Investigating the Relationship Between Battery Life and User Acceptance of Dynamic, Energy-Aware Interfaces on Handhelds

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Abstract. In a 24 x 7 mobile world experiencing a proliferation of handheld devices, battery life can be a limiting factor. In particular, handheld displays consume substantial battery power. One strategy to potentially reduce display battery consumption and support a positive user experience is to adopt emerging display technologies (e.g., OLEDs) that support energy-aware interfaces. The research reported here, the second investigation in a series, assessed user expectations regarding handheld battery life and explored the relationship between battery life and user acceptance of energy-aware, handheld interfaces. Twelve experienced handheld users engaged dynamic, prototype energy-aware interfaces to complete a scenario comprised of 5 representative tasks. Users identified battery life as an important handheld issue, were positive regarding a display-based approach to reducing battery consumption and varied consistently in their enthusiasm for specific interfaces. The findings highlight themes for the research and design of future energy-aware interfaces.

1 Introduction

With their ongoing proliferation and evolution, mobile handheld devices (e.g., MP3 players, PDA's, Cell Phones and Smart Phones) continue to represent an important hardware, software and services market [2]. However, battery life can fundamentally limit the functional utility of these devices [6]. In particular, handheld displays consume substantial energy [6, 7] that can account for nearly 60% of the total system power consumption [1]. Moreover, unlike other system components, display power consumption traditionally has remained relatively constant as devices become smaller. Thus, display power consumption may represent an increasingly large proportion of the total system power consumption of future smaller devices.

Contemporary strategies for reducing handheld display power consumption include powering off the device following a pre-defined interval of nonuse, designing devices with small displays and designing devices with reduced-quality displays. An alternative strategy for reducing display power consumption is to adopt emerging display technologies. One such technology, Organic Light Emitting Diodes (OLEDs), can reduce display battery consumption [5] by enabling *energy-adaptive interfaces* that consume energy only from specific regions of a display, such as those relevant to the user task. Therefore, these energy-adaptive interfaces have the potential to simultaneously reduce display power consumption and provide a positive user experience. Indeed, energy-adaptive interfaces have been found to reduce battery consumption up to a factor of 10 in laptop computers [4]. However, it is not clear how the adaptive nature of these interfaces -- which can dynamically modify the brightness, color and power status of display regions -- impact the user experience. We appear to be the first to investigate the relationship between battery life and user acceptance of dynamic, energy-aware interfaces on handhelds.

The goal of our research was to assess user expectations regarding mobile handheld battery life, and explore the relationship between battery life and user acceptance of dynamic, energy-adaptive handheld interfaces. From our research, we endeavor to: identify battery life parameters that are acceptable to users; understand the relationships (e.g., tradeoffs, enhancements, etc.) between the energy-saving and user-acceptance aspects of energy-aware interface designs; distill specific designs and design principles that maximize battery life and user acceptance of future energy-aware interfaces; and, identify user tasks and applications that can potentially benefit from these designs and design principles. In our first investigation [3], we found that participants were generally accepting of energy-aware interfaces, particularly notification and menu interfaces with high-contrast areas that promoted the interface region salient to the user task. The investigation reported here, the second in the series, went beyond the first and made several unique contributions that included: sharpening the focus of investigation regarding user expectations of handheld battery life; broadening the scope of evaluation to include a new and wider variety of interfaces and software applications; displaying dynamic interfaces on a PDA; and, recruiting participants not employed by our company and who all did not own the handheld brand sold by our company. These unique contributions served to enhance the scope and validity of our findings.

2 Methods

In this section we describe our user-evaluation methodology. To summarize, 12 experienced handheld users engaged dynamic, prototype energy-aware interfaces on a handheld device and completed a scenario comprised of 5 representative tasks. For each of 5 interface types, users evaluated multiple interfaces including a ‘control’ interface in contemporary use. Each interface displayed a unique combination of visual appearance and battery life. Based upon the battery life, visual appearance and perceived usability of each interface, users provided ratings, verbal comments and direct-comparison data.

2.1 Participants

Participants were 12 experienced PDA users from the Boston area that were contacted through a market research firm. The representative sample of users included men and women as well as a range of occupations (e.g., VP, Sales Rep., Teacher, Engineer, Owner, Manager) and industries (e.g., Financial, Healthcare, Retail, Consulting, Gov’t., Hi Tech) from small-, medium- and enterprise-scale employers. All participants regularly engaged their PDA for a combination of work and personal activities. All participants owned a PDA equipped with the MS Pocket PC OS, and most owned an iPAQ.

2.2 Materials

The dynamic, prototype energy-aware interfaces were implemented in Flash and displayed on an iPAQ h5550. Battery life was specified in an icon at the top, right of the interface (e.g., ‘4h 39m’ indicated 4 hours and 39 minutes). The battery-life estimates were derived from an engineering power analysis of the prototype interfaces. Prototypes supported user scrolling and the MP3 interfaces were fully functional. Five types of dynamic interfaces were displayed: E-mail inbox gradient interfaces; Acrobat Reader gradient interfaces; MP3 player interfaces; inversion interfaces; and, flashlight interfaces. Examples of the dynamic interfaces used in this investigation, and their respective battery lives, are displayed in Appendix A of this document.

Gradient Interfaces. Participants viewed 6 gradient interfaces (0, 20, 40 60, 80 & 100%) for both the e-mail inbox and reader applications. The 0% interfaces were not gradients, but rather the conventional MS Outlook Inbox and Acrobat Reader interfaces, and they served as comparison (control) interfaces in the present investigation. Compared to the contemporary (control) interfaces, the energy-aware interfaces achieved energy reductions of up to a factor of 2.5 for the inbox and up to a factor of 6 for the reader.

MP3 Interfaces. Participants viewed 3 MP3 interfaces: the contemporary (control), blue windows media player; a gray and black interface; and, a green and black interface. Compared to the contemporary (control) interface, the energy-aware interfaces achieved energy reductions of up to a factor of 21.

Inversion and Flashlight Interfaces. Participants viewed 4 inversion interfaces (start, calendar, e-mail inbox and Acrobat Reader) that displayed black backgrounds with white text -- except for the start interface, which displayed a tan background with black text. Participants also viewed several flashlight interfaces that displayed a dimmed interface with a user-movable region that was illuminated at standard levels. These interfaces enabled participants to move the 'flashlight' by depressing the stylus on the illuminated area (e.g., the edge) and dragging it. Several versions of the flashlight interfaces were created by varying 2 dimensions: the color of the dimmed area (gray, black); and, the shape of the illuminated area (square, horizontal rectangle). Compared to the contemporary (control) interfaces, the energy-aware interfaces achieved energy reductions of up to a factor of 5 for the inversion interfaces and up to a factor of 9 for the flashlight interfaces.

2.3 Design

Each session was comprised of 4 data-collection components completed in the following sequence: The participant background and handheld usage data-collection component; the gradient interface data-collection component (e-mail and reader); the MP3 interface data-collection component; and, the inversion and flashlight interface data-collection component.

Within each data-collection component, the specific interface presentation sequence was counterbalanced across participants to eliminate uninteresting interpretations of the data. Thus:

The gradient and interface-type presentation sequences were counterbalanced orthogonally. Specifically, half of the participants viewed the gradients in sequence from 0 to 100% and half viewed the gradients in sequence from 100 to 0%. Half of the participants viewed the e-mail interfaces prior to the reader interfaces and half viewed the reader interfaces prior to the e-mail interfaces.

A Latin square was used to counterbalance the presentation sequence of MP3 interfaces.

The inversion and flashlight interface presentation sequence was counterbalanced such that, half of the participants viewed the inversion interfaces prior to the flashlight interfaces and half viewed the flashlight interfaces prior to the inversion interfaces. The presentation sequences of the individual inversion and flashlight interfaces were also counterbalanced.

2.4 Procedure

The evaluation was conducted in a typical, well-illuminated office environment. One individual participated in each 90-minute session. Each session began with the participant providing background information regarding their PDA usage, observed PDA battery life and desired PDA battery life. The participant then performed 5 tasks as part of a scenario in which s/he traveled by train to meet with a business customer. Specifically, the participant reviewed an e-mail inbox and read a page from a book during the train ride to the customer meeting, viewed and used the MP3 player on the return train journey and, also on the return journey, viewed each of 4 inverted interfaces and multiple flashlight interfaces to reduce display consumption of dwindling battery power.

For each individual interface, participants engaged the prototype to complete the task (e.g., scroll and read), offered verbal remarks and then provided ratings based upon battery life, interface appearance and usability. After participants viewed all interfaces of one type (e.g., all 6 e-mail gradient interfaces), they completed a direct-comparison task based upon battery-life, visual-appearance and usability criteria. Specifically, for the gradient interfaces, participants specified the 1 interface of that type that they were most likely to use. For the MP3 interfaces, participants rank ordered the 3 interfaces to indicate their 1st through 3rd choices. And for the inversion and flashlight interfaces, participants were given the option to choose the inversion interfaces, the flashlight interfaces or indicate no preference.

3 Results

In this section we present the data regarding participant expectations of handheld battery life, and participant acceptance of handheld, energy-aware interfaces. To summarize, participants indeed indicated that handheld battery life is an important issue, and that they expected a longer battery life than currently supported by their device. In general, they were favorable regarding a display-based approach to reducing battery consumption and indicated that they wanted a choice of display settings, such that each setting provided a unique combination of battery life and interface visual appearance. Regarding specific interface types, participants were quite positive towards the inversion and MP3 interfaces and less positive towards the gradient and flashlight interfaces.

3.1 Battery-Life Expectations

PDA battery life was an important issue for participants and they were receptive to a display-based approach to extending battery life.

Participants rated the importance of several PDA attributes on a scale ranging from +2 (important) to 0 (neutral) to -2 (not important). Battery life received the third highest (i.e., most important) mean rating (+1.67). The ratings were obtained during participant recruiting, prior to their knowledge of the content or purpose of the study. The means, displayed in Table 1, are sequenced from most to least important.

Table 1. PDA attribute rating data

Memory	Processor Speed	Battery Charge Life	Productivity Applications	Screen Size	Graphics	Size	Communication Applications
1.75	1.75	1.67	1.33	1.17	1.08	1.08	1.08

During the testing sessions, several participants stated that battery life was an important issue. Most participants indicated that their PDA provided a battery life of 2 to 4 hours with continuous usage, and they all desired a longer battery life, with the most common request being a two- to three-fold proportional increase or an 8-hour absolute battery life with continuous usage. These requests were made to support a usage model characterized by a full day of work followed by recharging at night; most participants indicated that they did not want to carry additional equipment (e.g., charger, extra battery) on a daily basis. Several participants requested the option of choosing from display settings, such that each setting provided a unique combination of battery life (e.g., 2, 4, 6, 8 hours) and interface visual appearance.

Participants liked the conspicuous presentation of the remaining battery power at the top of the interfaces. Users were aware that their PDA contains a power-settings interface, but they would prefer to have the information conspicuous at all times, because they tend not to navigate to view the information and therefore typically do not know how much battery life remains. As one participant stated, "so if I was working for 15 minutes I could see how much battery power I'm using."

3.2 Gradient Interfaces

Ratings, direct-comparison data and verbal comments consistently indicated that participants were less than enthusiastic about the gradient interfaces because they were confusing, particularly if the participants scrolled, and because the interfaces did not facilitate the tasks of scanning and reading. Some participants stated that they would prefer to extend battery life by selecting from preexisting display settings, such that each setting provided a unique combination of battery life and a single-color (gray) interface background.

Ratings Data. After viewing each interface, participants used a scale ranging from +4 (definitely yes) to 0 (neutral) to -4 (definitely no) to rate the following statement: 'Overall, I would use this interface design on a regular basis.' Participant rating data for the gradient interfaces is displayed in Table 2. Overall mean rating decreased as the gradient % increased (i.e., became darker), $F(5, 55) = 5.91$, $MSE = 34.73$, $p = .004$. This finding also was observed for the respective e-mail and reader ratings, both p's $< .05$. Pairwise comparisons indicated that, for both the e-mail and reader interfaces, only the darkest gradient (100%) was rated lower than the control interface (0%), both p's < .05. Finally, the e-mail interface mean rating (1.42) was not reliably higher than the reader interface mean rating (0.97), $F(1, 11) = 2.04$, $MSE = 7.11$, $p = .18$.

Table 2. Gradient rating data

	Gradient						
Interface Type	**0%**	**20%**	**40%**	**60%**	**80%**	**100%**	**Mean**
E-mail	2.17	1.92	1.92	1.58	1.08	-0.17	**1.42**
Reader	1.75	1.75	1.33	1.17	0.42	-0.58	**0.97**
Mean	**1.96**	**1.84**	**1.63**	**1.38**	**0.75**	**-0.38**	**1.20**

Direct-Comparison Data. After rating all 6 gradients of each interface type, participants indicated which of the 6 gradients they would most likely use, based upon battery life, interface visual appearance and usability. The results are displayed in Table 3. Consistent with the ratings data, there was some participant interest in the 40% and 20% gradient screens. However, for both the e-mail and reader interfaces, the contemporary or control (0% gradient) interface was chosen most frequently. Two CHI Square tests, each with 6 categories, indicated that these findings differed from chance. For the e-mail gradients, $X^2(5) = 15$, $p = .01$, and for the reader gradients, $X^2(5) = 18$, $p = .003$.

Table 3. Number of participants who chose each gradient

	Gradient					
Interface Type	**0%**	**20%**	**40%**	**60%**	**80%**	**100%**
E-mail	6	1	4	1	0	0
Reader	7	1	3	0	0	1

Verbal-Comment Data. Participant ratings were, on average, less favorable for the 100% gradient than the 0% gradient because participants 'could not see the entire screen.' Additionally, participants stated that all of the gradients were somewhat distracting or confusing, particularly if they scrolled. Regarding the e-mail inbox, several participants commented that it was not clear which e-mail was highlighted. For the Acrobat Reader, several participants stated that the gradients imposed a discrete, artificial window on a continuous process that required them to see the entire page. Several participants noted that they would prefer inbox and reader interfaces with a single-color, light-gray background that would reduce battery consumption and enable sufficient contrast with superimposed text so that all of the text on the interface was easy to scan or read, depending upon the task. For example, the participants often commented that they liked the darkest shade of gray on the 40% gradients as a candidate for a single-color, gray background.

3.3 Inversion and Flashlight Interfaces

Ratings, direct-comparison data and verbal comments consistently indicated that participants liked the energy-aware inversion interfaces, tended to prefer them to the contemporary (control) interfaces and clearly preferred them to the flashlight interfaces. The inversion interfaces were received favorably because they reduced battery consumption relative to the contemporary interfaces and were readable. Participants generally perceived the flashlight interfaces as novel but lacking a task application.

Ratings and Direct-Comparison Data. After viewing each interface, participants used a scale ranging from +4 (definitely yes) to 0 (neutral) to -4 (definitely no) to rate the following statement: 'Overall, I would use this interface design on a regular basis.' The mean rating for the inversion interfaces (+3.08) was more favorable than the mean rating for the flashlight interfaces (0.00), $t(1, 11) = 3.56$, $p = .004$. Moreover, the mean rating for the inversion interfaces (+3.08) tended to be more favorable than the mean rating for the contemporary (control) interfaces (+1.96), $t(1, 11) = 2.08$, $p = .06$. After rating the inversion and flashlight interfaces, participants performed a direct-comparison task. Based upon battery life, interface visual appearance and usability, 9 of the 12 participants preferred the inversion interfaces, 2 participants expressed no preference and 1 preferred the flashlight interfaces. A CHI Square test with 3 categories indicated that these findings differed from chance, $X^2(2) = 9.5$, $p = .009$.

Verbal-Comment Data. Participants generally perceived the flashlight as a novelty without any practical application, despite each participant and the facilitator identifying several potentially-relevant tasks and scenarios. All 12 participants stated that they liked the inversion interfaces and would use them in scenarios in which reducing battery consumption was at issue. Several participants further indicated that they would consider using the inversion function as their default setting on a trial basis. Participants liked these interfaces because they provided substantial power savings compared to the contemporary (control) interfaces and they were easy to read.

Participants also noted that the implementation of the inversion interfaces was important. Thus, although several participants commented positively on the strong contrast afforded by white text on a black background (e.g., Acrobat Reader Interface), a few participants indicated that the text was a bit small or spindly, and therefore somewhat difficult to read. These participants wanted to select font size and type. Some participants also noted that they did not like the specific colors implemented in the inverted start interface.

3.4 MP3 Interfaces

Ratings, direct-comparison data and verbal comments indicated that, overall, the gray interface was the most popular, the green interface was the second-most popular, and the blue interface was the least popular. The gray and green interfaces were received favorably because they reduced battery consumption relative to the blue (control) interface, and they also provided a good visual design.

Ratings and Direct-Comparison Data. After viewing each interface, participants used a scale ranging from +4 (definitely yes) to 0 (neutral) to -4 (definitely no) to rate the following statement: 'Overall, I would use this interface design on a regular basis.' The gray MP3 interface received the most favorable mean rating (+2.08), followed by the green interface (2.00) and the contemporary (control) blue interface received the lowest mean rating (1.50). However, these differences were attributable to chance, $F < 1$.

After rating the interfaces, participants rank ordered the 3 MP3 interfaces to indicate their first (1) through third (3) choices. For their first choice, 6 participants chose the gray interface and 6 chose the green interface. A CHI Square test with 3 categories showed that these findings differed from chance, $X^2(2) = 6$, $p = .05$. The overall mean ranking for the three interfaces indicated that the gray interface was ranked most favorably (1.58), followed by the green interface (1.83) and finally the blue interface (2.58), $F(2, 11) = 4.09$, $MSE = 4.78$, $p = .05$. Comparison of means revealed that the mean ranking for the gray interface (1.58) was superior to the mean ranking for the contemporary (control) blue interface (2.58), $p < .05$.

Verbal-Comment Data. Participants preferred the gray and green interfaces to the blue interface largely because of their power-saving ability. For example, one participant who chose the green interface stated, "It's an mp3 player. I program it and stick it in my pocket. I don't look at it much." However, some participants also preferred the visual design of the gray and the green MP3 players relative to the blue player. Finally, some participants wanted the option of selecting from preexisting MP3 display settings (skins), such that each setting provided a unique combination of battery life and interface color/illumination.

4 Conclusions

As handhelds proliferate and evolve it becomes increasingly important to find new strategies to address --what one author recently called the handheld "Achilles Heel" [6] -- their battery life. Handhelds that reduce display battery consumption have been developed, but they often invoke a sleep mode, reduce the size of the display or reduce the quality of the display and thereby risk degrading the user experience. Alternatively, emerging display technologies (e.g., OLEDs) that enable energy-adaptive interfaces can potentially reduce display battery consumption and promote a positive user experience. Recent findings do indicate that energy-aware interfaces can greatly reduce battery consumption. However, it is not clear how these interfaces impact the user experience. We appear to be the first to investigate the relationship between battery life and user acceptance of dynamic, energy-aware interfaces on handhelds.

The goal of our research was to assess user expectations regarding mobile handheld battery life, and explore the relationship between battery life and user acceptance of dynamic, energy-adaptive handheld interfaces. Twelve experienced handheld users engaged functioning, prototype energy-aware interfaces on a handheld device in the service of completing a scenario comprised of 5 representative tasks. Based upon the battery life, visual appearance and perceived usability of each interface, participants provided ratings, verbal comments and direct-comparison data. Compared to contemporary (control) interfaces, the energy-aware interfaces generally achieved energy reductions of up to a factor of 4, and as much as a factor of 21.

The high-level findings that we presently observed were generally consistent with those of our previous investigation. For example, participants presently identified limited battery life as an important issue, were supportive of a display-based approach to reducing battery consumption and varied consistently in their enthusiasm for specific interfaces. That these findings presently were obtained with a new and wider variety of dynamic interfaces that were displayed on a PDA to participants not employed by our company and who all did not own the handheld brand sold by our company, all serve to increase the scope and validity of our findings.

Moreover, we presently observed some novel and, in one instance, unexpected findings. First, participants expected a longer battery life than currently supported by their handheld device, and they typically requested a two- to three-fold proportional increase relative to their current device battery life so that they could confidently complete a full day of work with their device and recharge it at night. Second, participants requested a choice of display settings, such that each setting provided a unique combination of battery life and interface appearance. Third, participants were quite favorable towards the energy-aware inversion and MP3 interfaces, and tended to prefer them to the respective contemporary (control) interfaces. Participants preferred these energy-aware interfaces because battery consumption was greatly reduced relative to the contemporary interfaces and participants could easily view all of the text to complete their task. Fourth, participants were less favorable regarding the energy-aware flashlight and gradient interfaces. This latter finding was somewhat surprising based upon the results of our first investigation in which participants stated that they would be interested in using gradient-type interfaces. However, in that study, participant comments were based upon an informal viewing of a static, gray gradient interface at the end of the session. Thus, the different reactions expressed by participants in the two investigations likely underscores the importance of conducting formal evaluations with functioning prototypes that are displayed on handhelds to a representative sample of external participants. Fifth and finally, participants in the present investigation stated that they would be relatively more interested in using e-mail and reader interfaces with a single-color background (e.g., gray) if the background reduced battery consumption and provided sufficient contrast to render the text easily readable.

From these findings, three themes emerge that are particularly worthy of further investigation: the identification and refinement of interface design principles that support reduced display battery consumption and a positive or enhanced user experience; the assessment of interfaces with single-color backgrounds that reduce battery consumption and provide a positive user experience, particularly in the context of text-intensive interfaces; and, the evaluation of handheld personalization, including the assessment of preexisting display settings, such that each setting provides a unique combination of battery consumption and interface color/illumination. Investigating these themes using formative, prototype design and testing will likely facilitate the identification of a sufficient number, variety and quality of interface designs so that it will become meaningful to perform a summative usability evaluation measuring behavioral performance as users engage fully functional interfaces.

In summary, given the ubiquity of handheld devices, user desire for longer battery life and user desire for robust displays, we believe that new strategies are needed to address the fundamental design tension currently existing between handheld display battery consumption and the user experience. One such strategy is to utilize emerging display technologies (e.g., OLEDs) that support energy-adaptive interfaces capable of reducing display battery consumption and providing a positive or even enhanced user experience. The present findings, together with other recent data, suggest that energy-adaptive interfaces have the potential to meet these criteria. We view this as an auspicious beginning for interfaces that promise to become an important component in mobile system design.

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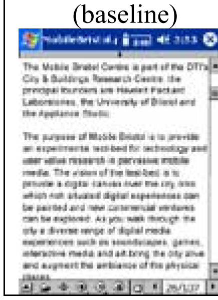
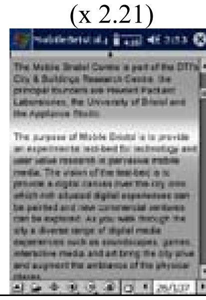
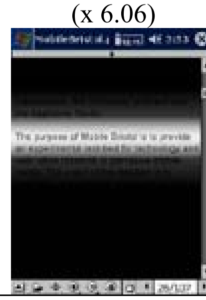
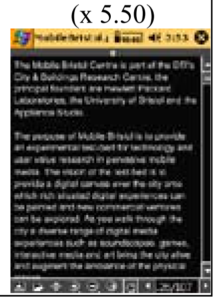
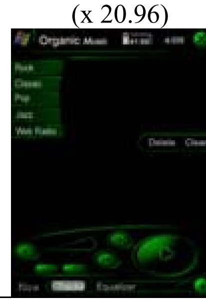
Appendix

Battery life is displayed relative to the baseline (control) battery life. For example, ‘x 2.86’ indicates a battery life that is longer than the baseline by a factor of 2.86.

Example Inbox & Reader Interfaces with Relative Battery Life			
0% Gradient	40% Gradient	100% gradient	Inversion
(baseline) 	(x 1.58) 	(x 2.56) 	(x 3.21) 
(baseline) 	(x 2.21) 	(x 6.06) 	(x 5.50) 

MP3 Interfaces with Relative Battery Life			Flashlight
Blue	Gray	Green	Black, Rectangle
(baseline) 	(x 2.86) 	(x 20.96) 	(x 8.77)