Reading on the Go: An Evaluation of Three Mobile Display Technologies

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Abstract. As mobile technology becomes a more integral part of our everyday lives, understanding the impact of different displays on perceived ease of use and overall performance is becoming increasingly important. In this paper, we evaluate three mobile displays: the MicroOptical SV-3, the Sony Librié, and the OQO Model 01. These displays each use different underlying technologies and offer unique features which could impact mobile use. The OQO is a hand-held device that utilizes a traditional transflective liquid crystal display (LCD). The MicroOptical SV-3 is a head-mounted display that uses a miniature LCD and offers hands free use. Finally, the Librié uses a novel, low power reflective electronic ink technology. We present a controlled 15-participant evaluation to assess the effectiveness of using these displays for reading while in motion.

1 Introduction

Mobile computing platforms are rapidly replacing the personal computer as the most widely adopted computing device on the planet. Mobile phones, PDA, smartphones, laptops, palmtops and wearables are becoming widely used: for example, in 2004 there were 1.3 billion mobile phone subscribers, and two billion are predicted by 2007 [1]. Wireless text messaging is widespread, with predictions that soon over one trillion messages will be sent per year [13]. Despite slow initial adoption, electronic books are becoming more popular, and some mobile phone manufacturers are working on integrating head-mounted displays into their devices.

These devices have one important thing in common: they are all used for reading on the go. Whether the use is browsing the web on a smartphone while waiting in line, using an electronic book to read a document on the way to a meeting, or simply trying to find a friend's telephone number while walking to a restaurant, the ability to read on the go is quickly becoming an important skill.

In this paper, we present an investigation into how three different mobile display technologies influence the ability to read while in motion. Participants perform reading

comprehension tests while moving, using a palmtop computer, an electronic ink book reader, and a head-mounted display; to avoid confounding effects of differing input techniques per device, we use a common input method across all of the devices. We assess the ability of participants to read on the go, as well as the perceived workload for each device.

2 Mobile Displays

We use three different mobile devices with different display technologies for our evaluation. Two of the displays are hand-held and one is head-mounted; two are transflective (using a backlight) and one is reflective (using ambient light). The hand-held displays are the OQO Model 01 palmtop computer with a transflective LCD (Figure 1) and the Sony Librié EBR-1000EP electronic book reader which uses a reflective electronic ink display (Figure 2). The head-mounted display is the MicroOptical SV-3 Instrument viewer, which uses a transflective LCD (Figure 3). Table 1 shows a comparison of the weight, display size and resolution for each device.

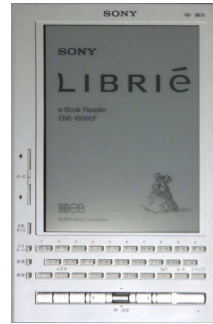**Fig. 1.** The OQO Model 01 palmtop computer.

Fig. 2. The Sony Librié e-book reader.

Device	Weight (gm)	Display Size (mm)	Resolution (pixels)	Pixel density (dpi)
OQO Model 01 (LCD)	397	109.5x66.6	800x480	185
Sony Librié (e-ink)	190	122.23x90.5	800x600	165
MicroOptical SV-3 (LCD)	35	N/A	640x480	34[1]

Table 1. Characteristics of devices and displays.

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[1] The focus of the SV-3 may be changed by the user, meaning the pixel density can change. At a focus depth of 1.6m, the SV-3 has approximately 34dpi.

2.1 OQO Model 01 Palmtop

Typically, mobile devices can be categorized as either low–power–use, low–performance devices, such as personal digital assistants (PDAs) and mobile phones, or as high–power–use, high–performance devices, such as laptop and tablet computers. Recently, however, a new category of mid-power-use, mid-performance devices has been introduced: the palmtop PC. The palmtop PC is usually equivalent in performance to an older laptop but is closer in size to a PDA. Palmtop PCs also usually have standard processors and run desktop operating systems, such as Windows XP. We selected the OQO Model 01 palmtop PC as one of the display devices for our study.

The OQO Model 01 (Figure 1) is a small form-factor palmtop computer. It weighs approximately 400g and fits comfortably in the palm of the hand. The OQO display is a transflective TFT liquid crystal display (LCD) that measures 109.5x66.6mm and has a resolution of 800x480, resulting in approximately 185dpi. The OQO has a Transmeta Crusoe 1Ghz processor, 256MB memory, and a 20GB hard drive. It also has a variety of peripheral ports including USB 1.1 host, VGA output, and Firewire. The screen on the OQO slides to reveal a miniature QWERTY keyboard; however, during our study the keyboard remained hidden.

2.2 Sony Librié E-book reader

Electronic book (or e-book) reader technology has yet to gain a significant consumer market share. Detractors of e-book readers mostly attribute their lack of commercial success to unwieldy size and weight (largely due to batteries) and hard-to-read displays (most e-book readers to date have used cheaper black-and-white LCDs such as those found in early PDAs). In the past few years, however, E-Ink Corporation has successfully commercialized a non-LCD display technology ideal for e-books. Called "electronic ink" or "digital paper," the display is reflective rather than transflective and offers a contrast ratio close to that of standard paper. Table 2 (from [5]) compares the reflectivity and contrast ratio of electronic ink technology to other reflective display technologies.

Display Technology	White State Reflectance	Contrast Ratio
Transflective Mono STN LCD (older PDA with touchscreen)	4.2%	4.1
E-Ink	41.3%	11.5
Wall Street Journal Newspaper	64.1%	7

Table 2. Characteristics of E-Ink displays and other reflective display technologies [5].

Electronic ink consists of microcapsules filled with a clear fluid, black particles and white particles. When an electrical charge is applied to a microcapsule, it causes the black particles to move in one direction and the white to move in the other direction, producing a change in color. Once the particles move within the microcapsule, no power is needed to keep them in place; the batteries can be removed from the device

and the display contents remain unchanged. Furthermore, for static images, this technology requires no refresh cycle. The speed of update when changing between images, however, is slow: an update takes approximately one second. Additionally, when a pixel is changed from black to white, a grey-colored residual "ghost" image remains which eventually needs to be cleared.

The Sony Librié (Figure 2) is one of the first publicly-available devices to use E-Ink's digital paper technology. The Librié is currently only sold in Japan, and was designed to be the same size and weight as a standard Japanese paperback book. The Librié runs a version of the Linux kernel and has a greyscale display with a resolution resolution of 800x600. We modified the Librié software to provide additional functionality to display images sent to it over USB from a host computer [2].

2.3 MicroOptical SV-3 HMD

Due to its expense, the head-mounted display (HMD) is still a relatively uncommon display technology. Although first developed in the 1960s, only recently have HMDs become sufficiently light and low–powered to be worn on a daily basis. Head-mounted displays are currently used by medical personnel, the military, and bridge inspectors. In addition, HMDs are being marketed as consumer DVD -player displays targeted for airplane use.

The MicroOptical SV-3 is a head-mounted display (HMD) which attaches to a pair of eye-glasses (Figure 3). It is monocular (seen by only one eye) and opaque. It contains a very small LCD and backlight, with a 90-degree mirror and lens to direct the image into the user's eye (Figure 4). The lens is adjustable and can be used to change the focus of the display from 0.6 to 4.5 meters.
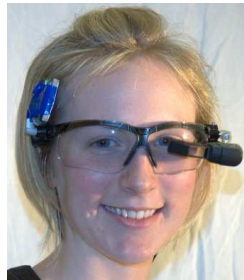

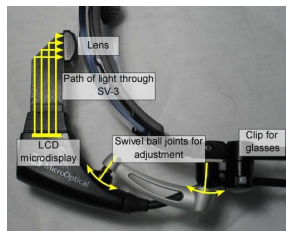**Fig. 3.** The MicroOptical SV-3 head-mounted display and the head-worn accelerometer.

Fig. 4. Top-down view of the MicroOptical SV-3 head-mounted display.

The SV-3 weighs 35g and has a resolution of 640x480. The viewport of the display measures 9.5x11mm, but the dimension is not a good indicator of the viewable

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[2] anonymized: url to software

display as the lens system creates a virtual image viewable by the user. The display has a horizontal viewing angle of 16 degrees, resulting in 40 horizontal dots per degree. For a focus depth of 1.6m (about floor depth), the display has about 34dpi; at a focus of 0.6m (about hand-held display depth), the display has 71dpi. The SV-3 accepts a standard VGA signal as input, and a small controller box converts the signal to drive the integrated LCD.

3 Related Work

As mobile technology becomes increasingly popular, it is important to evaluate the impact of mobile settings on these devices. Kjeldskov and Stage examined different usability techniques and ways to obtain results in a laboratory setting that are similar to findings from a more naturalistic field environment [9]. Oulasvirta et al. evaluated the use of a web browser on a mobile phone while walking in a city setting [15]. They found that while participants were waiting for web pages to load while walking on a busy street, their participants spent most of their time focused on their environment and interacted with the device in approximately four second bursts.

Reading is one fundamental task performed on mobile devices. Mustonen et al. evaluated legibility of text on mobile phones while walking at different speeds on a treadmill and while walking down an empty corridor [14]. They found visual performance deteriorates with increased walking speed and that as subjective taskload increases, performance declines. Studies conducted by Bernard et al. [2, 3] examined word search and reading comprehension on a PDA while either walking on a treadmill, following a path on the floor, and while sitting. They also examined contextual factors, in particular lighting level. Participants rated subjective workload higher while walking on a path as opposed to a walking on a treadmill. They also found participants read faster, had better comprehension, and perceived less workload while sitting as compared to walking on a path. The experimental procedure used in our study leverages the design from this work.

The above studies all examined various tasks on hand-held displays such as PDAs and mobile phones. Some studies have explored the use of head-up displays in aviation [18, 19], automobiles [6], and soldier combat [20]. There has also been work evaluating stationary use of head-mounted displays. Curry et al. examined the use of a HMD and a conventional desktop display for pointing tasks [4]. The pointing device, a standard mouse, was constant across all display types. The results indicated that "the human performance on the visual component of pointing tasks [for the HMD] is equivalent to that of a desktop display." Sheedy and Bergstrom compared different display types for use in paragraph reading, word count, and word search tasks [16]. All of the tasks were completed while stationary. The results of this study showed performance speed for the head-mounted display was comparable to the flat panel desktop and hard copy conditions. The monocular near-eye display and the hard copy display together showed best performance in paragraph reading, and the HMD was second in performance to the flat panel display for the word search tasks.

All drivers are responsible for refueling their vehicles at the end of each shift. All other routine maintenance should be performed by maintenance-department personnel, who are also responsible for maintaining service records. If a driver believes a vehicle is in need of mechanical repair, the driver should fill out the pink "Repair Requisition" form and give it to the shift supervisor. The driver should also notify the shift supervisor verbally whether, in the driver's opinion, the vehicle must be repaired immediately or may be driven until the end of the shift.

If the vehicle is due to have the oil changed, whose responsibility is it?

○ maintenance-department personnel

○ the drivers at the end of their shifts

○ shift supervisors

○ outside service mechanics

Done

Submit

Fig. 5. An example reading passage.　　**Fig. 6.** A multiple choice question example.

4　Method

4.1　Experimental Design

In order to test reading performance on the three devices, we designed a single-variable within-subjects experiment with one condition per device. The conditions were: the MicroOptical SV-3 head-mounted display, the Sony Librié e-book reader, and the OQO Model 01 palmtop computer. Our experimental design is largely based on the studies performed by Barnard et al. [2, 3] where participants walk a predefined path while performing reading comprehension trials.

Each participant is presented with ten reading comprehension trials. A reading comprehension trial consists of a short passage followed by two questions (Figure 5 and 6. Both the passages and questions were selected to be short enough to fit on one screen without scrolling, and were taken from a book designed to prepare high school students for standardized tests [12] (the same source used in the Bernard et al. experiments).

The experiment was conducted in a laboratory environment and a path was constructed by placing tape on the floor (Figure 7). We designed the path to be approximately 40 meters long and 30 cm wide across its entire length. The path was curvy and required the participants to navigate around several objects: tables, a tall garbage can, and a couch. Furthermore, the evaluation occurred in a functional computer science laboratory with many visual distractions in the environment including computers, shelving and office clutter. Both the path and positioning of obstacles remained constant across all participants. The start of the path was marked with red tape, and at 30.5cm (1 foot) intervals with pencil (barely visible to participants) to facilitate measuring distance.

The direction the participants walked on the path (clockwise or counter-clockwise) is randomized across conditions and participants. The order of the reading comprehension trials and the distribution of the passages across conditions is also randomized for each participant to prevent any effects ordering or variable trial difficulty may have on performance and workload measures.
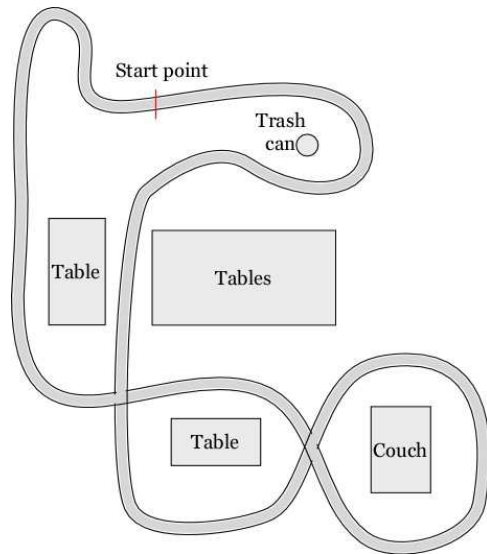
Fig. 7. The path particpants walked along.

Fig. 8. The keypad used for input.

4.2 Equipment and Software

The OQO serves as the base platform for the experiment. Our custom experimental software, written in Java, presents the reading comprehension passages and questions and performs all of the data collection. The OQO is also used to drive the Librié and MicroOptical displays.

During each condition, the participants wear a backpack and safety goggles and carry a custom keypad. The participant also carries (or in the HMD condition wears) the display for the current condition. The backpack contains the unused displays; this technique ensures that the participant carries the same amount of weight in each condition. Safety glasses are used for mounting the head-mounted display, but are also worn in the non-HMD conditions. Figures 9, 10, and 11 illustrate the apparatus for each condition.

The custom keypad used for input has five buttons (Figure 8). Four buttons are black and correspond spatially to answers in the reading comprehension task, and one button is red and conceptually corresponds to a "Done" or "Next Screen" key (Figure 6). We chose to use a separate keypad for input because we are interested in studying mobile displays; by standardizing on this input device across the conditions, we have attempted to remove input as a source of influence.

For all three devices, we controlled for the number of pixels used on the display. Regardless of the actual resolution of the screen, our software utilizes only 640x480 pixels. Any extra pixels are rendered white, and the text is centered on the screen. In normal use as an e-book reader, the Librié is held in portrait orientation (so its resolution is 600x800); we have participants hold it in landscape orientation (800x600).

Fig. 9. The OQO hand-held condition.

Fig. 10. The Librié hand-held condition.

Fig. 11. The SV-3 HMD condition.

The Librié is attached to the OQO with a USB cable. Since we did not have a direct method for writing to the screen, we devised software which pushes images from our experimental software over USB to the Librié. In the head-mounted display condition, the MicroOptical is attached to the OQO by a VGA cable.

To collect motion and orientation data, we utilize several wireless Bluetooth three-axis accelerometers. An accelerometer is strapped to each ankle. Additionally, an accelerometer was velcroed to the back of the hand-held displays, and an accelerometer was attached to the safety glasses on the side opposite of the dominant eye (Figure 3). Data from the accelerometers is sent directly to the OQO through Bluetooth and logged in a time-stamped file.

4.3 Procedure

The experiment begins for each participant with a brief description of the experiment, an introduction to the NASA Task Load Index (TLX) questionnaires, and a short background survey. Once the paperwork is complete, the participant performs a simple eye-dominance test as previous research has shown that HMDs should be worn over the dominant eye [10, 11]. The participant centers a small triangular hole in a piece of paper over a dot on the wall five meters away, and then close their left eye. If the dot remains centered in view with the left eye closed, the experimenter records the participant as being right-eye dominant. If not, the experimenter repeats the procedure testing the other eye to confirm left-eye dominance. Next, the participant is introduced to the accelerometers and the experimenter attaches an accelerometer to the participant's left and right ankles and one to the safety glasses on the side of the non-dominant eye.

Baseline data for average natural walking speed along the path is then collected. The participant is instructed to walk once around the path in each direction at a comfortable pace while wearing the glasses and backpack. The time to complete each lap is recorded.

Before the first condition starts, the experimenter explains the design of the study in more detail, including an introduction to the hardware and software and a demonstration of how to use the input device. At the beginning of each condition, the experimenter

configures the appropriate display. The participant then calibrates the display using a blank screen numbered one through nine with a number in each corner, at the center of each edge, and in the center of the screen. We included this step to ensure the head-mounted display is positioned properly and such that the entire screen is visible. For consistency, we performed this procedure for all three displays.

For the hand-held displays, the researcher places the device in the participant's non-dominant hand in the landscape orientation. For the head-mounted display condition, the experimenter shows the participant how the MicroOptical moves on two ball joints and what part of the device to move to adjust the focal depth (Figure 4). The experimenter mounts the display on the safety glasses over the participant's dominant eye. With the aid of the experimenter, the participant adjusts the display using the calibration pattern and changes the display's focal length to match the floor. After the display is calibrated and ready to use, the experimenter places the input device in the participant's dominant hand and starts the experimental software.

Each condition begins with one practice reading trial which is performed with the participant standing still at the beginning of the path. Once the reading trial has been finished, and the participant's questions have been addressed, the trials begin. Participants are instructed to walk along the path as during baseline measurement; that is, along the path and inside the lines. The participants are instructed to continue walking until they finish the last (10th) trial and informed that they can slow down or speed up as desired, but not to stop; they are also instructed to answer the questions as accurately as possible. The experimenter tells the participant when to start; the participant begins walking and must press the red button to see the first passage.

As the participant walks around the path and completes the trials, the experimenter follows behind as quietly as possible and uses a silent tally counter to keep track of the number of times the participant steps outside the path and the number of complete laps. When the participant completes the final trial, the software shows an ending screen asking the participant to stop. The experimenter notes the time required to complete the 10 trials and records the participant's final position.

At the end of each condition, the experimenter directs the participant to complete the NASA-TLX surveys, reminding them to consider only the most recent 10 trials and the display just used. After the TLX, the procedure is repeated with the remaining display devices. Once all three conditions are complete, another assessment of natural walking speed is conducted before removing the bag, glasses, and accelerometers. Finally, the experimenter asks the participants to share any comments they had about their experience with any of the displays and the task performed.

4.4 Participants

Twenty-two participants were recruited from the student body by word-of-mouth. We did not control for any demographic factors (i.e. gender, eye-sight, native language, etc.). All participants were compensated $10 per hour, regardless of their performance. Time to complete the study ranged from 1.25 to 2 hours, with a median of 1.5 hours. Of the 22 data sets generated, only 15 data sets were used. Seven of the twenty-two data sets were missing accelerometer data. We consider only the 15 complete data sets throughout the rest of this paper.

The 15 participants ranged in age from 21 to 49 years, with a median of 25 years. Two participants were left-handed, twelve were right-handed, and one was ambidextrous. Six participants were right-eye dominant and nine were left-eye dominant. The seven non-native English speaking participants had experience reading English ranging from 5 to 17 years, with a median of 12 years. Only two participants indicated having experience with a head-mounted display, and both noted that their experience consisted of simply looking through a display once.

4.5 Data Collection and Analysis

To assess participant performance, we record reading time, response time, response accuracy, path accuracy, walking speed and walking accuracy. Reading time is the time from when a passage is first displayed to when the participant presses the red button to proceed to the question. Response time is the time from when an answer screen is displayed to when the participant presses the red button to proceed. Response accuracy is whether or not the participant selected the correct answer. All of these values were calculated from the data logs after the experiment was competed. Path accuracy is the number of times the participant stepped outside the path. Total distance was calculated by counting the number of laps (full and partial) around the path. To assess perceived workload, each participant completes the standard NASA-TLX scale and demand comparison surveys after each display condition.

The accelerometers on each ankle are used to track the movement of each foot. Previous research anecdotally noted that users tended to increase or decrease walking speed with changes in task difficulty [3]. The time-stamped acceleration data provides quantitative data that can be used to analyze the changes in walking speed in relation to what the participant was seeing on the display and what buttons they were pressing. The accelerometers on the hand-held devices and head provide orientation information. Previous research has demonstrated both the utility and validity of using accelerometers in experiments designed to investigate mobile device while in motion [21].

5 Results

5.1 Passage and Question Performance

Our 15 participants read a combined total of 450 passages and answered 900 questions. Table 3 shows the percentage of questions answered correctly, the average time spent reading each passage, and the average times spent answering the first and second questions for each display condition. In terms of accuracy, the participants performed surprisingly poorly, regardless of display type. A repeated measures ANOVA on the display condition shows no statistical difference in ability to answer the questions correctly. The average accuracy across all conditions is only 69.4%.

Examining the average time spent during each of the three phases of the trials (reading the passage, answering question one, and answering question two) reveals statistically significant differences for the three conditions. While a post-hoc pairwise analysis reveals no significant effects for the time spent on each question phase, we do find

	Device			
	Librié	OQO	MicroOptical	p-value
Percent correct, overall	70.30	71.52	66.36	$p \approx 1.00$
Percent correct, Q1	68.48	72.73	67.27	$p \approx 1.00$
Percent correct, Q2	72.12	70.30	65.45	$p \approx 1.00$
Passage time (s)	68.04	66.05	89.46	$p < 0.01$
Time Q1 (s)	14.63	14.56	14.57	$p < 0.01$
Time Q2 (s)	14.25	15.66	17.69	$p < 0.01$

Table 3. Performance on passage questions.

significant pairwise effects for reading time. Results show participants read faster on both of the hand–held devices than on the head–mounted display. This finding is reinforced by participant comments stating they would often lose their place in the text while reading on the head-mounted display. Several participants indicated that they lost their place due to motion of the HMD, while others mentioned being distracted by the environment. The issue of distracting environmental backgrounds is consistent with findings from studies of stationary head-mounted display use [11].

5.2 Walking Performance

We also tracked measures related to the walking portion of the task: total distance traveled, total time spent walking around the path, and total number of steps outside of the path for each display condition. From this data we computed two additional, normalized values: walking speed and number of steps off the path per unit distance (meter). The mean values for each condition and the p-value from a one-way repeated measures ANOVA are shown in Table 4.

	Device			
	Librié	OQO	MicroOptical	p-value
Distance (m)	502.97	480.70	609.29	$p < 0.01$
Time (s)	697.45	673.62	1003.38	$p < 0.01$
Speed (m/s)	0.72	0.71	0.63	$p \approx 1.00$
Steps off path	112.00	116.67	197.67	$p < 0.01$
Steps off/m	0.22	0.23	0.31	$p \approx 1.00$

Table 4. Walking performance for the three conditions.

The analysis reveals statistically significant differences between the three conditions for distance, speed and number of steps off the path. Post-hoc pairwise analysis shows worse performance for the head-mounted display condition relative to each hand held display ($p < 0.01$). It is interesting to note, however, that our two normalized metrics (walking speed and steps off path per meter) show no statistically significant difference.

Using the data from the accelerometers, we calculated the angle at which the hand held displays were held relative to the ground. We calculated the mean angle for each

passage and set of questions. The Librié was held on average at an angle of 40.9 degrees (SD=10.8) where 0 degrees is parallel to the ground. In contrast, the OQO was held at 58.0 degrees (SD=9.0). A Student's t-test reveals a statistically significant difference between these two conditions ($p < 0.01$).

Finally, the data show that participants slowed down while reading and walking the path, regardless of display type. The baseline "natural" walking speed for the participants was 0.99 m/s (SD=0.18) while the mean walking rate in the conditions was only 0.69 m/s (SD=0.22).

5.3 Nasa Task Load Index

The NASA Task Load Index (TLX) is a questionnaire used to measure subjective workload ratings. Previous studies have indicated that it is both a reliable and valid measure of the workload imposed by a task [8, 7]. The NASA-TLX consists of six scales: mental demand, physical demand, temporal demand, performance, effort, and frustration; each scale has 21 gradations. For each scale, individuals rate the demands imposed by the task. In addition, they rank each scale's contribution to the total workload by completing 15 pairwise comparisons between each combination of scales. This procedure allows an investigation of how task demands load on each scale, as well as a measure of the total workload.

Interpretation of the mental, physical, and temporal demand scales are straightforward; each scale captures the demand imposed by its title. The performance scale captures how successful participants felt they were at accomplishing the given task. The effort scale captures how hard individuals had to work in order to achieve their level of performance; both mental and physical effort can contribute to this scale. The frustration scale captures how much the task annoys or discourages individuals.

The overall workload rating is calculated by summing the product of each scale's rating and weight. This calculation results in a score between 0 and 100. It reflects an individual's perception of the amount of workload devoted to each of the scales, along with each scale's contribution to overall workload [8]. Here, we analyze the overall workload ratings in addition to the six individual scale ratings. For each analysis a one-way repeated measures ANOVA is used.

	Device			p-value
	Librié	OQO	MicroOptical	
Total workload	30.84	34.29	42.56	$p < 0.01$
Mental	48.13	43.73	40.27	$p < 0.01$
Physical	10.80	28.00	30.53	$p < 0.01$
Temporal	6.13	4.40	4.47	$p < 0.01$
Performance	10.07	9.67	14.20	$p < 0.01$
Effort	13.87	13.07	22.67	$p < 0.01$
Frustration	3.53	4.00	15.53	$p < 0.01$

Table 5. Total TLX workload as well as weighted component scores (out of 100). Each metric shows that the three displays are statistically different at the p<0.01 level.

The analysis shows significant effects (p < 0.01) for the total workload as well as the six component scales (Table 5). Pairwise post-hoc analysis reveals statistically significant differences for total workload, frustration and effort with the Librié and OQO scoring better than the head–mounted display. In contrast, the physical dimension for the Librié is rated as less demanding than either the OQO or MicroOptical.

6 Discussion

Overall, our data and analysis show participants performed least well in the head-mounted display condition. When there are statistically significant differences, both of the hand-held displays yield better performance than the HMD. The only exception we found in the data is that participants rated the Librié as less physically demanding than either the OQO or MicroOptical. Rating the HMD worse than the Librié is consistent with the other findings. The difference of the Librié relative to the OQO is likely due to the weight of the devices. Even though the Librié has a large height and width, it is much thinner and lighter than the OQO. This result is supported by comments from several participants about the weight of the OQO.

The HMD may have seen a reduction in performance due to its monocular nature; the participants were able to see the hand-held displays with both eyes, but had to use only one to look at the HMD. Velger [17] identifies several characteristics that can cause difficulty in viewing when an image is only shown to one eye with an HMD: when presenting an image: brightness, image characteristics (i.e., text vs objects), viewing distance, contrast, resolution, color, motion and orientation. Velger also discusses the issue of binocular rivalry, where the brain causes the images from each eye to alternate. This factor may have caused difficulty in reading because of distracting backgrounds [11]. Another potential factor that may impact these results is that all of our participants were novices with head-mounted displays. As a result, the displays may not have been positioned optimally, and the participants did not have the benefit of strategies that might be developed by more experienced users.

We were anticipating some issues with the Librié due to its slow refresh rate. While several participants commented on the delay in screen updates, our data do not show statistically significant results indicating this delay had an impact on the reading comprehension task.

As expected, participants slowed their walking rate while performing the reading tasks using the mobile displays. On average, they slowed down from a mean "natural" walking speed of 0.985 m/s to 0.687 m/s during the trials.

Many participants commented that they were surprised by difficulty of completing the reading comprehension tasks while walking, regardless of display type. This issue is reflected in the data, with a mean response accuracy of 69.4% across all conditions. There could be several factors contributing to this effect. For example, it is possible the task may be unrealistically difficult. The reading comprehension passages and questions are designed for preparing students for standardized tests as opposed to a more typical task requiring less concentration such as reading a web page.

7 Future Work

We intend to further analyze the data collected from the accelerometers to get more detailed information about any potential gait changes that may have occurred while performing the reading comprehension task with the different displays. We also plan on examining more experienced HMD users to see if practice might mitigate some of the performance penalties observed in this study. It would also be interesting to explore these devices in a more longitudinal setting to see if training, particularly with the HMD, might impact participants' ability to read on the go.

While our laboratory experiment of reading comprehension ability while walking on a path provides interesting insights, we are also interested in exploring the capabilities of these displays in more natural settings. Walking on our path involved navigating static obstacles. A mobile device user in the real world would also encounter mobile obstacles such as other people. Furthermore, the user can be mobile in other ways, such as riding in an automobile or standing on a subway train.

As noted above, our experiment used passages designed help students practice for standardized tests. We would also like to explore other visual tasks that are likely to be performed on mobile devices such as browsing email or reading a web page. We would also like to examine more fundamental issues of the displays while in motion such as font size and psycho-perceptual factors like visual acuity. Another approach would be to evaluate the effects of visual layout on our participants' ability to read while in motion. Several participants commented in the HMD condition that while they were reading, they would lose their place and end up rereading the same line multiple times. It is possible that adding more white space or other visual separators might minimize this effect and alter performance.

In addition to the devices used in this study, there are other new interesting display technologies being created. In particular, Symbol has a small personal scanning projector [3] approximately 3.3 cubic cm in size. With this type of technology it will be possible to carry a projector to create a display on the floor. It would be interesting to explore if the technology has any potential benefit for use while in motion.

8 Conclusions

We evaluated in-motion reading performance on mobile devices using three different displays: a MicroOptical SV-3 monocular head-mounted display, a Sony Librié electronic ink e-book display, and an OQO palmtop computer display. Furthermore, we updated an existing framework for evaluating devices for use while in motion [2, 3] by introducing a method for decoupling input from output.

The results of our study indicate that the performance of our participants was worst when using the head-mounted display; we found no significant differences between the two hand-held displays for most measures. The only exception was the subjective measure of perceived physical demand, in which the Librié was perceived as being less demanding than the OQO. While the Librié screen takes longer to update than either of

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[3] http://www.symbol.com/products/oem/lpd.html

the other displays, our findings did not indicate any significant negative effects from the slow refresh rate.

9   Acknowledgements

References

1. S. Baker, H. Green, B. Einhorn, M. Ihlwan, A. Reinhardt, J. Greene, and C. Edwards. Big bang! BusinessWeek, June 2004. http://www.businessweek.com/magazine/content/04_25/b3888601.htm.

2. L. Barnard, J. S. Yi, J. A. Jacko, and A. Sears. An empirical comparison of use-in-motion evaluation scenarios for mobile computing devices. *International Journal of Human-Computer Studies*, 62(4):487–520, 2005.

3. L. Barnard, J. S. Yi, J. A. Jacko, and A. Sears. A new perspective on mobile device evaluation methods (in-press). *To appear in Personal and Ubiquitous Computing*, 2005.

4. M. Curry, J. Hobbs, R. Toub, and S. Douglas. Will using a head-mounted display affect pointing on wearable computers? Technical Report CIS-TR 97-03, Dept. of Computer and Information Science, University of Oregon, January 1997.

5. E Ink Corporation. *Display Readability*, 051702 edition, 2002. http://eink.com/pdf/eink_readability_02.pdf.

6. K. W. Gish and L. Staplin. Human factors aspects of using head-up displays in automobiles: A review of the literature. Technical Report DOT HS 808 320, National Highway Traffic Safety Administration, 1995.

7. S. G. Hart and L. E. Staveland. *Human Mental Workload*, chapter Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. North-Holland, 1988.

8. S. G. Hill, H. P. Iavecchia, J. C. Byers, A. C. Bittner, A. L. Zaklad, and R. E. Christ. Comparison of four subjective workload rating scales. *Human Factors*, 34(4):429–439, August 1992.

9. J. Kjeldskov and J. Stage. New techniques for usability evaluation of mobile systems. *International Journal of Human-Computer Studies*, 60:599–620, 2004.

10. D. Knudson and D. Klika. The impact of vision and vision training on sport performance. *The Journal of Physical Education, Recreation and Dance*, 1997.

11. R. S. Laramee and C. Ware. Rivalry and interference with a head–mounted display. *Transactions on Computer–Human Interaction*, 9(3):238–251, September 2002.

12. LearningExpress, editor. *501 Reading Comprehension Questions*. Learning Express, 1999.

13. Mobile CommerceNet http://www.mobile.seitti.com, January 2002.

14. T. Mustonen, M. Olkkonen, and J. Hakkinen. Examining mobile phone text legibility while walking. In *CHI '04 extended abstracts on Human factors in computing systems*, pages 1243–1246, New York, NY, USA, 2004. ACM Press.

15. A. Oulasvirta, S. Tamminen, V. Roto, and J. Kuorelahti. Interaction in 4-second bursts: the fragmented nature of attentional resources in mobile hci. In *Proceedings of SIGCHI*, pages 919–928, New York, NY, USA, 2005. ACM Press.

16. J. Sheedy and N. Bergstrom. Performance and comfort on near-eye computer displays. *Optometry and VisionScience*, 79(5):306–312, May 2002.

17. M. Velger. *Helmet-Mounted Displays and Sights*. Artech House, Inc., Norwood, MA, 1998.

18. P. M. Ververs and C. D. Wickens. Conformal flight path symbology for head-up displays. Technical Report ARL-98-5/NASA-981, Aviation Research Laboratory, 1998.

19. C. D. Wickens and J. Long. Object versus space-based models of visual attention: Implications for the design of head-up displays. *Journal of Experimental Psychology: Applied*, 1(3):179–193, 1995.

20. M. Yeh, J. L. Merlo, C. D. Wickens, and D. L. Brandenburg. Head-up vs. head-down: Effects of precision on cue effectiveness and display signaling. In *Proceeding of the 45th Annual Meeting of the Human Factors and Ergonomics Society*, 2001.

21. J. S. Yi, Y. S. Choi, J. A. Jacko, and A. Sears. Context awareness via a single device-attached accelerometer during mobile computing. In *Proceedings of MobileHCI*, pages 303–306, 2005.