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Human Factors Guidance for the Use of Handheld, Portable, and Wearable Computing Devices

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Technical Report

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16. Abstract

This report provides human factors guidance for the selection and use of handheld, portable, and wearable computing devices, including personal digital assistants (PDAs), tablet computers, and, to a more limited extent, head-mounted display systems. These devices are becoming more common in the workplace. The Federal Aviation Administration (FAA) wanted to know if these devices would be beneficial to maintenance specialists. Human factors researchers from the William J. Hughes Technical Center were asked to identify the advantages and disadvantages of these devices. These systems require different usage guidelines than standard desktop computing systems because of their size, portability, human-computer interface (HCI) designs, and intended work environments. In this report, we discuss differences between different maintenance tasks and how these differences may affect the selection of an appropriate device. We summarize the advantages and disadvantages of common handheld, portable, and wearable systems, specifically focusing on areas such as device size, screen size and resolution, input method, one- or two-handed operation, and heads-down time.

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Executive Summary

This report provides human factors guidance for the selection and use of handheld, portable, and wearable computing devices, including personal digital assistants (PDAs), tablet computers, and to a more limited extent, head-mounted display systems. These systems require different usage guidelines than standard desktop computing systems because of their size, portability, human-computer interface (HCI) designs, and intended work environments.

To optimize the selection and use of equipment for a specific job function, a detailed understanding of the user, user needs and goals, and the work environment is essential. Often, Human Factors Specialists (HFSs) conduct task analyses to obtain information about users and their environments by observing them as they perform their jobs in their normal work settings. Task analyses were beyond the scope of this project. However, we were able to conduct structured interviews with some maintenance specialists who provided us with insight on the environmental and task-related factors that would affect device selection.

A primary human factors consideration for a handheld, portable, or wearable device involves the device physical or ergonomic characteristics. Users must be able to hold, interact with, transport, or wear the device, possibly for extended periods of time. The device must provide the capabilities users require, while not interfering with their primary task responsibilities. These devices must also withstand a more stringent set of environmental stressors than their desktop counterparts. They must be rugged (resistant to damage when bumped into or dropped), water resistant, and operate in a wide range of temperatures.

The computer-human interface (CHI) must be critically evaluated to select a device that best meets user needs. Different devices may use keyboards, touch screens, or speech as their primary means of interaction. Display sizes and characteristics also vary across devices. The input device that is most appropriate depends on the task. For example, if the user needs to access documents and manuals or view images, a device with a high resolution display and a large screen will result in better readability.

PDAs, Blackberrys©, and smart phones are small in size and easily portable. They are most useful for accessing short lists of data, menus, and checklists, and for allowing limited mobile data entry or e-mail access. Due to their small screen size, they are less useful for accessing and viewing detailed text or images.

Tablet computers are similar to laptop computers in size and weight. Their screen size is adequate for allowing users to access detailed documents, images, etc., but many of them also rely on touch screen interaction. Since the tablet computer has similar functionality to a laptop, it allows the user the ability to access a greater number of applications than smaller portable devices.

A drawback of both PDAs and tablet computers is that users need to hold the devices or place them on a surface to use them. Wearable devices provide an alternative, allowing users increased hands-free operation. However, these devices are still in the early stages of development and use, and a number of problems have been identified with the systems that do exist. The weight, size, and placement of the device on the body must be considered because muscle strain and difficulties with posture and gait can result. In addition, head-mounted wearable systems that utilize monocular viewing displays can cause visual disorientation and balance problems.

The suitability of any device depends on the application for which it is intended, the environment in which it is to be used, and the characteristics of the user. A human factors evaluation should be conducted with representative users performing representative tasks to determine which device best meets user needs.

1. Introduction

This report provides human factors guidance for the selection and use of handheld, portable, and wearable computing devices, including personal digital assistants (PDAs), tablet computers, and to a more limited extent, head-mounted display systems. These systems require different usage guidelines than standard desktop computing systems because of their size, portability, computer-human interface (CHI) designs, and intended work environments. A summary of the relevant literature, key human factors considerations, and existing recommendations is included for each. This report focuses on currently available device features and characteristics rather than on future concepts and does not discuss ratings or comparisons of specific products. Since these technologies are relatively new, in many cases there is limited unbiased, empirical data available about their usability. As these devices continue to mature, these guidelines must be reevaluated and updated appropriately.

2. Background

As portable and wearable computers become less expensive and more widely available, decision makers within the Federal Aviation Administration (FAA) wanted to know whether these devices would be beneficial as tools for the maintenance workforce. Engineering research psychologists from the Human Factors Group at the FAA William J. Hughes Technical Center were asked to survey the literature and identify human factors pros and cons associated with different handheld and wearable computer devices.

2.1 User Needs and Goals

To optimize the selection and use of equipment for a specific job function, a detailed understanding of the user, user needs and goals, and the user's work setting is essential. These considerations allow the most appropriate human-system fit to be identified. Often, Human Factors Specialists (HFSs) conduct task analyses to obtain information about users and their environments by observing them as they perform their jobs in their normal work settings. This process helps determine how users are currently performing their work, which functions are used most often, which are most critical, and what difficulties are encountered. As a result, the analysis helps identify problems with existing technologies, equipment, and procedures. The scope of this effort permitted us to talk with a few maintenance specialists, but the majority of the information within this document is based on information obtained from existing research. More extensive analyses are necessary to validate these recommendations against current maintenance job functions, tasks, and user needs and goals.

2.1.1 Maintenance Specialists

In our discussions with maintenance technicians, we found that first and second level maintenance support personnel vary considerably in their information needs and work environments. While a detailed description of each of these jobs is beyond the scope of this report, we provide a general description of these users' tasks and work environments to assist the reader in understanding the potential suitability of handheld and wearable devices for the different user groups.

The second level support specialists help Field Services Specialists (FSSs) troubleshoot problems from a remote location. This type of troubleshooting often requires the FSS to describe a problem to the second level support specialist over the phone, and to send a screen shot illustrating the problem via email. Based on this information, the second level support specialist can then provide possible solutions to the FSS. The specialists we spoke to said that the time to troubleshoot a problem would be greatly reduced if they could view the screens remotely in real time. In cases in which remote troubleshooting does not solve the problem, the second level support specialist travels to a facility.

According to the specialists we interviewed, some FSSs (e.g., radar) work primarily inside, in areas that are typically dark or dimly lit, cold, and quite noisy. Some specialists wear head-mounted lights to help them navigate and work in these darkened environments. FSSs often have to access small, cramped spaces to work on equipment, making it unsafe for them to wear anything that could get caught easily on surrounding equipment (e.g., watches, rings). On the more positive side, these work areas often have surfaces on which to place tools, books, computers, etc., and outlets to plug in equipment.

In contrast, other specialists, such as those who work in the environmental area, work outside in bright light, under varying temperatures. Their work environment typically does not provide surfaces on which the users can place materials, nor do these settings usually have power sources available for additional devices, or local area network connectivity.

The specialists we spoke with said that any computing device they use would require an easy means of connecting to and transferring data to or from other systems. Lack of connectivity was a common concern for both first and second level maintenance support specialists.

2.1.2 User Constraints

According to FAA statistics, the majority of support specialists formerly classified as airway facilities specialists are over the age of 40 (Broach, 2005). As people age, their perceptual abilities decline and they tend to lose height and gain weight. Many people over 40 require bifocals or reading glasses. One subject matter expert told us that many of the field service specialists have a difficult time reading smaller fonts. Aging can also affect strength and fine motor control. Within the technical operations workforce there are specialists over 70, and even some who are over 80 years old. Thus, age limitations are an important consideration for selecting devices for FAA specialist use.

The FAA maintenance population includes both males and females of different backgrounds. Males and females and different ethnic populations vary considerably with respect to their anthropometrics. Therefore, any handheld, portable, or wearable device must accommodate this wide range of users.

The knowledge and skill level of the user must also be understood. If a device is to be used with minimal training, then critical features and functions must be easily accessible and intuitively presented. Overall, devices that have good legibility and color contrast, and are easy to learn will be more effective and more readily accepted by users.

2.1.3 Task and Environmental Constraints

To ensure that a device will adequately meet user needs, a set of criteria must be established to determine whether candidate systems meet task performance expectations. Criteria are typically established relative to a standard (e.g., users must be able to complete a task in no more than two minutes) or with respect to other systems or devices. For example, if the objective is to enable the user to perform a task more quickly than it is currently performed, with no loss in accuracy, quantitative comparisons must be made to evaluate differences in task speed and accuracy when using each system.

Environmental conditions may affect the user's ability to interact effectively with the device (e.g., too little or too much ambient light), as well as the performance of the device itself (e.g., temperature extremes). In the case of the radar field service specialist, the device must be legible in darkened environments, or have backlighting capabilities, particularly since radar specialists may need to view detailed information such as a screen capture or output from an oscilloscope.

Environmental specialists, on the other hand, will need to see images of hurricane damage, pictures of an incorrectly installed latch, or pictures of a suspicious package in more brightly lit conditions, necessitating different display capabilities. These different specialists have different information needs and workplace constraints. As a result, a handheld device that may be appropriate for one group may not be appropriate for another.

2.2 Uses of Handheld, Portable, and Wearable Devices in Aviation

Although there have been no studies on the use of handheld devices specifically for National Airspace System (NAS) ground maintenance use, there have been studies on the use of portable computing devices by aircraft maintenance technicians. It is worth reviewing these studies, as it is likely that there are similarities between the tasks and needs of NAS ground maintenance and those of the aircraft maintenance technician.

Casner and Puentes (2003) investigated the use of various computing devices at a sample of 18 aircraft maintenance facilities. The portable computers in use included laptops, PDAs, and tablet computers. Technicians were primarily using these devices to access documents (e.g., maintenance manuals), check inventories, monitor alerts, write up and distribute reports, and communicate with others. Some important usability issues were noted. The technicians indicated that they had difficulty working with devices with small screens and that low screen resolution was a problem. They were also concerned about device durability, battery life, and problems with connectivity (e.g., unavailable or intermittent) over wireless networks.

In another study, Hastings and Lizarzaburu (2000) evaluated Aviation Maintenance Technicians' (AMTs) use of and reaction to pen-activated and touch screen portable devices for accessing technical documents (e.g., maintenance manuals, parts catalogs, repair manuals) as part of a vendor-selection process. The AMTs were asked to work through scripted, simulated, maintenance problems on a 737-500 aircraft and provide subjective assessments of three different systems. Overall, the AMTs found the devices very useful and easy to work with. However, a number of concerns were raised. These included slow system response times, glare, pens that were easy to lose, and intermittent wireless coverage in various parts of the aircraft.

Another important concern was that devices with smaller screens were not well-suited for accessing and displaying pdf files. Users had to "zoom in" to see detailed information and in doing so, then had to scroll more to access different parts of the document. The largest, brightest, and most legible display was rated highest by these users.

3. General Human Factors Considerations for Handheld, Portable, and Wearable Computers

Handheld, portable, and wearable computers are typically designed for intermittent use in a non-traditional (i.e., desktop unavailable) environment. The benefit of these devices is their relatively low weight and small size, which make them suitable for carrying. However, portable devices can lead to ergonomic problems if used for the same tasks (e.g., continuous data entry) as desktop computers (Straker, Jones & Miller, 1997), as most are not designed for extended periods of use.

The Department of Defense (Department of Defense, 1995) provided human factors guidance for portable test equipment, including hand held testers. Although these guidelines were developed before the specific devices discussed in this report became widely available, the guidelines address human limitations for handheld equipment, and thus, they are applicable to handheld computers as well. General guidelines include the following:

- Handheld equipment should not require attachment to an electrical outlet.
- The equipment should be equipped with a means (such as a string, strap, or clip) to attach the device to the user's body or clothing when not in use so that the equipment does not interfere with the accomplishment of other tasks when not in use.
- The equipment should have a non-slip surface and be shaped so as to prevent it from slipping out of the user's hand.
- Hand held equipment should be used for performing tasks at locations not practical for normal sized equipment.
- Hand held equipment should be small, lightweight and conveniently shaped.
- The display should accommodate expected operational lighting conditions, both high and low illumination.
- Portable equipment should have rounded corners and edges.

Handheld, portable, and wearable computers have several design features that dictate whether they are appropriate for use in particular situations. These devices vary considerably along several dimensions, which affect their suitability for different tasks. Each device has advantages and disadvantages, which should be considered relative to the intended use. In the sections that follow, we present the most important human factors considerations associated with these devices.

3.1 Size and Weight

A primary human factors consideration for a handheld, portable, or wearable device involves its physical or ergonomic aspects. Users must be able to hold, transport, or wear the device, possibly for extended periods of time. The appropriate physical dimensions for such devices are based on the knowledge of the size, strength, reach, etc., of the existing population of users. The FAA uses ergonomic design standards based on the capabilities and limitations of the 5^{th} percentile female through the 95^{th} percentile male (Ahlstrom & Longo, 2003). Devices must meet the physical requirements of users through this range. MIL-HDBK-759C (Department of Defense, 1995), recommends that hand-held equipment should not weigh more than 5.1 pounds (2.3 kg) and should be capable of being held and operated with the same hand. These devices should be smaller than 4 inches (100 mm) high, x 10 inches (255 mm) long, by 5 inches (125 mm) wide.

3.2 Computer-Human Interface

Another critical consideration involves the CHI of the device. The CHI may include a keyboard, a touch screen, or speech-based interaction. The CHI also involves the specific interaction elements such as display type and size, character sizes, fonts, colors, etc. Identifying a device with an appropriate CHI is essential for meeting basic user requirements. For example, if a device is to be used to read documents or manuals or view detailed images, one with high display resolution is preferable because it will result in better readability. Higher screen resolutions help minimize the differences in readability between different types of displays (Sanders & McCormick, 1993; Ziefle, 1998).

3.3 Environmental Conditions

Another important consideration in device selection involves the environmental conditions under which the device is to be used. For example, ambient lighting levels affect the visibility of many displays, some more so than others. Devices vary in their suitability for low or high ambient illumination. Some screens feature backlighting which can enhance visibility of the screen contents in dim illumination. Some feature glare filters, which can enhance visibility in high illumination. Devices that are intended for use in high ambient light conditions should have glare filters, and devices that are intended for use in low light conditions should have backlighting sufficient to allow the users to perform the intended task.

Other conditions, such as heat, humidity, changes in air pressure, and dust, can affect the performance of certain devices, making them less useful in some environments. Such conditions would call for more rugged devices that are better able to withstand extreme environmental conditions.

3.4 Ruggedness and Durability

If more rugged devices are required, it is important to evaluate what aspects of durability are relevant. Typically this includes resistance to temperature and humidity extremes, resistance to vibration, shock, dust, chemicals, and resistance to damage if dropped. Any manufacturer claims about device ruggedness need to be evaluated with respect to available standards to ensure validity. Different standards are available depending on the conditions specific to the intended operational environment. For example, a device that may be left in the car may need to withstand high temperatures and a device that will be used outside may need to resist high humidity.

Military standard, MIL-STD 810F (Department of Defense, 2000), specifies standards for mobile devices primarily with respect to their ability to withstand shock and vibration, and their ability to perform safely in hazardous conditions. This standard specifies that a laptop computer should withstand a four foot drop on all sides to concrete and still operate properly. The computer should also operate properly in temperatures as low as -22° F (-30° C) and in hazardous environments (e.g., near flammable gases, vapors, etc.) as indicated by the "intrinsically safe" (I-safe) approval rating. It must be noted, however, that I-Safe certification is environment specific for each device, and a rating in one category may not be equivalent to a rating in another.

Other measures of ruggedness and durability include Ingress Protection (IP) ratings, defined by the International Electrotechnical Commission (IEC) as a device's ability to allow materials to penetrate. Higher numbers indicate better protection. Manufacturer's ratings must also be certified by an independent organization for verification. The National Electrical Manufacturers Association (NEMA) (n.d.) also provides standards for electrical enclosures and the types of environments in which they can be appropriately used (see http://www.nema.org/).

Another way of protecting a device from environmental stressor is by providing a cover to protect the sensitive parts of the device. MIL-HDBK-759C (Department of Defense, 1995) recommends that portable equipment have hinged, permanently attached covers. This is an increasingly common feature found on cellular phones. Often referred to as the clam shell design, the phone folds in half to protect the liquid crystal display (LCD) screen from dirt, damage, and prevent unintended activation (dialing) of the phone.

3.5 Physical Manner of Use

The physical manner in which the user is expected to work with the device is also important for appropriate selection and use. While an advantage of portable and handheld devices is that users are not constrained to a workstation or desk, this flexibility also means that some portable devices will be better suited to particular tasks than others. For example, some tasks may require the user to work while sitting, standing, or in a prone position, to enter data while moving around the work environment, or to have his or her hands and/or eyes free to manage repairs.

4. General Ergonomic Guidelines for Handheld, Portable, and Wearable Devices

The increased use of portable devices has resulted in an increase in ergonomic problems for users (e.g., Smith, Carayon, & Cohen, 2003). There are currently few specific standards and guidelines for most of these devices. Smith et al. (2003) indicate that while considerable work has been done to develop appropriate standards and guidelines for desktop workstations (e.g., seating, lighting), little has been put forward for portable devices, whose means of interaction can vary quite substantially from more traditional systems. For example, some portable devices rely on the thumb for primary data input (Pascoe, Ryan & Morse, 2000). This method allows the user to hold the device in one hand, freeing the other hand for other tasks, but may result in tendonitis, which doctors have attributed to overuse (Brasington, 1990). Sufficient data is not yet available to determine safe limits on the use of the thumb for interacting with computer devices in this manner.

Villanueva, Jonai, and Saito (1998) compared some of the postural differences associated with laptop use to desktop computer use. They found that, “viewing and neck angles became progressively lower and the trunk became more forward inclined” when laptops were used. Neck muscle activity (as measured via Electromyography) was higher, discomfort levels increased, and keying was more difficult when users worked with laptops. Saito et al. (2000) provided recommendations for laptop use that essentially involved creating a work environment that parallels the one available when the desktop is used (e.g., appropriate lighting, work posture). Information for other types of portable devices and work environments is not as readily available.

Most portable devices are designed to be held in one or both hands. As seen in Figure 1, PDAs are generally held in the palm of one hand with the fingers and thumb curled around the device. A stylus is held in the other hand to enter data. Although some PDAs have been set up with specialized software to allow one-handed use, the current size and shape of most PDAs may not allow all users to accomplish one-handed input comfortably. BlackBerrys© are often held in both hands with the thumb of each hand used to enter data via the keyboard. Crossover devices, called smart phones, are emerging which combine aspects of cellular phones, computers, and PDAs that can be held in one hand while the thumb of that hand also enters data. Tablet personal computers (PCs) are larger devices usually held resting across one forearm with the fingers wrapped around the edge of the device. The other hand holds the stylus used to enter data.

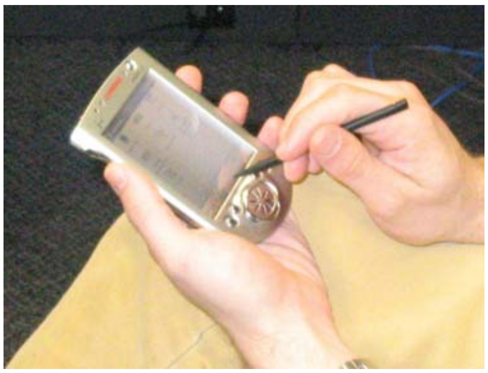

Figure 1. Typical interaction with a PDA, held in one hand with stylus in the other.

Other devices are designed to be worn rather than carried. However, the addition of weight to the body can result in changes in posture and alter movement and stability. Baber, Knight, Haniff, and Cooper (1999) describe ergonomic issues related to wearable devices and provide some guidelines for their use. Weight, size, and device design must be considered as well as placement on the body. Heavier devices are typically more suitably worn around the waist. However, this can cause users to alter their posture and can restrict the movement of the users' legs and torsos, making these devices poor choices if users need to bend or reposition themselves frequently. Additionally, this type of device is not likely to be feasible for many Technical Operations users who already carry other equipment around their waists (e.g., tool belts).

Some wearable devices are designed to be worn on the arm or wrist, where positioning is an important consideration. The closer the devices are worn to the hand or wrist, the more muscle activity and force are required to move them, even when the devices are fairly low weight (e.g., 3-5 lbs or 1.4- 2.3 kg). Yet, for viewing and access, locations closer to the hand and wrist are preferable (Baber et al., 1999). PDAs that are the size of watches are already commercially available and used in this manner.

5. Issues and Guidelines for Handheld, Portable, and Wearable Computers

Handheld, portable, and wearable devices are continuing to evolve. The distinction between types of devices is becoming blurred, with a trend towards an integration of computer features with cellular phones. Given the many variations on handheld and wearable devices, it would be nearly impossible to cover all variations in detail. Therefore, this section will present some of the advantages and disadvantages of the more common handheld and wearable devices including PDAs, BlackBerrys©, compact computers, and tablet PCs.

The number of features that are available in each of these device categories is increasing, with many systems now including photographic and video recording capabilities. Based on the input from subject matter experts described earlier in this document, these features could be useful for technicians involved in providing remote assistance. Temin (2002) describes a video-enabled system designed to allow Navy technicians to troubleshoot and repair Tomahawk missile launching systems on aircraft carriers. Using video, Navy personnel transmitted images to maintenance experts who were able to guide them through a repair process. The biggest problems noted in making this operationally feasible were in ensuring security and transmitting video into small bandwidths available on the ships.

5.1 PDAs

5.1.1 Size

Most PDAs are approximately 3 x 5 inches (7.6 x 12.7 cm) and weigh between 4 to 8 ounces (113 to 227 grams).

5.1.2 Input Method

The primary input method for most PDAs is via a touch screen and stylus. Data may be input using either a virtual keyboard on the touch screen or through handwriting/character recognition using the stylus. Although many different layouts have been suggested for virtual keyboards, MacKenzie, Zhang, and Soukoreff (1999) found that the QWERTY layout (found on most traditional keyboards) allowed the fastest rate of data input.

While PDAs can accept handwritten input, this feature is not without its drawbacks. Handwriting recognition systems are not error free. Accuracy rates range from about 85 - 93% (Bohan, 2000a). At an input rate of about 16 - 18 words per minute (Bohan, 2000b), this method is slower than input via a virtual keyboard using a touch screen and stylus or a standard keyboard (Lewis, 1999). Additionally, using a handwriting recognition system typically requires some initial training, so that the device can become accustomed to the user's style of writing and can recognize character strokes. Handwritten input may require the user to learn a specialized alphabet (e.g., Palm's Graffiti system; Microsoft's Jot system), although many users are willing to spend the time needed to learn the new alphabet to ensure reliable data entry and find this data entry method acceptable (MacKenzie & Zhang, 1997; Schneiderman, 2003). It can be difficult for users to write due to space limitations on the input area (Lewis, 1999). Add-on keyboards (either wireless or attachable) are often available, though many are not full-size, and have small, closely spaced keys, which fall below the recommended minimum key size of 12 mm (.47 in) and minimum inter-key spacing of 18-19 mm (.71-.75 in) (Ahlstrom & Longo, 2003). These keyboards can be useful for periodic data entry, but are not recommended for frequent or continuous data entry. Full size keyboards that are available as PDA add-ons provide the most rapid and familiar means of data entry. However, they require a work surface, thereby eliminating some of the reasons why the device may have originally been selected.

5.1.3 Display

Most PDAs have LCD screens that are about 2.8 inches wide by 4 inches long (7.1 x 10.16 cm). The resolution of the screen varies across devices. Most PDA displays have 240 x 320 dots per inch (dpi) but some have higher resolutions. Some models have color capabilities, while others are monochromatic. The standard type size is 10-point font and is typically not user-changeable. A full PDA screen holds about 11 lines of text and approximately 35 characters per inch (cpi) from left to right.

5.1.4 Advantages

A clear advantage of PDAs is their small size and low weight. Many PDAs have docking stations which allow quick and easy transfer of data from the PDA to a desktop computer and back.

5.1.5 Disadvantages

Limited applications and storage capabilities - PDAs are limited in terms of the number of applications they provide and in their ability to store information. This may restrict their usefulness for meeting the needs of users who need to access, store, and transmit detailed documents or other large files. Smart phones are often seen as a replacement to PDAs because they offer the functionality of a PDA and a phone in a single device, and offer additional features such as built in cameras and voice recording capabilities.

Small screen size - One of the biggest concerns about PDA usability relates to its small screen size. The display area is limited and may be too small to effectively display detailed text and graphics. For specialists who must access manuals and maintenance resources, these devices are not likely to adequately meet their needs.

Low resolution and contrast - The low resolution and low contrast of many models reduces image quality. Chung, Kolatch, Sculimbrene, and Wen, H. (2000) conducted a study comparing legibility/readability of targets across a PDA, a tablet PC, and a laptop computer and found that it took significantly longer to locate targets on the PDA than on the other devices, though accuracy did not differ between them. Users also found the text on the PDA more difficult to read. Kim and Albers (2001) found similar results. They required users to search for target information on pages consisting of 100 to 850 words on either a standard desktop or a PDA. Users were significantly slower using the PDA, though accuracy was not affected.

Albers and Kim (2000) indicate that in addition to readability concerns, navigation on the PDA is a problem. Users need to scroll more, both horizontally and vertically, in order to access information on pages designed for larger displays. The inability to see a page in its entirety requires users to remember the location of links and data, and reduces their ability to use a document's "landmarks" to help them navigate. Unless specifically adapted for the PDA, some web sites may be nearly inaccessible. As an example, one on-line resource available for maintenance technicians can be found at http://technet.faa.gov/, which provides information on NAS status, delays, alerts, outages, etc. Detailed tables of information appear in small font size on many of the web pages. Site navigation and data entry would be difficult with a PDA because of the small size of the links and entry fields, and because of the proximity of the links and entry fields to one another.

Requires two-handed operation - PDAs are generally used while held rather than placed on a surface, with one hand holding the device and the other holding the stylus. Thus, the user is not able to manage other tasks while interacting with the device, making it unsuitable for some users or in certain work situations.

Some specialized applications for PDAs are designed to allow the devices to be used with one hand via thumb touch screen input (Pascoe et al., 2000), though this method of input is not widely used. Although using the thumb for data entry may allow one-handed operation, as shown in Figure 2, it changes the type of grip used to hold the device, which may introduce other ergonomic concerns.

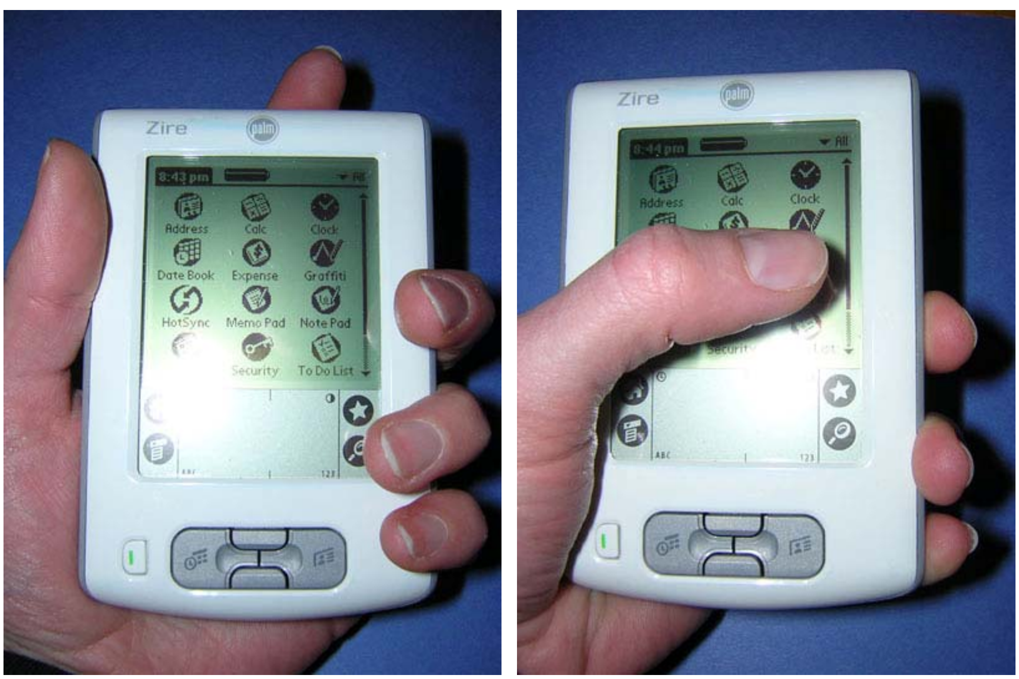

Figure 2. Normal grip (left) and thumb input grip (right) of a PDA.

May require substantial heads-down time - PDAs have on-screen interaction capabilities, allowing the user to select letters, digits, icons, and other options by choosing the appropriate targets on the screen. This method requires that the user direct visual attention to the screen, resulting in increased "heads down" time. This is a problem if the maintenance task requires users to be looking and attending elsewhere to carry out troubleshooting activities.

Difficult data entry - Data entry with touch screen and stylus is more error-prone and cumbersome than keyboard data entry (Goldstein, Book, Alsio, & Tessa 1999; MacKenzie & Zhang, 1997). Though full-size, foldable keyboards are now available for PDAs, making data entry easier, they require that the PDA be placed on a surface. Although these external keyboards can improve data entry ease and speed, they are not always used on a desktop surface. The desktop computer is preferred for frequent or continuous data entry because it allows the user to adopt ergonomically correct postures (Straker et al., 1997).

5.2 Smart Phones

Smart phones integrate aspects of a PDA and a cellular phone into a single device (see Figure 3). They generally have a standard telephone keypad for both numeric and alphanumeric input rather than a miniaturized QWERTY keyboard. Smart phones often come with additional features such as integrated cameras and voice recording capabilities. They usually have smaller screen sizes than PDAs.

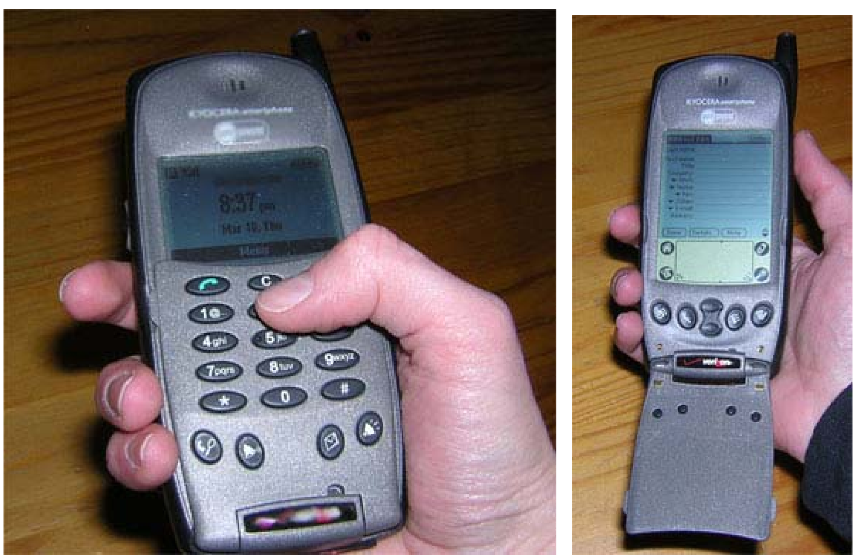

Figure 3. Smart phone shown closed (left) for phone use and open (right) for PDA use.

5.2.1 Size

These devices are the same size as most cell phones and are designed to fit in the palm of one hand.

5.2.2 Input Method

The input method for this device is the standard telephone keypad or stylus. The keys are small, which may cause difficulty for users with larger fingers. Users enter alphanumeric data using a multi-tap method, e.g., hitting the key once for the first letter, twice for the second letter, etc. on the numeric key. Some phones have "autocomplete" features for frequently used words that speed the data entry process. Autocompletion of text based on frequently used words can significantly increase the speed for data entry on multicharacter keyboards such as these (Kreifeldt, Levine, & Lyengar 1989).

5.2.3 Display

The display size for this device is often smaller than that of a PDA because the keyboard takes up part of the device. Most devices have color screens.

5.2.4 Advantages

Smart phones are small and lightweight, making them easy to transport. They combine cellular phone and data entry into a single device so that users do not have to carry two devices, and they can be used with one hand. Some smart phones have a clamshell design, which protects the screen from the accumulation of dirt and debris and helps to prevent accidental activation.

5.2.5 Disadvantages

The screen size on a smart phone is usually smaller than that on the PDA. Resolution and contrast are also limited, and in many cases are not as high as they are on a PDA. As a result, the problems noted for the PDA screen size are even more apparent with smart phones.

5.3 BlackBerrys©

BlackBerry© devices combine aspects of a PDA and a cellular phone into a single device, and are similar to smart phones. Unlike a smart phone, BlackBerrys© come with a reduced size QWERTY keyboard and a thumb-operated trackwheel rather than a phone keypad. They are designed to be held in both hands with the thumbs of both hands operating the keyboard and trackwheel. The screen size is usually smaller than that on a PDA.

5.3.1 Size

These devices are similar to a PDA in size and weight (3 x 5 inches [7.6 x 12.7 cm] and 4 to 8 oz. [113 to 227 grams]).

5.3.2 Input Method

The data entry method for a Blackberry© is via a miniaturized keyboard and a trackwheel. The keys are small, which may cause difficulty for users with larger fingers. Holding the device with two hands and typing with the thumbs can cause wrist extension, particularly for users with larger hands. Non-neutral wrist positions are also linked with higher carpal tunnel pressure (Rempel, Bach, Gordon, & So, 1998). Although the small keyboard is intended to ease user input, full-sized keyboards are preferable for frequent or continuous data input (Goldstein et al., 1999).

5.3.3 Display

The display size for a BlackBerry© is smaller than that of a PDA because the keyboard takes up part of the device. Screen resolution is usually 240 x 160 or 240 x 240 dpi. Some devices have color screens, while others are monochromatic.

5.3.4 Advantages

The BlackBerry's© advantages are similar to those of smart phones. It is small and lightweight, making it easy to transport and combines cellular phone and data entry into a single device. The reduced size keyboard may be easier to use than a touch screen and stylus. The physical keyboard can be distinguished tactilely, allowing users the ability to enter data without looking at the device, thereby reducing heads-down time.

5.3.5 Disadvantages

The BlackBerry© has many of the same disadvantages as the PDA. The screen size is small and resolution and contrast are limited. In many cases, the screen resolution is lower than that of a PDA. BlackBerrys© also require both hands to hold and operate if used as intended.

5.4 Tablet Computers

Tablet computers are similar in a number of respects to laptops. As a result, the two share a number of human factors considerations. Some tablet computers are essentially laptop computers whose keyboards can be folded back or detached, allowing users to work with them as a slate and accepting handwritten input via a stylus. These models allow users the flexibility of working in a more traditional manner when at a desk or workstation, or using pen-based entry when mobile. Many tablet computers can be used while held, placed on a surface, or worn (e.g., on a belt), though they are often not as rugged as many available models of laptops. However, rugged newer models are emerging (Breeden, 2004). The Air Force recently purchased a number of rugged portable PCs and tablet computers for use by aircraft repair technicians. These users are working with the devices to perform many common technician tasks such as accessing repair manuals and parts inventories, and finding out the status of parts that have been ordered (Jackson, 2004).

5.4.1 Size

Tablet computers are heavier than PDAs, BlackBerrys©, and smart phones, usually weighing from one to seven pounds (.45 to 3.15 kg) and have the approximate dimensions of a clipboard.

5.4.2 Input Method

Tablet computers accept pen-based entry which allows users to write, create sketches, or annotate documents. The pen can also function like a mouse, with switches that enable the user to choose the equivalent of right and left mouse clicks. Typically, a screen protector covers displays that accept pen input to minimize display damage. The pens themselves must be handled fairly carefully to prevent them from being damaged. This feature makes them less rugged than other systems with alternate input devices. Hinckley (2003) reports that users expect pen-based input devices to allow them to select targets on the screen. Therefore, these targets should be large enough to accommodate this capability.

Tablet computers, unless worn, generally require the use of both hands, one to hold device and the other for input (see Figure 4). It is important that a device that is held across the forearm, such as depicted in Figure 4, not produce so much heat as to become uncomfortable to the user.

Tablet computers require the user to devote visual attention to the screen, thus diverting mental and physical resources from other tasks. As a result, this mode of operation may not be a viable option for users who need to have their hands free and attention available for other responsibilities.

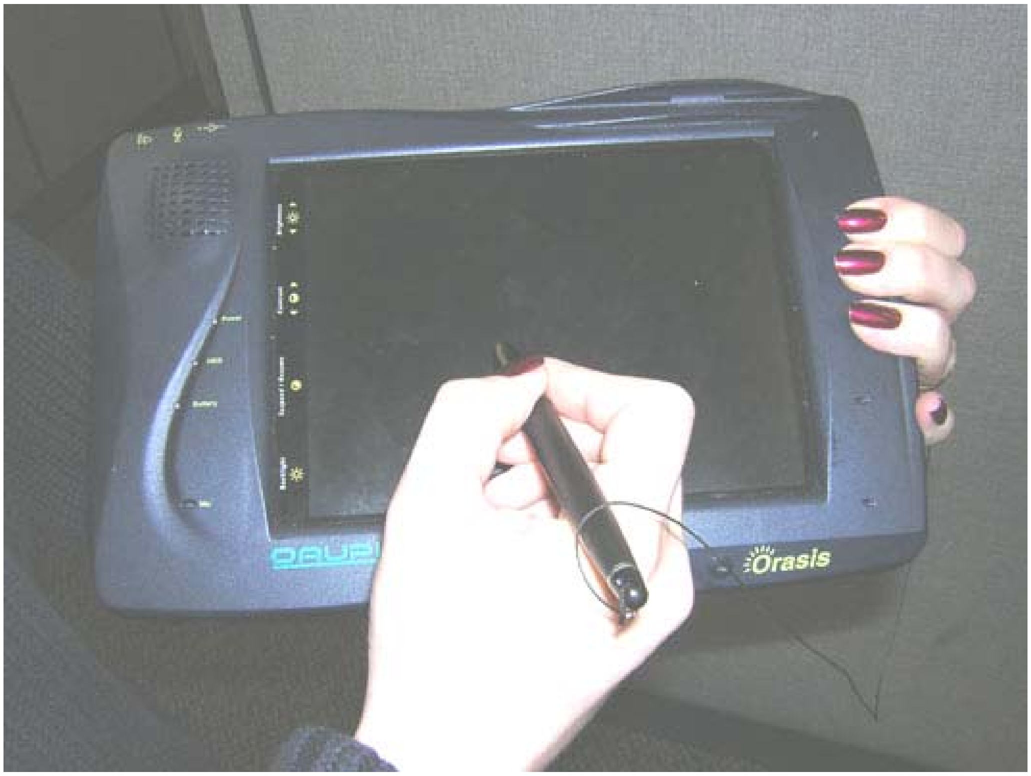

Figure 4. User holding tablet computer with clipboard grip.

Many tablet computers use touch screen interfaces. Hinckley (2003) reported that when touch-sensitive components are added to displays, transmissivity (transmitted light), luminance, and contrast may be reduced, and as a result, display legibility is compromised. Viewing angles may also not be as wide for touch screens as for other types of displays. This is due to parallax that may result when users view the display from off center. Parallax may produce perceptual errors, leading users to assume they are selecting one target when, in fact, they are selecting another. Touch screens are also prone to fingerprints and smears, which can interfere with their operation (Ahlstrom & Kudrick, 2004).

Pen-based entry allows users to create sketches or annotate documents by hand. The pen can also function like a mouse, with switches that enable the user to choose the equivalent of right and left mouse clicks. Typically, a screen protector covers displays that accept pen input to minimize display damage. The pens themselves must be handled fairly carefully to prevent them from being damaged. This feature makes them less rugged than other systems with alternate input devices. Hinckley (2003) reports that users expect pen-based input devices to allow them to select targets on the screen. Therefore, these targets should be large enough to accommodate this capability.

5.4.3 Display

Tablet computers typically have 8-, 10-, or 12-inch (20, 25, or 30 cm) screens, but some models may have screens as small as 5 inches (12.7 cm) or as large as 15 inches (38 cm). The screen resolution of the tablet PC is also higher than that of a PDA, making them better suited for presenting large, detailed information.

5.4.4 Advantages

A major advantage of the tablet computer is its larger screen size. The major difference between the tablet computer and the laptop is its ability to accept input via stylus instead of a keyboard, an advantage if the task requires the user to select items from lists or drop down menus.

5.4.5 Disadvantages

The larger size and weight of the tablet computer may make it difficult for users to hold or carry the device for extended periods of time. The user typically holds the device across the forearm of the non-dominant hand, using the fingers to grip the edge of the device (i.e., the "clipboard grip"). This grip can be difficult for users to sustain for long periods of time. The device also requires the user to devote visual attention to the screen. Thus mental and physical resources are diverted from other tasks. This mode of operation may not be a viable option for users who need to have their hands and eyes free for other responsibilities.

Breeden (2003) described a comparison of several models of tablet computers in which ease of use was one of the characteristics evaluated. The most usable model was one that could be used just like a laptop, with touchpad mouse and full-sized keyboard. A disadvantage many models shared concerned the mechanism for storing the stylus. On some devices, it was very easy to dislodge the pen, which if lost, may render the device useless.

5.5 Wearable Devices

Some wearable devices are small PCs or tablet computers that can be worn, typically around the waist. Others, however, are less traditional in both their appearance and functionality, and as a result, "…represent a new paradigm in computing, there is no consensus on the mechanical/software human-computer interface or the capabilities of the electronics" (Siewiorek & Smailagic, 2003). Wearable systems often require fairly substantial amounts of training before users can work with them proficiently. Not all users benefit from such systems or feel comfortable wearing them (Baldwin, 2000). Most wearable devices are designed to be more rugged than standard laptops or tablet computers. They must be large enough to enable adequate usage, but small and lightweight enough to be worn comfortably, particularly by users who are already carrying heavy loads (Daukantis, 2001).

Head-mounted displays are often a component of wearable computer systems (see Figure 5). Head-mounted displays can cover both eyes (for augmented or virtual reality), or can cover a single eye (for ubiquitous computing). Wearable, head-mounted devices have some unique considerations. Some users find head-mounted displays difficult to wear, reporting that they cause strain on the neck, back, and head. Baber et al., (1999) examined ergonomic and performance issues related to a fairly lightweight (4 oz) head-mounted display and found that the users made significantly more head movements when wearing the device to complete a tracking task than when completing the task without it. They also noted that head-mounted devices with monocular displays resulted in additional head movements to see around the areas blocked by the eyepiece. These additional movements can produce greater neck strain and affect posture and gait. The use of these devices has also been shown to affect peripheral vision, causing disorientation and balance problems (Ambard & Carblanc, 1980; Nuclear Regulatory Commission, 1997; Seagull & Gofer, 1994). Head-mounted displays must be adjustable to support diverse head shapes and sizes, and must be lightweight (with the weight centered). The images must be of high quality and binocular displays must be well-aligned.

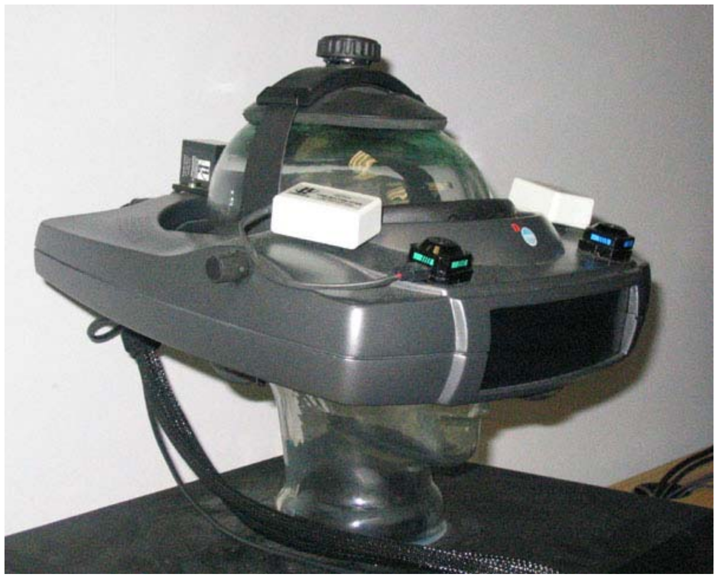

Figure 5. A head-mounted display that covers both eyes.

Gemperle, Kasabach, Stivoric, Bauer, and Martin (1998) provide design guidelines for wearable systems, focusing largely on the dynamic aspects of the user, based on their review of studies on human form and movement. Their guidelines consider the goal of placing the device in a relatively unobtrusive location while still allowing users a wide range of motion. The locations they proposed as most effective were: 1) the collar area, 2) the rear of the upper arm, 3) the forearm, 4) around the ribcage, 5) on the waist and hips, 6) the thigh, 7) the shin, and 8) the top of the foot. Gemperle et al. indicated that the device must be contoured properly for the location on which it is to be worn. They further proposed it helpful to incorporate properties of familiar devices to help make the new wearable device more readily accepted by users. They describe an example of a wearable device they created for aircraft maintenance technicians that included a belt similar to the tool belts these users were already using.

Siewiorek (2001) noted that challenges for wearable devices exist primarily with respect to their input methods. Wearable devices do not accommodate standard size keyboards or traditional mice easily, and these input devices are not suitably portable. Therefore, other input methods are needed. One possibility is a wearable mouse, utilizing a touchpad, similar to that used on some laptop computers. Wearable devices with touch screen interfaces are being used by aircraft maintenance technicians in the field (Wood, 2002). Thomas, Grimmer, Makovec, Zucco, and

Gunther (1999) and Thomas, Grimmer, Zucco, and Milanese (2002) evaluated user performance on a target selection task using a wearable touchpad mouse and a head-mounted display screen. The touchpad was placed on several different locations on the user's body: 1) the upper arm, 2) the torso, and 3) the front and side of the thigh, and while the user was in different postures: 1) sitting, 2) standing, 3) kneeling, and 4) prone. Measuring both task accuracy and speed, they found that, overall, the forearm was the best position for the device if it needed to be used in all four positions. Touchpad placement at the front of the thigh worked well while users were sitting, kneeling, and standing. The torso was the poorest location for the touchpad. Overall, performance was significantly worse while users were prone than when in other positions.

Speech-based interfaces are used as an alternative to keyboard or touch screen entry by some wearable devices. Speech entry typically requires fewer steps than traditional keyboard entry, potentially making systems that integrate them more efficient. This method also allows for hands-free operation. However, speech technology also can result in a lower accuracy rate, difficulty in correcting errors, and sometimes longer system response times (Smailagic & Siewiorek, 1996). Specific considerations and guidelines for speech-based interfaces can be found in Ahlstrom and Longo (2003).

6. Summary and Recommendations

General considerations for handheld, portable, and wearable device selection include the need for users to be able to hold and operate the device comfortably. The device should accommodate the physical characteristics of a wide range of users (i.e., 5^{th} to 95^{th} percentile) in critical dimensions, such as strength. The device must also have an acceptable battery life and be suitably rugged, depending on the extremes expected in the work environment. Network/internet connectivity problems and interference from other nearby devices must also be evaluated.

When choosing a device, the user, task, and work environment must be well understood for the most appropriate selections to be made. When systems are appropriately matched to the target user group, productivity and efficiency can be maximized. Choosing a device that is not well matched to the user and his needs can result in fatigue, strain, frustration, and confusion, and lead to lower efficiency and increased error.

FAA Technical Operations specialists have varied responsibilities and work in a range of environments, though most need to access detailed text documents and images, and often need to transmit files to one another. As a result, each of these user groups is likely to benefit more from devices with larger screens that offer better contrast and resolution. Differences between these users are most evident with respect to their work locations. Some work indoors, in dark, small, and crowded spaces, while others work outdoors. Indoor areas may be too small to adequately or safely accommodate wearable devices. Some specialists who work in these environments even forgo wearing watches, rings, belts and other "wearables" because of their potential to catch on equipment. Head-mounted displays may also not work well in these environments because of space limitations and because many users are already wearing head-mounted light systems to navigate through and work in these areas. The indoor facilities, however, often do provide surfaces on which devices can be placed, and may also have power sources nearby or LAN connectivity available, making a laptop or similar device suitable.

Users in outdoor environments, on the other hand, need to select devices that do not need to be used on surfaces, are legible in bright sunlight, have longer battery life, and can withstand a harsher set of environmental stressors. These devices must be rugged (resistant to bumps and drops), water resistant, and operate in a wider range of temperature and humidity extremes. Given the differences between these user groups, it is unlikely that a single device will match the needs of all of the users. A human factors evaluation should be conducted with representative users performing representative tasks to determine which device best meets each groups' needs.

This document presents the pros and cons for some of the more common handheld and wearable computer devices. By presenting the pros and cons of these devices, we hope to help FAA decision makers make informed choices.

Many of the recommendations within this document are device-specific. Others are more general. Some of the general recommendations for these types of devices are as follows:

- Devices must have an easy means of connecting to and transferring data to or from other systems.
- Devices should have good legibility and color contrast, and be easy to learn.
- Devices should have sufficient screen size and that resolution for the task.
- Devices should be sufficiently durable to withstand drops and knocks associated with normal use.
- Devices must have sufficient battery life for task completion.
- If the device is used to transmit data over a wireless network, it should have consistent and available connectivity.
- Areas which the user may come in contact with on handheld or wearable devices should not produce so much heat as to be uncomfortable to the user.
- If a stylus is used, it should be attached to the device.
- Handheld equipment should not require attachment to an electrical outlet (DoD, 1995).
- The equipment should be equipped with a means (such as a string, strap, or clip) to attach the device to the user's body or clothing when not in use so that the equipment does not interfere with the accomplishment of other tasks when not in use (DoD, 1995).
- The equipment should have a non-slip surface and be shaped so as to prevent it from slipping out of the user's hand (DoD, 1995).
- Hand held equipment should be used for performing tasks at locations not practical for normal sized equipment.

- Hand held equipment should be small (less than 4 x 10 x 5 inches), lightweight (less than 5 pounds) and conveniently shaped (DoD, 1995).

- The display should accommodate expected operational lighting conditions, both high and low illumination.

- Devices should have hinged, permanently attached covers.

- Portable equipment should have rounded corners and edges (DoD, 1995).

- Head-mounted displays must be adjustable to support diverse head shapes and sizes, must be lightweight, with the weight centered. The image must be of high quality and binocular displays must be well-aligned.

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Acronyms

AMT	Aviation Maintenance Technician
CHI	Computer-Human Interface
cpi	characters per inch
dpi	dots per inch
FAA	Federal Aviation Administration
FSS	Field Service Specialist
HCI	Human-computer Interface
HFS	Human Factors Specialist
IEC	International Electrotechnical Commission
IP	Ingress Protection
LCD	Liquid Crystal Display
NAS	National Airspace System
NEMA	National Electrical Manufacturers Association
PC	Personal Computer
PDA	Personal Data Assistant