to *Focus* due to its significant power savings.

Result: Focus is Perceived As Usable

Figure 5 shows the perceived usability of *Focus* for both profiles and the 6 test applications. (The scores for the 2^{nd} question, "The most important portions of the application are still visible", showed the same pattern and are thus omitted.) In the Figure, higher values are better (indicating that the users agree with the question "This version of the application is as usable as the original version"). We observe, that in every case, the "Default" profile achieved acceptable usability scores (every value is above the neutral 3 middle mark). This is a very encouraging result as it suggests that *Focus* is still usable even when saving significant display power (average 23% savings for this profile). However, the "Customised" profile that the research team provided was rated as below neutral for 4 of the 6 applications. This was because the "Customised" profiles turned off parts of the screen and the participants found this jarring — especially since they did not know the purpose and effectiveness of *Focus*.

However, as we shall see next, when the participants understood the purpose of *Focus* and were able to pick their own "best" profiles, more than half of them picked profiles that were at least as aggressive as the default profile, while a handful picked profiles that were even more aggressive (in terms of darkening the screen) than our "Customised" profiles.

Experiment 2: Are Supplied Profiles Good Enough?

In the second experiment, our goal was to understand if the participants, after being told what *Focus* did, could design their own profiles to achieve what they believe to be the best balance of power savings and usability. In particular, this experiment would allow us to understand if the participants would voluntarily pick settings for *Focus* that either matched or exceeded either our "Default" or "Customised" profiles — instead of deciding that the most usable form of *Focus* would be to turn off all the dimming settings. For experiment 2, each

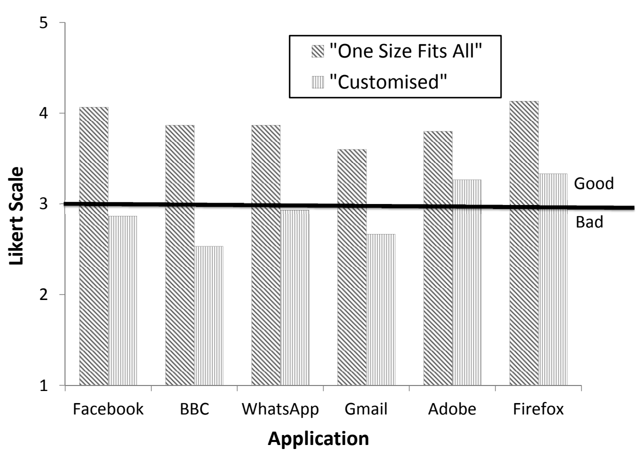
Application	Minimum (%)	Median (%)	Maximum (%)
Facebook	5.68	18.74	47.03
WhatsApp	0.38	16.67	29.39
BBC News	9.02	35.19	43.17
Gmail	1.87	25.54	45.06
Adobe Reader	0.00	32.05	54.67
Firefox	2.67	27.82	31.40
Average	3.27	26.00	41.79

The table shows the % improvement of the minimum (least aggressive), median, and maximum (most aggressive) participant generated profiles relative to the baseline unmodified power consumption values (using the values shown in Table 2) for the same application. We used the same testing procedure used to generate the "Continuous Usage Scenario" entries in Table 2. Note: for *Adobe Reader*, one participant (the min. value) decided that the best profile would be to turn off *Focus*.

Table 4. Power Savings Achievable by Participant Generated Profiles

participant was asked to customise the dimming profile for 3 applications. We only chose 3 applications as each participant was given 5 to 10 minutes per application to create and test their "best" dimming profile. We counterbalanced the order of the applications presented to each participants.

The experiment started by explaining *Focus's* power saving technique to the participants. Each participant was then given a Powerpoint slide deck, that included embedded Visual Basic Application (VBA) scripting, allowing them to customise, via movable sliders, the three dimming areas for each application used in this experiment. The dimming areas were 1) the size of the top dimming area, 2) the size of the bottom dimming area, and 3) the plateau position in the bottom dimming area. All user manipulations to the sliders immediately changed the image on the slide to show the resulting screen output, as well as provided an updated estimate for the resulting OLED display power savings. (These predictions were computed by interpolating real measurement studies done with various slider settings for each application.) When a participant wanted to test her Powerpoint settings, she could transfer and deploy it onto a Galaxy S III phone and test the application to see if the *Focus* settings were optimal for her. If not, the participant could iterate through the whole process until she obtained her "best" profile.



The self-reported scores for the question "This version of the application is as usable as the original version" using a 5 point Likert scale (5–Strongly Agree to 1–Strongly Disagree)

Figure 5. Perceived Usability Of Focus

Result: Users Can Pick Effective Profiles

In total, 15 profiles (each from a different user) were created for each of the 6 test applications. Table 4 shows the results of this experiment and we observe that at least half the users (looking at the "Median" values) picked profiles that achieved comparable power savings to our "Default" profile. In the best case ("Maximum" column), some users were even dimming more aggressively than our "Customised" profile!

Overall, the median % power improvement with the participant supplied profiles was similar to that achievable with the "Default" profile — indeed many of the user profiles looked very similar to the "Default" profile. This suggests that developers can supply profiles with their applications that are acceptable to many users. At the other extreme, the users who wanted extreme power savings ended up with profiles that looked and behaved (in terms of power savings) very similar to the research-team created "Customised" profiles — again supporting the claim that developer supplied profiles might be sufficient. However, there were also some users who picked very conservative profiles. We will need further studies to understand if this attitude changes under low power situations. Overall, this experiment suggests that developer-supplied profiles, for both the "Default" and extreme power savings "Customised" cases, might be good enough for the majority of users. This greatly reduces *Focus's* entry barrier as users need not supply their own specific profiles.

Results: Summary

Focus saves, on average, between 23 to 34% of the OLED display power when using applications with minimal impact on task completion times. As stated earlier, OLED displays consume as much as 67% of the overall system power [3]. Hence, the power savings translates to at least a few extra hours of phone use. We then showed, via a user study with 30 participants, that *Focus* is usable and that developer-supplied profiles might be good enough. Overall, the results are very positive and demonstrate that *Focus* is effective at saving OLED display power without affecting usability significantly.

DISCUSSION

Supporting Games & Other Operational Issues

While our results suggest that *Focus* is quite effective and usable, *Focus* still has some practical limitations. First, we need to also support games. However, games are much harder to support as they have very different ROI from applications. In particular, games can be broadly classified into those that continously divert user attention to random screen areas (most casual games (*Angry Birds, Cut The Rope*, etc.) do this) or those that focus attention to the middle of the screen (most first person shooting and driving games do this). Hence, the top-down or bottom-up dimming approaches used for applications won't work for games.

Unfortunately, these different ROIs makes it much harder to produce a game-agnostic solution. For example, in casual games, the best way to save power, is to dim the background images while leaving the foreground objects clear (e.g., leave the bids, pigs, and structures clear in *Angry Birds* but dim everything else). However, doing this requires understanding the exact composition of the pixels in the game's framebuffer (as the foreground objects could be anywhere on screen) — a harder than expected task as games use the OpenGL-ES and not the standard rendering framework. While we have extended *Focus* to support OpenGL-ES games, this continues to be work-in-progress (albeit with promising initial results of up to 40% reduction in display power consumption with no perceptible latency impact [24]).

The user study was a key component in evaluating the efficacy of *Focus*. However, it also has its limitations. While our user population was large, it comprised solely of undergraduate technically oriented students; it is possible that a general or larger population might show different results. Also, this study was done in a well-lit office environment. To generalise our solution, we need to conduct studies in other indoor and outdoor environments. Finally, the user study lasted only about 30 minutes; it is possible that the results would be quite different if *Focus* was deployed and used daily. Clearly, additional studies are needed to ascertain the true power savings that can be achieved under normal dailyuse.

Finally, the *Focus* profiles currently only work in portrait mode and will need to be modified to support landscape orientations, and then tested for effectiveness.

Comparison with other techniques

As stated earlier, there are other techniques such as colour remapping and other ways of dimming the screen, that can, in principle, achieve the same results as *Focus*. In this section, we discuss how these other approaches compare with *Focus*. All of these techniques are orthogonal to and can be used concurrently with *Focus*— with each technique benefitting from the strengths of the other. However, we do not evaluate concurrent usage in this paper.

We were unable to directly compare with colour remapping systems such as Chameleon [9] as these systems are extremely complicated and hard to replicate. For example, Chameleon was implemented and evaluated on just a single custom browser (Fennec browser on a Google Nexus One phone). Instead, we point out that their reported power savings of ≈40% when browsing is a little higher (but albeit with a much more significant engineering effort) than *Focus*.

To compare against other dimming techniques, we performed a task on 6 applications (Facebook, WhatsApp, BBC News, GMail, Adobe Reader, FireFox) and captured screen shots on each key application screen for that task. We then applied the appropriate dimming routines to these screen shots. We then replayed the screen shots on a real phone (to simulate the task being performed) and measured the power consumed by the display. This gave us an excellent idea of the power savings achievable by each dimming method across 6 applications. However, without a real implementation and user study, we make no claims as to the usability of these approaches.

We compared *Focus* against two different dimming techniques; 1) a uniform dimming the entire screen by a specified percentage, and 2) a reduction of the screen resolution while preserving the aspect ratio (unused pixels were set to black).

The results are shown in Table 5 for different dimming percentages. We observe that the "Default" profile of *Focus* has comparable power savings to either a 20% reduction in either resolution or screen brightness while the "Customised" profile is comparable to a 30% resolution or screen brightness reduction. We suspect that both the resolution and screen brightness reduction methods will impact usability far more than *Focus* as they do not differentiate between important and less important areas of the screen. Hence, key content could be too dim for the user to see (using uniform dimming) or too small for the user to interact with (using resolution reduction). However, this validation is left as future work.

RELATED WORK

Numerous approaches have been investigated to reduce the power consumption of mobile devices and phones. These range from reducing the power of the communication radio [4, 23], the processing [2], and the display. We focus the rest of this section on prior display work. For phone devices, prior work has focused on reducing the power consumption of the LCD or OLED displays used. In the LCD space, prior work focused on reducing the use of the LCD backlight which is the source of most of the LCD's power drain. In particular, prior work reduced the backlight levels while adjusting the displayed image to compensate [1, 5, 7, 19].

OLED displays require different solutions as they do not have a backlight. Early on, Kamijoh et. al [16] showed that saving OLED display power was possible by reducing the image brightness. Subsequent work extended this idea by using colour inversion (white to black), changing the colour schemes to a darker colour, and employing a gradient approach (darkening parts of the screen that are less interesting), showed that decent power savings can be achieved with good user acceptance [14, 20]. However, these approaches were tested with just a few scenarios and applications. Our system expands on this body of work by building a general framework that supports any application.

Other researchers have extended the work by Ranganathan et.al [20] to show that OLED display power can be saved by changing the colours used to display various images [9]. In particular, by converting images from "expensive" colours to "cheaper" colours, albeit in an application-specific way, significants power savings with good usability could be achieved. Finally, researchers have reduced the OLED display power [6, 21] by using dynamic voltage scaling (DVS) to change the power consumed by the diodes in an OLED pixel. However this approach degrades the luminance of the image, which can affect the end user experience. Our current solution is complementary to and can be used in tandem with both colour-remapping and hardware-based approaches.

CONCLUSION

In this paper, we presented *Focus*, a novel system that saves OLED display power by dimming the screen in effective and efficient ways by exploiting the *saliency* properties of individual applications. We evaluated the performance of *Focus* with 15 popular applications. Our evaluation showed that *Focus* saves, on average, between 23 to 34% of the OLED display

Application	Baseline (mW)	*Focus* Default	*Focus* Customised	Uniform Dimming (% Reduction) 10	20	30	40	50	Resolution Reduction (% Reduction) 10	20	30	40	50
Facebook	1627.94	27.85	42.05	15.67	27.72	37.42	44.51	51.06	13.66	23.53	32.25	40.59	46.79
WhatsApp Messenger	1682.60	25.31	18.46	14.17	26.36	36.71	45.16	51.53	14.71	24.62	33.43	41.54	48.54
BBC News	908.45	9.03	23.84	6.87	13.43	19.02	23.08	27.27	9.15	14.69	19.30	24.33	28.54
Gmail	1780.11	24.82	43.47	14.74	26.45	37.41	46.22	53.47	13.19	23.84	33.23	41.99	49.57
Adobe Reader	773.56	9.73	12.43	5.60	7.75	12.28	15.60	19.20	8.75	12.44	15.62	18.92	21.27
Firefox Browser	1534.48	23.02	29.70	12.31	23.97	33.83	41.81	49.40	11.81	21.79	30.23	38.57	45.43
Average Improvement	—	19.96	28.33	11.56	20.94	29.45	36.06	41.99	11.88	20.15	27.34	34.32	40.02

All values shown are the % improvement in Power consumption relative to the Baseline

Table 5. Comparing the Power Savings of *Focus* with Other Dimming Methods

power when using applications with minimal impact on task completion times. In addition, we showed, via a user study with 30 participants, that the usability of *Focus* was still quite high. We also showed that it is possible for developers to bundle useful dimming profiles together with their applications — thus reducing the burden on the user.

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