AN ELECTROPHYSIOLOGICAL ASSESSMENT OF MENTAL FATIGUE DURING LCD VERSUS E-INK READING

by

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ABSTRACT

Early research comparing print versus electronic reading found that reading from screens leads to cognitive deficits across many dimensions. However, recent studies suggest that modern high definition displays may eliminate these deficits, despite users still rating print as preferred. The current study combined EEG and questionnaires to assess cortical arousal as an index of mental fatigue, as well as subjective visual fatigue and mental workload. College students rated their preference for electronic or print reading and participated in two sessions, each consisting of two 30-minute blocks of continuous reading while EEG was recorded. All subjects read from print in one session, and either an LCD or E-Paper device in the other. There were no effects of reading medium in any subjective report or EEG measure, despite subjects reporting an overwhelming preference for print reading. However, subjective results did show increased visual fatigue and decreased arousal over time, regardless of reading device. In agreement with recent studies, these results suggest that any deficits to high definition electronic reading may be purely due to subjective preference rather than differences in cognition. Subsequent EEG computations and statistical analyses could reveal more intricate time-sensitive or electrode-dependent differences between reading mediums.

I. INTRODUCTION

In recent years, developments in computer technology have led to the personal computer becoming more affordable, powerful and accessible than ever. Handheld computing devices such as tablets and smartphones are now completely integrated into the daily lives of individuals in the first world. These major changes in human access to computing technology have brought forth many questions as to how humans consume digitally presented information. Is digitally presented information remembered as well as printed information? Do people learn and comprehend what is presented on a computer screen the same way as print? Is reading from computer screens somehow slower or more fatiguing than reading from paper? These questions, among others have been a popular area of interest for human factors and ergonomics researchers.

Along with the evolution of computers over the past few decades, display technologies have also shown significant transformation. Early research occurred when the cathode ray tube (CRT) screen technology was prevalent. The 2000's featured the introduction of liquid crystal display (LCD) which would take over as the most predominantly used screen technology. Recently, electronic paper (e-paper) has emerged as a popular technology used in handheld reading devices. Overall, modern visual display units (VDUs) are of higher image quality and resolutions than ever before, regardless of the technology used. According to Gould, Alfaro, Finn, Haupt, and Munito, (1987), image quality is likely the single most important factor that causes differences in electronic reading versus print. With this in mind, it is important to continue research in this area to see if these improvements in image quality have made up for the deficits found in prior research. This chapter will provide a comprehensive review of the literature that has examined differences in reading from screens versus reading from paper. Research in the field will be described chronologically, first addressing early research which used CRT technology and then comparing those results to modern research which employs the newer LCD and e-paper technologies.

Early Research

Early research explored the nature and potential causes of differences in reading from VDUs versus paper. Dillon, McKnight and Richardson (1988) published a comprehensive review of the significant research in the field that had been done at that time. Many of the articles discussed in his review did not specify the types of VDUs that were used. However, because of the prevalence of CRT technology at the time, it can be assumed that this is what was used in most, if not all of the studies during this time. Dillon et al. (1988) identified 5 major differences between the two reading mediums, citing many studies that suggested that reading from VDUs is “slower, less accurate, more fatiguing, decreases comprehension and is rated inferior by readers” (p. 457). They also sought to find the causes of these differences, proposing variables such as screen dynamics, display polarity, orientation, viewing angle and user characteristics. Ultimately, Gould et al. (1987) suggested that the overall image quality - a product of the interaction between many variables - is the most important factor influencing performance differences between the two mediums.

Speed

Perhaps the most common finding was that reading from VDUs is 20-30% slower than paper, although this difference was less than conclusive. While this conclusion was supported by many studies, Dillon et al. (1988) criticized the disparities in procedure across these studies. The studies reviewed had vast differences in text and background color, text size, viewing distance, room lighting, image quality, or did not report many of these critical variables. However, despite the varying procedures, Gould et al. (1987) claimed that the evidence supporting slower VDU reading is robust.

Accuracy

To examine accuracy, early studies used proofreading exercises to look for possible differences between the two mediums. The findings for this variable were also less than conclusive. Dillon et al. (1988) gives examples of numerous studies both supporting and denying any differences in accuracy between the two mediums. Because many of these results come from the same studies as previously mentioned, the same criticisms in procedure apply. In addition to the variations in procedure, the measurements of accuracy also widely varied. Gould and Grischkowsky (1984) asked participants to identify the misspellings of words, but this method was criticized by Wilkinson and Robinshaw (1987), who claimed that this method did not accurately reflect the task of proofreading. They instead used a task of searching for five error types: missing or additional spaces, missing or additional letters, double or triple reversions, misfits or inappropriate characters, and missing or inappropriate capitals. They claimed that this is a more relevant task of proofreading than the one used by

Gould and Grischkowsky (1984). Creed, Dennis and Newstead (1987) on the other hand, made distinctions between visually similar errors, visually dissimilar errors, and syntactic errors. They claimed that this method covered some of the shortcomings of the previous studies' procedures by requiring the reader to visually discriminate, as well as rely on grammatical knowledge when proofreading. Dillon et al. (1988) concluded that performance deficits are more likely to occur during more visually or cognitively demanding tasks rather than for routine spelling checks.

Fatigue

Dillon et al. (1988) also reviewed studies examining possible fatigue differences between the two display mediums. Gould and Grischkowsky (1984) had subjects perform six 45-minute work periods using CRT monitors and hard-copy in two respective study sessions. They found no differences in responses on a 16-item 'Feelings Questionnaire' that asked subjects to rate symptoms of fatigue. This supported several other findings which concluded that VDUs themselves do not produce fatiguing effects (Muter, Latremouille, Treurniet & Beam, 1982; Sauter, Gottlieb, Rohrer & Dodson, 1983; Starr, Thompson & Shute, 1982). However, other studies disputed these findings. Cushman (1986) compared positive (dark text, light background) and negative (light text, dark background) presentations with paper. He found that users reading from positive presentation VDUs had more general fatigue than paper, and had more visual fatigue than from negative presentation VDUs. Cushman attributed this fatigue increase to image flicker, which is an inherent characteristic of CRT displays. Image flicker refers to a persistent visual artifact created by an image being rapidly refreshed on the screen.

Cushman notes that the monitors used had a refresh rate of 60 Hz, which was typical of most VDUs at this time (refresh rate refers to how frequently the image is refreshed on the screen, with higher rates leading to less noticeable flicker). Wilkinson and Robinshaw (1987) also found significantly higher fatigue from VDUs, and explained that no subjects reported lack of clarity or flicker, and that their VDUs were typical, normal VDUs that many people would read from. They criticized the study by Gould (described above; 1984) as having equipment that was "too good to show any disadvantage" and that they used an artificial measurement of fatigue. Gould took fatigue measurements *after* a task, and across a working day, missing the effects of fatigue *during* a working session. Wilkinson's results showed performance decrements during a 50-minute task, suggesting that extended periods of reading from VDUs likely leads to greater fatigue. Dillon concludes that VDUs alone aren't necessarily fatiguing, but that performance levels are difficult to sustain over time when reading from average quality screens.

Comprehension

At the time of Dillon's review, surprisingly few studies examined possible differences in comprehension between the different reading mediums. Dillon states that analyzing comprehension is a difficult task because it is difficult to measure; one must be careful that post-task questions aren't simply assessing recall skills. Muter et al. (1982) gave 25 multiple-choice questions to subjects after two 1-hour reading sessions. They found no differences in comprehension between presentation mediums. Studies by Kak (1981) and Cushman (1986) had similar findings, with Cushman adding that slower readers had higher levels of comprehension. Dillon et al. (1988) concludes that there aren't significant differences in presentation medium on comprehension, but notes the lack of a proper measurement of comprehension as a possible reason for the lack of findings.

Preference

When comparing the discussed research to the present day, perhaps an even greater difference than the drastic improvements in display quality are the changes in user experience levels and attitudes towards computers. Many of the individuals who participated in the research described were novice users. According to Dillon et al. (1988), the folklore in the human factors field is that inexperienced users dislike using computers, causing possible contamination of the results of preference ratings. On the contrary, Cakir, Hart and Stewart (1980) studied the preferences of 800 VDU operators and found that even amongst these VDU-experienced users, high-quality typewritten hardcopy is still rated superior. Considering the combination of changes in image quality and user experience and behavior, preference is perhaps the variable that is most subject to change when conducting modern research.

The review by Dillon et al. (1988) provides a solid foundation in this area laid by researchers in the 1980s. Dillon himself claims that these measurements and methods are not an "end all, be all", but these studies do provide us with a contextual basis for which to conduct new research. As previously mentioned, one must take into account two major considerations when thinking about how this research relates to today. Firstly, the VDUs used in these studies are very different from what is now predominant. While CRT monitors dominated the tech-market in the 1980's and 90's, LCD is now the most commonly used technology. Whereas LCDs and CRTs both have strengths and weaknesses, this shift was due to LCDs featuring a much slimmer profile and consuming much less power than CRTs. While LCDs don't necessarily exhibit higher quality images than CRTs, advances in display technology have led to modern screens having far superior image quality than those used in the past. Secondly, and perhaps even more importantly, the users between these two time periods have vastly different VDU experience levels. Belmore (1985) suggested that the performance decrement he found was due to the participant's lack of experience and familiarity with computers and reading from VDUs. In fact, most of these studies did not attempt to use regular computer users as the sample. Today, any typical sample will naturally include a majority of participants who have plenty of experience using computers and reading from electronic screens.

Later Approaches

Noyes and Garland (2008) conducted a review similar to that of Dillon et al. (1988), but at a later time period. Not only are these studies more relevant because of the use of newer technology and more experienced users, but the research methods and performance assessments have also been refined. Despite these refinements, these studies have also found inconsistencies. A study by Mayes, Sims and Koonce (2001) found that VDU reading took significantly longer than paper, supporting Dillon et al.'s (1988) prior conclusion of slower reading. However, there is contrasting evidence for possible comprehension differences in these newer studies. Many studies have found no differences in comprehension between the two mediums (Mason, Patry, and

Bernstein, 2001; Mayes et al. 2001; Noyes & Garland 2003; van De Velde & von Grunau, 2003; Bodmann & Robinson, 2004; Garland & Noyes 2004), but Wastlund et al. (2005) found that comprehension was greater with paper. Noyes and Garland (2008) stated that due to the lack of consistent findings when directly comparing speed and accuracy, research should focus towards more comprehensive metrics which measure overall performance during tasks (such as online test taking assessments).

Cognitive Performance

Ziefle (1998) ran two experiments examining the possible effects of CRT display resolutions on visual performance. Their first experiment measured possible speed and accuracy differences between 2 CRT resolutions, and a paper condition. The CRT conditions had resolutions of 60 dpi (832x600 pixels) and 120 dpi (1664x1200 pixels), while the paper condition had a higher resolution of 255 dpi. While there were no significant differences between the two CRT resolutions, reading from paper was significantly faster than either CRT condition. Ziefle suggests that while one may attribute the benefit of paper to the much higher resolution, there are other inherent physical differences between the two mediums. Prior research states that information processing is impaired by image flicker and phosphorescence effects (Kennedy & Murray, 1993; Krummenacher, 1996) from CRT displays. Furthermore, CRTs emit light directly from the display, while paper simply reflects natural light from the environment. The second experiment by Ziefle examined effects of 3 different CRT resolutions on eye movement patterns during a visual search task. The conditions featured resolutions of 32 dpi (720x540 pixels), 69 dpi (800x600 pixels), and 89 dpi (1024x768 pixels), respectively. Search reaction times and subjective reports of fatigue were also measured. Subjects in the low resolution condition had slower reaction times and longer eye fixations, supporting the idea that lower resolutions lead to stronger fatigue. Because of this, Ziefle recommends using high resolution displays (90 dpi and greater) to avoid performance deficits and visual fatigue.

A study by Mayes et al. (2001) compared VDUs to paper in terms of reading speed, comprehension, and workload measures. In contrast to the early studies mentioned in this review, Mayes made a point to ensure that the text presented on the two mediums was as similar as possible. They attempted to match the resolution, character size, color, and visual angle across the two mediums. Early research was replicated in that the VDU group read significantly slower than the paper group. They conducted a second study in order to see if the slower reading time was due to an increase in use of the cognitive resources involved in working memory. This study introduced a new condition in which half of the participants would perform a working memory task of hearing and recalling a list of letters that is read to them during reading, inducing more memory load in these participants. They found that those reading from VDUs and under a working memory load, indeed performed somewhat lower on comprehension scores, indicating that VDUs may reduce the capacity for working memory. These results were especially important given the improvements in VDU quality and the presentation matching method used by Mayes. Considering that resolution, character size, color, and visual angle were matched across reading conditions, the only remaining uncontrolled variable between the mediums other than ‘page-turning’ are the inherent physical differences between them (contrast, luminance and refresh rates). Noyes and Garland (2003) argue that these differences are what interfere with cognitive processes and lead to decreased performance.

In response to the study by Mayes et al. (2001), Noyes and Garland (2003) examined possible differences in the two mediums in regards to reading speed, correct answers, and a memory retrieval measure. In order to measure memory retrieval, they used the Remember-Know learning paradigm (Tulving, 1985), a means of distinguishing two main types of recognition memory. According to this paradigm, to ‘Remember’ is to recall knowledge from contextual information such as the event in which it was remembered. To ‘Know’ is to recall information without any such associations. While Noyes and Garland (2003) found no differences in presentation medium on reading speed or correct answers, their VDT condition had significantly less ‘Know’ responses than those of paper. A previous study assessed test performance and memory type after four consecutive 6-week psychology courses, and after a delayed re-test (Conway, Gardiner, Perfect, Anderson & Cohen, 1997). Higher performing students had more ‘remember’ responses on earlier tests, and more ‘know’ responses on later tests, demonstrating a shift from ‘remembering’ to ‘knowing’ over time. Prior research states that ‘knowing’ represents a more coherent conceptualization of information, which can facilitate encoding by providing a pre-existing mental structure for which to organize new information (Anderson, 1987). Thus, Noyes and Garland claimed that studying on print may lead to better learning, and more applicable knowledge than studying on a VDT.

To further explore possible cognitive differences, Noyes, Garland and Robbins (2004) compared comprehension performance and cognitive workload between the two mediums. Although no differences were found in overall performance or cognitive workload, there was a significant difference among the 'effort' dimension of the NASA-TLX, a subjective measure of mental workload. This further supports their theory that there are differences in cognitive processing between the two mediums. Interestingly, the original study reporting the creation and initial assessment of the NASA-TLX (Hart and Staveland, 1988) did find that this instrument revealed higher workload levels when the computer was used.

Wastlund (2005) conducted two experiments to respectively assess consumption and production of information on VDTs. In the first experiment, consumption of information was assessed via a reading comprehension test. The second experiment assessed production of information in the form of a verbal creativity "headlines" test, in which subjects were told to create newspaper headlines that contained the essential text derived from a complete newspaper article. This research found that for both consumption and production of information, performance was superior with paper. Additionally, VDU participants in the first experiment reported higher levels of stress and tiredness, leading the authors to conclude that a higher cognitive workload while using VDUs may be a cause of these differences.

User Preference

As previously mentioned, due to the drastic changes in VDU technology and user familiarity, user preference may be the most likely variable to change when comparing modern studies to those reviewed by Dillon et al. (1988). The classic mere exposure effect (Zajonc, 1968) would indicate that those who are more familiar with computers, would be more likely to rate them positively. Later research began focusing on differences between VDUs and paper in the context of learning assessments and standardized testing. Unsurprisingly, these studies began to see a shift towards users preferring computer assessments to paper ones. Some studies found that many users preferred computer versions of tests (Pinsoneault, 1996, Hansen et al., 1997; Vispoel, 2000, 2001), while others found that learning information is preferred on a computer (Horton & Lovitt, 1994; Hallfors et al., 2000). These findings seem to support the idea that as computers become integrated into the everyday lives of users, they will be more accepting of them, at least during learning and testing assessments.

An important distinction should be made between these learning assessments, and long-term sustained reading. Even if one of these standardized tests takes the same amount of time as a sustained reading task, sustained reading may require the processing of more visual information. During a test, a question is read but most of the mental work comes from remembering what was learned and creating associations between what is known and what is being asked. This presumably requires much less visual attention and processing compared to sustained reading. Previous studies suggest that screen flicker is a likely cause of visual fatigue (Kennedy & Murray, 1993;

Krummenacher, 1996), so perhaps the lack of sustained reading is a reason for the VDUs being preferred to paper in the context of these learning activities and online test assessments.

Display Technology

As computers have evolved over the decades, display technology has concurrently undergone significant transformation. When comparing any of the research cited here, one should consider the fact that there are vast variations in quality and technical specifications of the VDUs implemented. Since image quality is likely the most important cause of differences in electronic reading versus print (Gould et al., 1987), these specifications are of utmost importance. Although each individual screen can have variations in size, resolution, contrast ratio and refresh rate, they can be broadly categorized by the underlying display technology that they use.

Developed at the turn of the 20th century, Cathode Ray Tube (CRT) refers to an electronic display technology that was widely used in the beginning of the computer age. A CRT is a vacuum tube which features an electron 'gun', called a cathode, which emits a stream of electrons that eventually reach a phosphorescent surface to produce an image (Chen, Cranton & Fihn, 2012). An ever-present feature of CRTs is an image 'flicker' which is caused by the phosphors repeatedly energizing and fading as the cathode emits electrons across the panel in a top to bottom pattern (Geske, 2005). Many of the authors cited to this point have suggested that this image flicker is likely a primary cause of differences in information processing between CRT and print media.

Liquid Crystal Displays (LCDs) were developed around the same time as CRTs, although they took longer to popularize in the computer age. In contrast to CRTs, LCDs are made up of millions of tiny blocks called pixels, each made up of sub-pixels that are red, blue or green. Each pixel is controlled by a separate transistor which can rapidly change the state of a liquid crystal, which ultimately either blocks or passes light through (Chen et al., 2012). Unlike CRTs, LCDs require a separate backlight to portray an image but nonetheless, both technologies emit artificial light from the screen. Perhaps the most obvious advantage LCDs have with regards to human cognition is the lack of image flicker.

Unfortunately, most of the authors discussed to this point only gave vague descriptions of the VDUs used in their studies. Of those that did, however, CRT technology was reported almost exclusively. Because LCD monitors did not begin outselling CRTs until late 2003 (Chen, et al., 2012), it can be assumed that most, if not all studies prior to then employed CRTs. While LCD existed for many decades prior to this, it wasn’t until the 2000s when it became affordable and desirable enough to take over as the most widely used screen technology.

Electronic paper (e-Paper) refers to a special category of display technology that has recently emerged and is popularly used in handheld reading devices. Because there are many types of display technologies that can be considered ‘e-Paper’, a single definition is difficult to devise. However, there are some shared characteristics of these technologies which set them apart from traditional VDUs. E-Paper requires no internal light source, is insensitive to viewing angles or external light sources, and consumes zero power to display a still image (Heikenfeld, Drzaic, Yeo and Koch, 2011). To produce an image, millions of tiny electrically charged particles are brought to the surface of the display via an electric field. Rather than being powered by an artificial backlight, these particles create an image surface which reflects natural light that is already present in the environment. The result is a physical, ink-like texture which appears very much like regular ink on paper.

The makers of popular e-Paper devices claim that their products are easier on the eyes and cause less fatigue than traditional devices which use LCD displays. Studies have shown that reading from e-Paper is indeed similar to reading from print (Siegenthaler, Wurtz, Bergamin & Groner, 2011). However, research comparing fatigue between e-Paper and LCD has been mixed. A study concluded that reading on the two display types is similar (Siegenthaler, Bochud, Bergamin & Wurtz, 2012), while another claims that LCD triggers more visual fatigue than e-Paper and print (Benedetto, Drai-Zerbib, Pedrotti, Tissier & Baccino, 2013).

Mental Arousal, Fatigue and Workload

Mental arousal refers to the mental state of being awake, attentive, and reactive. This state is accompanied by the general activation level of the cerebral cortex which can be described as cortical arousal. As one would predict, cognitive and task performance is largely influenced by a person's arousal levels. The Yerkes-Dodson Law (Yerkes & Dodson, 1908) states that the relationship between arousal and performance follows an 'inverted-U' shape; while a certain level of arousal is required for cognitive tasks, performance can be impaired at very low and very high levels of arousal. Since a person in a low-arousal state is by definition nonreactive and inattentive, it is obvious that this state would cause performance detriments. In contrast, excessive levels of mental arousal are usually caused by excessive task demands, which lead to the narrowing of one's attentional capacity (Easterbrook, 1959).

Mental fatigue is a psychophysiological state characterized by a sense of weariness, decreased cognitive efficiency, lowered cortical arousal levels, and an overall lack of motivation to work (Grandjean, 1979). Mental fatigue occurs due to the long-term continuous cognitive demands of certain tasks (Kato, Endo, & Kizuka, 2009). Over the course of a demanding task, arousal levels tend to decrease which lead to deficits in performance. In contrast, visual fatigue refers to a more subjective experience of visual discomfort such as pain around the eyes, blurred vision or headaches (World Health Organization ICD-10, H53.1), usually in response to visually demanding tasks.

In addition to assessing mental fatigue and cognitive performance, human factors researchers are also interested in addressing how demanding certain tasks are on cognitive resources. Mental workload is the amount of attentional resources and effort required to perform a certain task. Similar to the effect of arousal, performance can also be lowered if workload is too low or too high. Obviously, if a task is overly demanding a person will likely have trouble meeting such task demands. In contrast, an undemanding task may also lead to performance detriments due to the task's inability to maintain a certain level of arousal and awareness in the person. The current study will take subjective measurements of arousal, visual fatigue and mental workload with the hopes of assessing how different display mediums may affect these variables.

Electrophysiology

Electroencephalography (EEG) uses electrodes to measure changes in electrical potentials of the cortex, which are the result of the activity of complex neural networks and the firing of billions of neurons that comprise them. This electrical activity exhibits an oscillatory pattern which is characterized by the amplitude and frequency of such oscillations. These varying frequencies of EEG signal are divided into distinct groups, or 'frequency bands' which have different oscillatory characteristics and represent varying states of cognition. Theta waves are slower, high amplitude signals occurring between 4-8 Hz. Alpha waves are slightly faster, medium amplitude signals occurring between 8-12 Hz. Beta waves are high frequency, low amplitude signals occurring between 13-30 Hz.

EEG frequency activity is highly sensitive to task conditions (Gevins, Smith, McEvoy & Yu, 1997) and is a robust way of assessing cortical arousal in subjects. Cortical arousal refers to an increase in the general activation level of the cortex, which produces a state of being awake and reactive to stimuli (Pfaff, 2005). In general, beta waves are associated with high alertness and attentiveness, alpha waves are seen in a relaxed resting state, and theta waves are indicative of drowsiness and sleep onset (Okogbaa, Shell & Filipusic, 1994). Beta waves are most present at high levels of cortical arousal, and when a person is in a heightened state of attention and is mentally engaged in a demanding task (Horst, 1987). Theta waves are also known to increase during heightened states of arousal and attention. Occurring over frontal midline areas, theta power increases have been demonstrated in visual search tasks (Yamada, 1998), flight simulations (Smith, Gevins, Brown, Karnik & Du, 2001; Dussault, Jouanin, Philippe & Guezennec, 2005; Borghini et al., 2011) and during working memory load (Gevins et al., 1998, Klimesch, Doppelmayr, Schimke & Ripper, 1997). Additionally, theta can increase in parietal areas due to increases in task demand (Fairclough, Venables & Tattersall, 2005). In contrast, however, alpha waves are inversely related to cortical arousal. Many studies have found that alpha levels are suppressed when a person is engaged in attention demanding tasks (Gevins & Schaffer, 1980; Klimesch, 1996; Pfurtscheller, 2001; 2003). This level of alpha suppression has also been found to depend on task difficulty; high task demands and mental workload lead to less alpha activity (Smith, Gevins, Brown, Harnik & Du, 2001; Sterman, Kaiser, Mann, Suyenobu, Beyma & Francis, 1993). With regards to fatigue, studies have shown increases in theta and alpha activity in relation to decreased vigilance and performance during vigilance tasks (Davies, 1965; Gale, Davies & Smallbone, 1977). Recently, a simulated driving task elicited a similar pattern. Theta and alpha power were increased while beta power was decreased from the beginning to the end of the 90-minute driving task (Zhao, Zhao, Liu & Zheng 2012).

The earliest research that used EEG to investigate differences between different display mediums compared the effects of CRT, LCD and print mediums on attention in terms of alpha and beta activity (Geske, 2005). In this study, subjects sat with their eyes closed establishing a baseline alpha pattern, and subsequently opened their eyes to read from the display medium. In this within-subjects design, participants performed this task for each of the reading mediums. Five seconds of eyes closed data was compared to five seconds of reading, with lowered alpha and increased beta powers representing better attention. It was found that subjects showed better attentional response to print media versus CRT screens, but that LCD was similar to print. Additionally, these differences were pronounced in the parietal lobes, but not in the occipital lobes. Potentially the occipital activity reflected the ventral, ‘what’ stream of visual processing, but this distinction should be interpreted with caution due to the spatial blurring effects of EEG.

Another EEG study examined the effects of CRT versus print mediums on memory and EEG response (Shieh, Chen & Wang, 2005). The focus of this research was on frontal midline theta rhythms, which have been recommended as an effective way of assessing attention and mental workload during VDU work (Yamada, 1998). In Shieh’s study, subjects attended two separate sessions in which they were exposed to each of the display mediums, respectively. In each session, they performed a memory task in which they were exposed to two sets of 16 Chinese words for 30 seconds, and were then asked to recall the items. They found that memory performance and midline and temporal alpha and theta were similar between the two mediums. Despite the objective similarities, however, subjects rated higher preference for print material. The authors concluded that any differences between the two mediums may be purely subjective.

Following up their previous research, Geske & Bellur (2008) were interested in comparing CRT to print in terms of time-locked, ‘bottom-up’ and ‘top-down’ attentional responses. These components refer to two distinct mechanisms in which visual processing occurs. In the ‘bottom-up’ mechanism, attention is triggered by raw sensory data and is a quick, automatic process that does not rely on previous experience. In contrast, ‘top-down’ processing occurs later and is guided by previous experience rather than pure sensory data (Corbetta & Shulman, 2002). Geske and Bellur compared changes in alpha and beta activity between a 50 ms baseline interval and 50-100 ms after stimulus presentation for the bottom-up attention response. For the top-down response, a 50 ms baseline interval was compared to a 250-300 ms interval after stimulus presentation. Participants again sat with their eyes closed during baseline, and then opened their eyes to read from the respective medium. Print reading exhibited greater beta and suppressed alpha activity in both bottom-up and top-down attention responses, indicative of better attention. The authors stated that image flicker is likely the cause of such physiological differences, and that future research should see if these differences extend to memory and comprehension of the reading material.

A more recent study compared elderly and young adults across LCD, print and an e-paper device in terms of eye fixations and EEG theta power (Kretzschmar, Pleimling, Hosemann, Füssel, Bornkessel-Schlesewsky & Schlesewsky, 2013). Each participant read three texts on each display while EEG and eye tracking were recorded. Interestingly, older adults showed decreased theta activity and fixation times when reading from the LCD device, indicating that reading from this device actually required less effort. Young adults showed no differences between the three mediums. Strikingly, subjective results contradicted these objective findings. Both young and old adults preferred reading from the book page over either the LCD or e-paper tablet devices. This replicates the previous research by Shieh et al. (2005) which presented the idea that differences between print and electronic reading may be purely subjective, rather than cognitive.

Present Study and Hypotheses

Most research investigating differences in electronic reading versus print was conducted in the 1980's and 90's – a time when VDUs produced poor quality images and users were inexperienced with computers. Modern research implementing newer display technologies is sparse. While reading from e-paper appears to be cognitively similar to reading from print, it is unclear whether improvements in LCD image quality have made up for deficits found in past studies. Also, there is lack of physiological measures used to assess fatigue, with many studies showing an overreliance on behavioral and self-report methods. While self-report methods are important, their use comes with limitations. When answering questions, participants may be inclined to answer how they feel they are expected to answer, rather than be objective and precise. Even if they are being honest, humans have a limited ability to accurately introspect; physiological measures can give insights to mental processes that are undetectable by a person's subjective experience. Also, most questionnaires produce ordinal data – data that has a rank order, but doesn't reveal precise distance between units. This study intended to give a broader assessment of fatigue and mental workload by combining self-reports with physiological measures which gather data that is objective, real-time, and provides precision which is otherwise unobtainable using solely self-reports.

An EEG power spectral analysis was conducted to assess cortical arousal levels as an indicator of fatigue in participants during extended, continuous reading. The relative power of theta, alpha and beta frequencies were computed for LCD versus print, e-paper versus print, and LCD versus e-paper reading. If reading from a modern, high-quality LCD device does still lead to fatiguing effects in users, it should be expected to see increases in theta and alpha activity, and decreases in beta activity, in line with previous studies on task-induced fatigue (Zhao et al., 2012).

Subjective measures of fatigue and mental workload were obtained in the form of 4 questionnaires: the Karolinska Sleepiness Scale (KSS; Akerstedt & Gillberg, 1990), the Accumulated Time with Sleepiness (ATS; Kecklund & Akerstedt, 1993) scale, the Visual Fatigue Scale (VFS; Heuer, Hollendiek, Kröger, & Römer, 1989), and the Workload Profile (WP; Tsang & Velazquez, 1996). The KSS and ATS measure sleepiness, which is a proxy index of mental arousal. The VFS measures eye fatigue specifically. The Workload Profile was developed by Tsang and Velazquez (1996) to assess subjective workload across multiple dimensions; Tsang & Velazquez showed that the WP has high test-retest reliability ($r = 0.92 – 0.94$, $p < 0.05$). In the current study, the KSS/ATS and VFS were given before reading, and after each of two 30-minute reading blocks for each session, while the WP was given after each of the reading blocks. These questionnaires will provide valuable information as to how each display medium impacts arousal levels and elicits eye strain and mental work. Furthermore, administering these scales across multiple time points will demonstrate how these variables may change over time. It was predicted that due to the long blocks of continuous reading, LCD would induce more sleepiness (lowered arousal), visual fatigue, and mental work than e-paper or print.

Finally, the Reading Medium Preference Scale (RMPS) was created by the author of the present research for the purposes of assessing user's preference levels on electronic versus print reading. This measurement will extend previous literature by addressing the idea that there may be a cultural reluctance to accepting electronic reading as a preferential norm. If there are no physiological differences between the display mediums but users prefer print reading and report being more fatigued by LCD, this would add to the evidence that any cognitive differences are purely subjective.

II. METHOD

Participants

39 Texas State University students with normal or corrected-to-normal vision participated in this study for course credit or monetary payment. Data from 7 subjects were excluded from analysis due to incomplete participation or poor EEG recording, thus, 32 participants remained for analyses (28 female, 4 male, mean age = 22.22 years, age range = 18 – 36). This study was approved by the Human Subjects Institutional Review Board (IRB) at Texas State University with written informed consent from all participants.

Reading Content and Apparatuses

The electronic reading devices consisted of an Amazon Fire tablet (LCD; 7”, 5-th generation, 171 ppi) and Amazon Kindle (E-Paper; 6”, 7-th generation, 167 ppi) e-readers. These devices were closely matched in screen size, resolution, text font and text size. The print device was constructed in-house using Microsoft Word and high-quality print materials (see Figure 1). The print device was matched as closely as possible in text size to the electronic devices, but print resolution is natively set at 220 ppi. Importantly, luminance levels emitted from each surface was matched. Before every study session, a luminance meter was placed 5 inches in front of the display. Ambient light in the room was adjusted so that reflected light from each display was approximately 130 lux in every session.

Before each reading task, participants were instructed to place their chin in a chinrest which was affixed to a desk in front. They sat in a standard, high quality computer chair, and were given the opportunity to adjust the chair and/or chinrest to a comfortable position prior to the reading task. The appropriate reading device was then placed on a stand, and a distance of 50 cm was measured from the person's eye to the page.

The reading content consisted of two distinct excerpts from the book, *Pastures of Heaven* by John Steinbeck. The book was proofread to ensure that the content was void of any extreme emotional content. *Pastures of Heaven* is a collection of short stories, which allowed for separate excerpts to be read in each of two reading sessions. Chapters 1-5 served as reading excerpt 'A', and chapters 6-10 served as reading excerpt 'B'. The order in which these excerpts were read were counterbalanced across subjects (see Table 1).

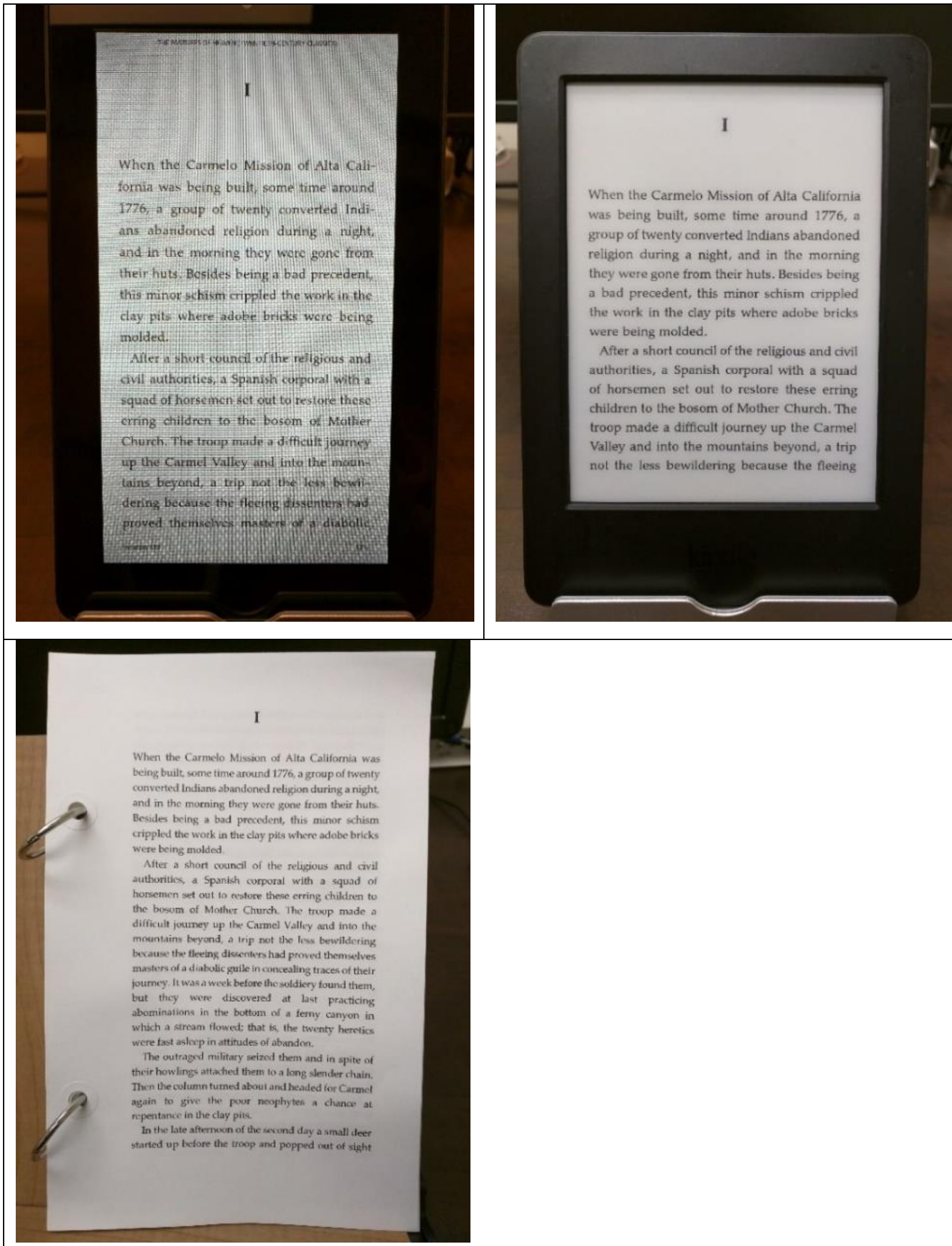

Figure 1. Images of each display medium. Top left: Amazon Fire – 5th Generation (LCD); Top right: Amazon Kindle – 7th Generation (E-Paper); Bottom: custom print device

Subjective Measures

The Reading Medium Preference Scale (RMPS), which was created by the author of this research, was administered to each subject prior to any reading tasks. This scale consists of 4 items measured on a 10-point scale asking questions such as, '*I prefer hard-copy over electronic text in most scenarios*'. Because two items on this scale imply a preference for electronic reading while the other two indicate a preference for print, the latter items were reverse coded and then a mean score for electronic reading preference was calculated for each individual (for total possible score of 1-10). Subjects who scored below 5.5 were considered to be individuals who preferred hard-copy, while those who scored above 5.5 were considered to be individuals who prefer electronic reading. One subject scored exactly 5.5 and was excluded from the group comparison.

To measure sleepiness, a proxy index of arousal, the Karolinska Sleepiness Scale (KSS) and Accumulated Time with Sleepiness (ATS) scale were administered. Given as a baseline prior to reading, the KSS asked participants to indicate how sleepy or alert they feel by placing a mark on a line (far left – very alert, far right – very sleepy), and by making a rating on a scale from 1 (extremely alert) to 9 (extremely sleepy – fighting sleep). The ATS was given after each reading block and asked participants on a 6-point scale how often they felt certain symptoms of sleepiness during the task such as, 'heavy eyelids', 'difficulty focusing attention', and 'periods when you were fighting sleep'. Responses to these scales were normalized by calculating percentage scores for each participant at each time point (before the reading task, and after each of the two reading blocks), for each of their two sessions.

Visual fatigue was assessed via the Visual Fatigue Scale (VFS) which consists of six items measured on a 10-point scale, asking participants to rate how they feel on items such as, '*My eyes feel tired' and 'I have a headache'*. Mean scores of the six items were calculated for each participant at each time point, for each of their two sessions.

Mental workload was assessed via the Workload Profile (WP). It asks participants to give a 0-1 decimal rating across eight different workload dimensions such as, '*Perceptual & Central processing*', and '*Visual Processing'*. Because this survey asks questions pertaining to a specific task, it was administered only after each reading block. Mean scores of the eight items were computed for each participant and block.

EEG Recording & Analysis

72 channels of EEG signals were recorded during the reading task using active Ag/AgCl electrodes. 64 electrodes were mounted in a Biosemi electrode cap (BioSemi B. V., Amsterdam, The Netherlands; www.biosemi.com, see Figure 2) and additional freestanding electrodes were placed at each mastoid, the left/right inferior orbit, left/right outer canthi, nasion, and NFPZ to monitor eye movements and blinks. All channels were amplified by a Biosemi Active II amplifier system in 24-bit DC mode at an initial sampling rate of 2048 Hz (400 Hz bandwidth) downsampled online to 256 Hz. All electrodes were referenced online to a common mode sense (CMS) electrode placed between sites PO2 and POZ, while a drive right leg (DRL) "ground" electrode was placed between POZ and PO4. Half-cell potentials of the electrode/gel/skin interface were kept between ±40 mV following standard recommendations for the Active II system. EEG data were imported offline into MATLAB computing software environment (The Math

Works, Inc., Natick, MA, USA) using the EEGLAB toolbox (Delorme & Makeig, 2004) for MATLAB, where all subsequent analysis was performed via in-house scripts utilizing EEGLAB functions.

EEG data was divided into 2 second epochs with 75% overlap, producing 3600 epochs for each of 4 reading blocks for each subject. Data was then re-referenced to an average-reference montage. Next, data was visually inspected and trials with muscle and signal artifacts were manually marked and removed. Bad EEG channels were replaced using an EEGLAB-based spherical spline interpolation algorithm (Perrin, Pernier, Bertrand, Giard, & Echallier, 1987).

Two electrooculargram (EOG) channels were computed for the purpose of correcting for ocular artifacts. A vertical electrooculargram (VEOG) channel was computed from the bipolar montage of site NZ and the average of the left and right inferior orbit sites (sensitive to blinks and vertical saccades). A horizontal electrooculargram (HEOG) was computed from the bipolar montage of left and right outer canthi EOG sites. Trials with ocular artifacts were then corrected via an adaptive filter-based regression procedure (He, Wilson, & Russell, 2004). Finally, EEG spectral power density ($\mu V^2/Hz$) was computed via Fast Fourier Transformation (FFT) using a 2-second Hamming window. For each subject and display condition, mean power density converted into decibels (dB) according to the formula $10*\log_{10}(\mu V^2/Hz)$. Spectral power was extracted as the average of two electrode clusters over the left (P1, P3, P5, PO3) and right (P2, P4, P6, PO4) hemispheres, respectively (see Figure 2). Initially, average power values were computed for each hemisphere separately, but preliminary analysis did not reveal any interhemispheric differences, so data were collapsed across electrode sites to simplify all the power analyses reported here (see Figures 2-3).

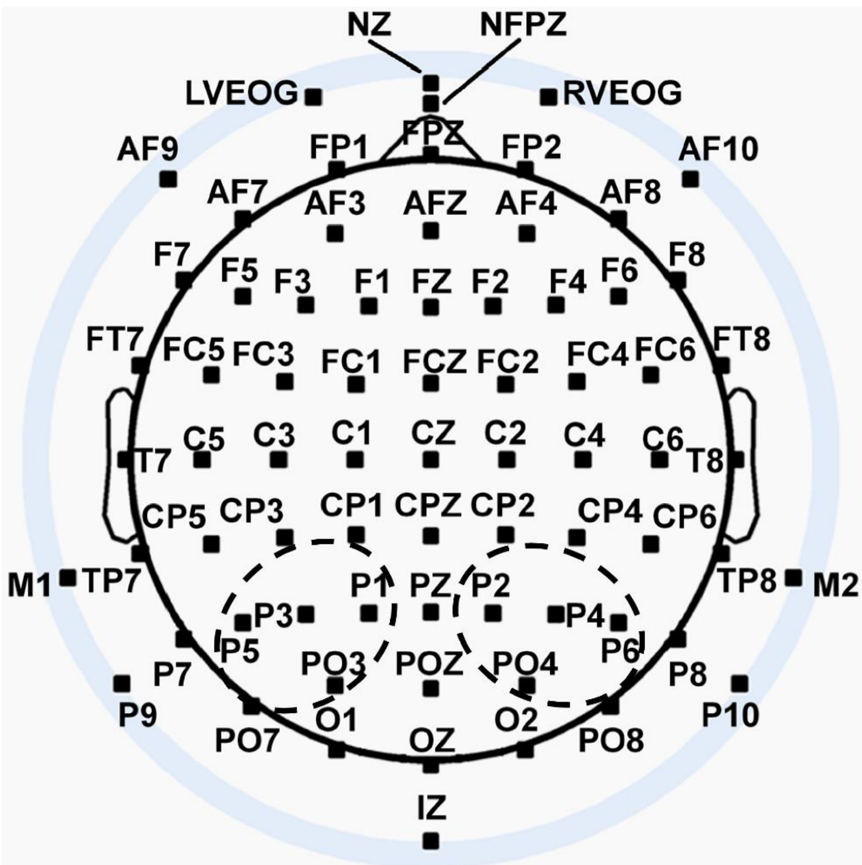

Figure 2. Sites of all electrode recording locations. Circled area indicates regions of interest that were included in analyses.

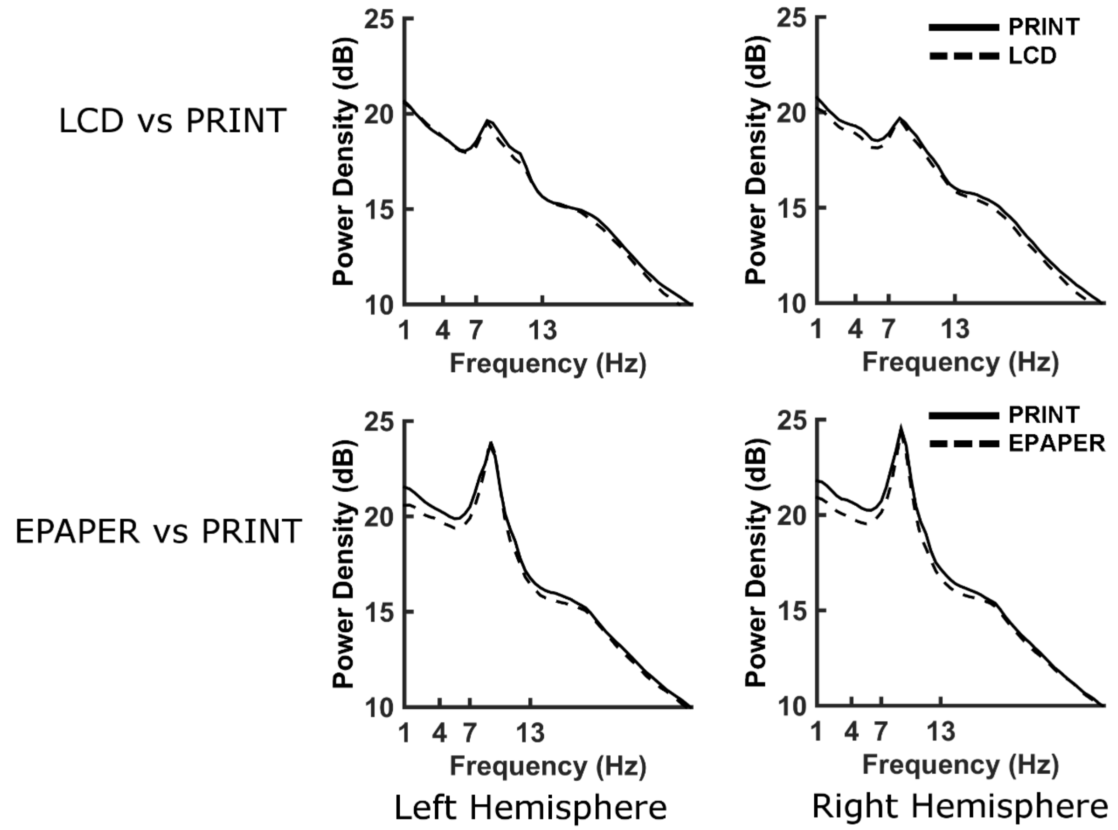

Figure 3. Power spectral plots. Compares all reading conditions between left and right hemispheres. Because there were minimal interhemispheric differences, data were collapsed across hemispheres to simplify power analyses.

Experimental Procedure

Each participant completed two, two-hour sessions in the electrophysiology lab at Texas State University. Each individual completed both sessions at the same time of day to control for between-session differences in circadian rhythms. All sessions consisted of EEG setup, and a two-block reading task during which EEG was recorded. After giving consent, EEG setup began and participants completed a demographics questionnaire and the RMPS. After EEG setup, participants were prepared for the reading task. They were instructed to remain still and relaxed during the recording, and were given a brief moment to familiarize themselves with the reading device and practice turning the pages. Prior to reading, the KSS and VFS were administered to assess baseline sleepiness and eye fatigue. Then, two thirty-minute reading blocks commenced in which the person sat alone in a quiet room and read continuously to themselves. After each reading block, the ATS, VFS and WP surveys were administered. Participants were thanked and compensated for their participation. Procedures for every session were identical, save for the implementation of different reading mediums for experimental comparison. Each subject read from the Print device in one session, and either the LCD or E-Paper device in the other session. This allowed for within-subjects comparisons between Print versus LCD reading and Print versus E-Paper reading, as well as between-subjects comparisons between LCD and E-Paper reading. The order in which each subject experienced their respective reading device was counterbalanced to avoid potential confounds in motivation or effort (see Table 1).

Table 1. Reading device order of counterbalancing. Shows every possible order that each respective reading device and book excerpt were given.			
Session 1		Session 2	
Reading Device	Book Excerpt	Reading Device	Book Excerpt
LCD	A	Print	B
E-Paper	A	Print	B
Print	A	LCD	B
Print	A	E-Paper	B
LCD	B	Print	A
E-Paper	B	Print	A
Print	B	LCD	A
Print	B	E-Paper	A

III. RESULTS

Subjective Fatigue and Workload

To assess subjective fatigue and mental workload, a series of two-way repeated measures ANOVAs were run using display medium and time as within-subjects factors. These analyses were run independently for each dependent measure across LCD versus Print, and E-Paper versus Print comparisons. Means and standard deviations for each of these comparisons are reported in Tables 2-4. Regarding the LCD versus E-Paper comparison, a two-factor mixed ANOVA was run, with display medium as the between-subjects factor, and time as the within-subjects factor. This was run for each dependent measure.

LCD vs. Print

Sleepiness

Significant effects were found for time ($F(2,32)=11.947$, $P<.001$) but not for display medium ($F(1,16)=2.586$, $p = .127$) or the interaction ($F(2,32)=.221$, $p=.803$). A Bonferroni-corrected post-hoc test indicated that there were differences in subjective sleepiness between Pre-test and Block 1 ($p = .002$), and between Block 1 and 2 ($p = .001$). Subjects were sleepiest at Pre-test, became alert after Block 1, and then became sleepier after Block 2.

Visual Fatigue

Significant effects were found for time ($F(2, 32) = 9.834$), $p < .001$) but not for display medium ($F(1,16)=1.298$, $p=.271$) or the interaction ($F(2, 32) = .027$, $p=.974$). A Bonferroni-corrected post-hoc test revealed differences between Pre-test and Block 1 (p=.001), and between Pre-test and Block 2 (p=.014). Subjects became more visually fatigued after either reading block compared to baseline, but there were no differences between the two blocks (p = .841).

Mental Workload

Because the WP was given only after each reading block, there were only 2 levels to the time factor. No significant effects were found for time (F(1,16)=.055, p=.817), reading medium (F(1,16) = .429, p = .522) or the interaction (F(1,16)=.233, p=.146).

Table 2. Questionnaire responses for LCD vs Print reading. Means are listed first and standard deviations are in parenthesis.

	LCD			PRINT		
	Pre-test	Block 1	Block 2	Pre-test	Block 1	Block 2
Sleepiness	.53 (.19)	.26 (.24)	.41 (.15)	.46 (.18)	.23 (.19)	.36 (.19)
Visual Fatigue	1.88 (.69)	2.50 (1.17)	2.36 (.84)	1.66 (.74)	2.29 (.94)	2.07 (1.06)
Mental Workload	-	.20 (.13)	.23 (.15)	-	.25 (.14)	.22 (.17)

EPAPER vs. Print

Sleepiness

A significant effect was found for time (F(2,32) = 15.777, p < .001), but not for display medium (F(1,16) = .151), p = .703) or the interaction (F(2,32) = .262, p = .771). A Bonferroni-corrected post-hoc test revealed differences between Pre-test and Block 1 (p < .001), between Block 1 and Block 2 (p = .001), but not between Pre-test and Block 2 (p = .824). Participants became more alert after Block 1 compared to baseline, but then returned to a sleepy state after Block 2.

Visual Fatigue

A significant effect was found for time (F(2,32 = 9.157, p = .001) but not for display medium (F(1,16) = 2.515, p = .132) or the interaction (F(2,32) = .484, p = .621). A Bonferroni-corrected post-hoc revealed differences between Pre-test and Block 1 (p<.001), but not between Pre-test and Block 2 (p = .061), or between Block 1 and Block 2 (p = 1.00). Participants showed significantly increased eye strain after Block 1 compared to baseline, which was qualitatively sustained throughout Block 2 (although this was statistically a non-significant difference compared to baseline).

Mental Workload

No significant effects were found between for time (F(1,15) = 1.295, p = .273), display mediums (F(1,15) = .000, p = .990), or the interaction (F(1,15) = .022, p = .883).

Table 3. Questionnaire responses for E-Paper vs Print reading. Means are listed first and standard deviations are in parenthesis.

	EPAPER			PRINT		
	Pre-test	Block 1	Block 2	Pre-test	Block 1	Block 2
Sleepiness	.45 (.22)	.23 (.22)	.41 (.30)	.48 (.23)	.26 (.22)	.41 (.22)
Visual Fatigue	1.60 (.73)	2.15 (1.05)	2.11 (1.53)	1.75 (.90)	2.66 (1.29)	2.46 (1.56)
Mental Workload	-	.24 (.20)	.20 (.15)	-	.23 (.15)	.21 (.16)

LCD vs. EPAPER

Sleepiness

Lastly, a 2 x 3 mixed ANOVA compared subjective ratings between the two electronic devices. For these analyses, display medium was the between-subjects factor, and time was the within-subjects factor. A significant effect of time (F(2,64) = 19.603, p < .001) was found, but not for display medium (F(1,32) = .371, p = .547) or the interaction (F(2, 64) = .485, p = .618). A Bonferroni-corrected post-hoc test revealed sleepiness differences between Pre-test and Block 1 (p = <.001), between Block 1 and Block 2 (p = <.001), but not between Pre-test and Block 2 (p = .347). Participants began the study sleepy, became alert after Block 1, and returned to being sleepy after Block 2.

Visual Fatigue

A significant effect of time (F(2, 64) = 5.190, p = .008) was found, but not for display medium (F(1,32) = 1.132, p = .295) or the interaction (F(2,64) = .036, p = .964). A Bonferroni-corrected post-hoc test revealed differences between Pre-test and Block 1 (p = .005), but not between Pre-test and Block 2 (p = .121) or between Block 1 and Block 2 (p = 1.000). Participants showed increased eye strain after Block 1 compared to baseline, and sustained a level of strain through Block 2 (although this was statistically a non-significant difference compared to baseline).

Mental Workload

There were no effects of time (F(1,32) = .109, p = .744), display medium (F(1,32) < .001, p = .991), or interactions between these variables (F (1,32) = 2.217, p = .146).

Table 4. Questionnaire responses for LCD vs E-Paper reading. Means are listed first and standard deviations are in parenthesis.

	LCD			EPAPER		
	Pre-test	Block 1	Block 2	Pre-test	Block 1	Block 2
Sleepiness	.53 (.19)	.26 (.24)	.42 (.15)	.45 (.22)	.23 (.22)	.41 (.30)
Visual Fatigue	1.88 (.69)	2.50 (1.17)	2.36 (.84)	1.60 (.73)	2.15 (1.05)	2.11 (1.53)
Mental Workload	-	.20 (.13)	.23 (.15)	-	.24 (.19)	.20 (.15)

Overall, we observed a general pattern of sleepiness and visual fatigue increasing over time during the reading task. However, there were no effects of display medium. Additionally, mental workload stayed constant throughout all reading blocks regardless of display medium used.

EEG

A series of two-way repeated measures ANOVAs were run using display medium and time as within-subjects factors to analyze theta, alpha and beta spectral power. These were run independently for each frequency band across LCD versus Print, and E-Paper versus Print comparisons. Standard parametric tests were used because the spectral power data was logarithmically- transformed during the conversion to decibels (see Methods – EEG Recording & Analysis section), which has been shown to approximately normalize non-normally distributed data (such as power data).

In regards to the between-subjects LCD versus E-Paper comparison, two-factor mixed ANOVAs were run for each frequency band using display medium as a between-subjects factor, and time as a within-subjects factor. A subtraction method was used to account for possible between-groups confounds. Because there are usually vast individual differences in biophysical factors (skull thickness, scalp density), typical between-groups comparisons are not recommended for electrophysiological data. To solve for this issue, electronic-print subtractions were made for each subject, thus holding idiosyncratic biophysical variations constant when computing electronic versus print contrasts and removing their effects when comparing LCD versus E-Paper data.

There were no significant effects of display medium, block, or interactions between these variables on theta, alpha or beta spectral powers across any of the display medium comparisons. Spectral power means, standard deviations and ANOVA results are reported in Tables 5-10.

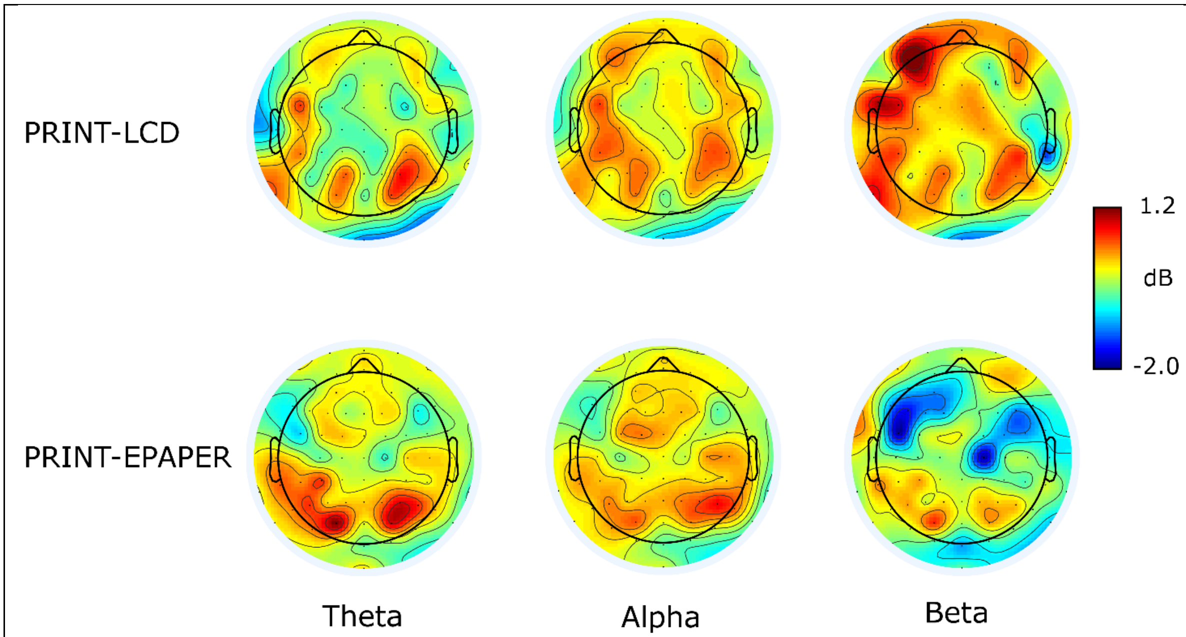

Figure 4. Topographical maps. Depicts electronic (top: LCD, bottom: E-Paper) versus print spectral power differences.

Table 5. LCD vs Print spectral power results. Data obtained from sites P1, P2, P3, P4, P5, P6, PO3 and PO4 for theta, alpha and beta frequency ranges. Means are listed first and standard deviations are in parenthesis. Units are in dB.

	LCD		PRINT	
	Block 1	Block 2	Block 1	Block 2
Theta	70.71 (26.36)	71.59 (26.45)	76.95 (32.93)	73.71 (34.25)
Alpha	65.19 (29.25)	65.41 (28.01)	70.14 (30.24)	68.40 (30.73)
Beta	19.68 (10.29)	19.70 (9.93)	21.18 (11.00)	20.51 (10.86)

Table 6. LCD vs. Print ANOVA results. All df = 1, 15.

	Theta			Alpha			Beta		
	F	P	$\eta 2_P$	F	P	$\eta 2_P$	F	P	$\eta 2_P$
Display Medium	.633	.439	.040	1.319	.269	.081	1.219	.287	.075
Block	.295	.595	.019	.176	.680	.012	1.012	.330	.063
Display Medium x Block	1.368	.260	.084	.624	.442	.040	2.509	.134	.143

Table 7. E-Paper vs Print spectral power results. Data obtained from sites P1, P2, P3, P4, P5, P6, PO3 and PO4 for theta, alpha and beta frequency ranges. Means are listed first and standard deviations are in parenthesis. Units are in dB.

	EPAPER		PRINT	
	Block 1	Block 2	Block 1	Block 2
Theta	93.20 (48.95)	93.70 (53.88)	112.62 (84.70)	107.27 (72.08)
Alpha	123.27 (138.42)	130.71 (148.16)	141.21 (152.97)	135.53 (142.32)
Beta	24.17 (12.68)	24.81 (13.86)	26.43 (15.98)	25.73 (15.08)

Table 8. E-Paper vs Print ANOVA results. All df = 1, 15.

	Theta			Alpha			Beta		
	F	P	$\eta2_P$	F	P	$\eta2_P$	F	P	$\eta2_P$
Display Medium	2.387	.143	.137	1.418	.252	.086	1.333	.266	.082
Block	.640	.436	.041	.080	.781	.005	.007	.933	.001
Display Medium x Block	.877	.364	.055	2.048	.173	.120	1.126	.305	.070

Table 9. LCD vs E-Paper spectral power results. Data obtained from sites P1, P2, P3, P4, P5, P6, PO3 and PO4 for theta, alpha and beta frequency ranges. Means are listed first and standard deviations are in parenthesis. Units are in dB.

	LCD		EPAPER	
	Block 1	Block 2	Block 1	Block 2
Theta	6.25 (24.63)	2.22 (19.86)	19.42 (53.28)	13.57 (33.48)
Alpha	4.94 (17.30)	2.99 (11.44)	17.95 (47.76)	4.82 (36.27)
Beta	1.50 (4.40)	.81 (4.15)	2.27 (7.00)	.92 (4.92)

Table 10. LCD vs E-Paper ANOVA results. All df = 1, 30.

	Theta			Alpha			Beta		
	F	P	$\eta2_P$	F	P	$\eta2_P$	F	P	$\eta2_P$
Display Medium (between-subjects)	1.056	.312	.034	.533	.471	.017	2.520	.123	.002
Block (within-subjects)	1.916	.176	.060	2.520	.123	.077	2.314	.139	.072
Display Medium x Block	.066	.800	.002	1.384	.249	.044	.235	.632	.008

Reading Preference

In contrast to previous studies, this scale was given to each participant at the beginning of the study, so as to assess the person's general attitude towards electronic reading, without influence from the specific devices used in this study. We did this with the hopes of creating a grouping variable to compare those who prefer hard-copy to those who prefer print. 27 of the 32 subjects reported a preference for hard-copy over electronic reading. Due to the overwhelming majority of subjects preferring hard-copy, these results were left as frequencies and not included in the inferential analyses.

IV. DISCUSSION

This study combined subjective and electrophysiological methods to assess mental fatigue during extended blocks of LCD, e-paper and print reading. While display medium had no effects on any dependent measures, subjective sleepiness and eye fatigue showed changes over time; participants were aroused by performing the first block of the reading task, and became sleepier after the second block. Participants also reported more eye strain after reading compared to baseline. These general effects of time on subjective measures are unsurprising. It is not uncommon that participants arrive to a lab sleepy, and then become alert and engaged after performing a certain cognitive task. In regards to visual fatigue, the reading blocks were successful in inducing eye strain in participants – an expected result of the long, continuous reading task.

Strikingly, the different display technologies in this study seemed to have absolutely no effect on any of the dependent measures. The primary goal of this study was to implement modern, high-definition displays to see if improvements in image quality have made up for deficits found in older CRT and low-quality LCD displays. The most ambitious interpretation of these results would say that VDUs are now so high quality that they are equivalent to reading from print media. However, this interpretation should be made with caution. The lack of findings could instead be a result of limitations in data quantification and analysis. Spectral power was ultimately computed for group averages, which may have failed to capture possible individual differences in frequency or scalp activity outside the regions of interest. We were interested in parietal areas based off of previous observations of visual processing streams (Geske, 2005; 2008), but other studies have found differences in frontal theta rhythms during similar tasks (Yamada, 1998; Smith et al., 2001). Furthermore, it's possible that subjects reached a fatigue ceiling, and computing spectral power across the entire reading blocks masked any time-sensitive differences between the display mediums. Perhaps computing a wavelet transformation, which gives information regarding how frequency strength changes over time, would reveal intricacies that were blurred by computing power over entire 30-minute blocks of data. Alternatively, spectral power could be computed over smaller portions of the reading task. Zhao et al. (2012) compared only the first and last 5-minutes of EEG data during a 90-minute driving task and found differences in theta, alpha and beta spectral densities.

Despite many previous findings that VDUs lead to higher mental workload (Hart & Staveland, 1988; Noyes et al., 2004; Wastlund, 2005), the current study found no such differences. Although most of the prior studies used shorter reading blocks than the current study, many of them implemented post-reading questionnaires to assess comprehension in addition to fatigue and workload. These post-reading assessments introduce task demands that are similar to what is present in the real world. Students and employees doing computer work usually have to meet expectations regarding the quality of their work, and are often under time constraints. It is likely that subjects in the current study did not feel pressure or stress that is commonly associated with such tasks, which explains the lack of findings regarding mental workload. One study used a working memory task during reading in addition to a post-reading comprehension questionnaire, and found that VDU readers under a working memory load performed worse on comprehension (Mayes et al., 2001). Future studies should use such stressors when assessing fatigue and mental workload, since it appears that differences between print and modern high-quality VDUs are diminishing.

In line with previous studies, current users reported an overwhelming preference for hard-copy reading. Despite this, there appeared to be no fatigue or workload benefits to reading print. This replicates two previous studies that suggest that differences between electronic and print reading may be more subjective rather than cognitive (Kretzschmar et al., 2013; Shieh et al., 2005). Krestchmar speculates that the preference for print reading may be due to some cultural fondness towards traditional books. In their study, younger participants were just as likely to prefer print reading as older participants, suggesting that this phenomenon is not due to lack of experience using electronic devices. Given that that current study was conducted 4 years later and also used a young sample, the preference towards print reading regardless of cognitive implications appears robust. Nonetheless, user experience levels will continue to evolve over the next decade. Future studies could see if these results can be replicated in individuals who were regular users of electronic devices from the time they were toddlers.

In conclusion, the results of this study provide no evidence that reading from modern LCD or e-paper devices leads to greater mental or visual fatigue than reading from print, whether physiologically or subjectively. However, subsequent analyses could reveal intricate differences that were not discernible using the current methods. Despite the lack of cognitive differences, young users who are presumably experienced with electronic devices still rate paper as being the preferred reading medium. This finding appears to be robust, but can be readdressed at later time points using populations that were exposed to electronic media from a very young age. Nonetheless, differences between modern electronic displays and print seem to be negligible compared to before, thus subjective attitudes towards these devices may be the more interesting research topic moving forward.

APPENDIX SECTION

Demographic Information

We need to have some information about your general background. Please answer the following questions by filling in the blank, or putting a check mark in the appropriate column. Thank you for your cooperation. **All information will be kept confidential and will not be shared with individuals not involved in this study.** If you fill out this questionnaire it is assumed that you have given consent as described on the consent form.

Date of Birth __ __ / __ __ / __ __ __ __ Age ___ Gender___ Handedness___ Occupation___________

Ethnicity (Circle one): Hispanic/Latino, Not Hispanic/Latino
Race (Circle all that apply): African American, Asian, White/Caucasian, Native American/Alaska Native, Native Hawaiian/Pacific Islander, Other – please specify_______________________________________

Highest Level of education? (circle one): grade school, some HS, graduated HS, trade school, some college, BS/BA, some grad school, MS/MA, JD, PhD, MD, Other. If other, explain:______________________________
What area of Study?____

____

Years of education (use HS 12; AA 14; BA 16; MA 18; Law 19; PhD/MD 20 or round down!!) ____________

Are you a native English speaker?

Yes No

If no, at what age did you begin formal education in English?_________________

____

Are you fluent in any language(s) other than English?

Yes No

If yes, which one(s)?

____

____

Do you engage in regular structured physical exercise (more than ½ hour per week)? Yes No

If yes, please indicate:

How many hours per week?________ On how many days per week?_______

What do you normally do (please circle)? Running Swimming Weight-Training Biking Hiking Other (please describe)___________________________________

Do you play computer/video games more than ½ hour per week?

Yes No

If yes, then please indicate:

How many hours per week?____________On how many days per week?__________

Please list the names(s) and type (i.e. action, puzzle) of game you play

____

____

____

____

____

How did you hear about this experiment? _____________________________

____

Would you be willing to be contacted regarding participation in other experiments? Yes No

Your participation is voluntary and you are free to decline participation if you wish.

Medical Information

We need to have some information about your general health. Please answer the following questions by filling in the blank, or putting a check mark in the appropriate column. Thank you for your cooperation. **All information will be kept confidential and will not be shared with individuals not involved in this study.** If you fill out this questionnaire it is assumed that you have given consent as described on the consent form.

Have you ever had a seizure?

Yes No

If yes, when? Do you still have them? How often did you have them? Medications?________________________

____

____

Have you ever had a head injury?

Yes No

Have you ever lost consciousness?

Yes No

If yes to either of the above:

Age	Circumstances	Lose consciousness? Y/N If Y, how long?	Hospitalized? Y/N If Y, how long?	Any noticeable changes? (includes headaches) Y/N If Y, explain.

Have you ever had a neurological disorder or any other problem with your brain or head? Yes No

If yes, explain: ____
____
____
____

Have you ever had any surgeries (especially on the heart or head)?

Yes No

If yes:

Date	Reason	Amount of Time in hospital

Do you have any problems controlling your movements that would prevent you from being able to write or manipulate small objects?

Yes No

If yes, explain: ____
____
____

Do you have any other serious illnesses?

Yes No

If yes, explain: ____

____

____

Are you seeing a health care practitioner for any current medical or psychological problems (e.g. depression, anxiety, ADHD)?

Yes No

If yes, explain.

____

____

____

Are you taking any medications for these problems or for any other reason (Including vitamins, aspirin, and other regularly taken medications)?

Yes No

If yes:

Med Name	Dosage	Prescribed? Y/N	Duration of Medication	Reason/Illness

Do you wear glasses or contacts?

Yes No

If yes, circle all that apply: regular glasses, bifocals, trifocals, contacts

Are you: near-sighted or far-sighted? (circle one)

Are you color blind?

Yes No

If yes, explain: ____

____

____

Do you have cataracts?

Yes No

If yes, explain: ____

____

____

How much sleep do you usually need in order to feel rested (in hrs)?________________

How much sleep did you have prior to this experiment (in hrs)?____________________

Please rate your current physical and mental state on the following scales:

Low Average High

Physical ____ ____ ____ ____ ____ ____ ____ ____ ____

Mental ____ ____ ____ ____ ____ ____ ____ ____ ____

Reading Medium Preference Scale

Please rate how much the following statements apply to you.

I use electronic forms of text (PDFs, Word Docs, e-books) as often as possible

1 2 3 4 5 6 7 8 9 10

Not at all Very much

I prefer electronic reading over print reading in most scenarios

1 2 3 4 5 6 7 8 9 10

Not at all Very much

I use physical texts as often as possible

1 2 3 4 5 6 7 8 9 10

Not at all Very much

I prefer hard-copy over electronic text in most scenarios

1 2 3 4 5 6 7 8 9 10

Not at all Very much

Karolinska Sleepiness Scale

S#:___________Date:__________Time:_________

Please place a mark on the line indicating how sleepy/alert you feel right now.

Very Alert	________________________________	**Very Sleepy**

Please rate how sleepy/alert you feel right now.

1 **Extremely Alert**

2

3 **Alert**

4

5 **Neither Alert Nor Sleepy**

6

7 **Sleepy, But No Difficulty Remaining Awake**

8

9 **Extremely Sleepy – Fighting Sleep**

Karolinska Accumulated Time With Sleepiness Scale

S#:______________Date:________________
Time:_________________________________

Did you experience any of the following symptoms during the test, and if so, for how long (please check)?

	Did Not Occur	A Few Times	25% of the Time	50% of the Time	75% of the Time	Most of the Time
Heavy Eyelids	________	________	________	________	________	________
Sand in Your Eyes	________	________	________	________	________	________
Difficulties in Focusing Your Eyes	________	________	________	________	________	________
Difficulties in Keeping Your Eyes Open	________	________	________	________	________	________
Difficulty Focusing Attention	________	________	________	________	________	________

Difficulty Concentrating ____________ ___________ ________

________ ________ ____________

Periods When You Were Fighting Sleep ____________ ___________ ________

________ ________ ____________

Irresistible Sleepiness ____________ ___________ ________

________ ________ ____________

Visual Fatigue Scale

Please rate how you currently feel on each of the following items.

I have difficulties in seeing

1	2	3	4	5	6	7	8	9	10
Not at all									Very much

I have a strange feeling around the eyes

1	2	3	4	5	6	7	8	9	10
Not at all									Very much

My eyes feel tired

1	2	3	4	5	6	7	8	9	10
Not at all									Very much

I feel numb

1	2	3	4	5	6	7	8	9	10
Not at all									Very much

I have a headache

1	2	3	4	5	6	7	8	9	10
Not at all									Very much

I feel dizzy looking at the screen

1	2	3	4	5	6	7	8	9	10
Not at all									Very much

Workload Profile

Please rate the proportion of attentional resources (mental workload) you used for each task that you performed today on a scale from 0 to 1. For each task, you will provide a rating for eight different dimensions of mental workload described below:

1. Stages of processing

(1) Perceptual & Central processing. These are attentional resources required for activities like perceiving (detecting, recognizing, and identifying objects), remembering, problem-solving, and decision making.

(2) Response processing. These are attentional resources required for response selection and execution. For example, there are three foot pedals in a standard shift automobile; to stop the automobile, we have to select the appropriate pedal & step on it.

2. Processing codes

(1) Spatial processing. Some tasks are spatial in nature. Driving, for example, requires paying attention to the position of the car, the distance between the current position of the car and the next stop sign, the geographical direction that the car is heading, etc.

(2) Verbal processing. Other tasks are verbal in nature. For example, reading involves primarily processing of verbal, linguistic materials.

3. Input modality

(1) Visual processing. Some tasks are performed based on the visual information received. For example, playing basketball requires visual monitoring of the physical location & velocity of the ball. Watching TV is another example of a task that requires visual resources.

(2) Auditory processing. Other tasks are performed based on auditory information. For example, listening to the person on the other end of the telephone is a task that requires auditory attention. Listening to music is another example.

Note that spatial information may be processed visually or auditorily. For example, you can get to a new restaurant by following a map (visual processing) or by following the directions spoken by your friend (auditory processing). Similarly, verbal information may be processed visually or auditorily. Listening to the news on the radio requires auditory processing of verbal materials; reading the news from the news- paper requires visual processing of verbal materials.

4. Output modalities

(1) Manual responses. Some tasks require considerable attention for producing the manual response as in typing or playing a piano.

(2) Speech responses. Other tasks require speech responses instead. For example, engaging in a conversation requires attention for producing the speech responses.

Workload Dimensions								
	Stage of Processing		Code of Processing		Input Modality		Output Modality	
Task	Perceptual & Central	Response	Spatial	Verbal	Visual	Auditory	Manual	Speech
1								
2								
3								

Note:

- A rating of 0 indicates a workload dimension required no attention for a given task
- A rating of 1 indicates that a workload dimension required maximum attention for a given task
- A rating of 0.5 indicates that a workload dimension required a degree of attention located halfway between zero & maximum attention for a given task.

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