Mobile-Enabled Conversion of Neuropsychological Tests for Minimal Hepatic Encephalopathy

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Abstract

Since the emergence of mobile telecommunication and multimedia devices, such as Android enabled devices and iOS enabled devices, mobile applications for health care services and products offer the potential for better access to care, more efficient resource utilization, and more effective care practices (Health Research Institute, 2010).

The term “mhealth” has been broadly used to describe the vast array of health services and technologies that leverage mobile telecommunication devices and multimedia technologies to address health care services (Istepanian & Lacal, 2003). Improvements in mobile infrastructures, increases in mhealth consumer products, and new operational and service models of patient care have led to increased adoption of mhealth solutions. As provider-facing mhealth products and services arise, the challenges of mobile infrastructural support, mhealth technology regulations and information privacy concerns are some of the areas that need due attention.

This paper will first addresses the benefits and challenges of provider-facing mhealth applications. Then it examines the conversion of the paper PSE-syndrome test for the iPad. Finally, the benefits and challenges to health care providers inherent in building a mobile health application were analyzed.
I. Introduction

The term mobile health (also known as mhealth) is used to describe the application of mobile technologies (tablet devices, PDA’s, and mobile phones) to improve public health and health care services. The term broadly falls under the category of electronic health (also known as ehealth), or the use of information and communication technology (ICT) for health-related services. To date, there are many sectors in health care where mhealth services are relevant, such as the collection of health information in community health research and the delivery of real-time health information to providers, health care professionals, and patients (Germanakos, Mourlas, & Samaras, 2005).

Many of today’s existing mhealth services are leveraging new mobile technologies, such as smartphones and tablet devices, to tackle health care challenges. The emergence of the iPhone, the iPad, the Android phones, the Windows phones, and other mobile-enabled devices have encouraged health care professionals to tap into the exciting and relatively new area of mhealth (Bedno & Vicsik, 2013).

II. Drivers for Adoption

To date, there are three major drivers for the adoption of mhealth solutions in hospitals: improvements in hardware support for mobile devices, increased availability of mhealth consumer products and services, and new operational and clinical models for patient care.

A. Improvements in Hardware Support for Mobile Devices
The first and foremost factor for increased mhealth adoption is improvements in hardware support, particularly in hardware performance, in global cellular coverage, and in smartphone consumption. The first of these improvements is mobile hardware specifications, particularly in processor speed, graphic acceleration, RAM capacity, storage size, cellular connectivity, WiFi connectivity, and other hardware features. Over the last six years, many mobile phones have undergone significant hardware improvements, enabling them be sophisticated computing devices. For instance, the 2011 iteration of the iPhone (iPhone 4.0) has drastically improved since the iPhone’s inception in 2007. Compared to the first generation iPhone (iPhone 1.0), the fourth generation iPhone (4.0) boasts dramatically improved processing speed (1.0 GHz compared to 620 MHz) and enhanced graphics capabilities (multi-cored GPU compared to single-cored GPU) in addition to many other hardware improvements (Toor, 2011). These hardware improvements in turn give rise complex mobile operating systems and mhealth applications.

The second significant area of improvement is improved global cellular coverage coupled with decreased data transfer costs. Improved global cellular coverage has led to an increase in mobile phone penetration. To date, the International Telecommunication Union (ITU) estimates there are globally 6 billion cell phone subscriptions in 2013, constituting an average of 87 subscriptions per 100 people (Whitney, 2010). Similarly, global short-message service (SMS) consumption according to the Cellular Telephone Industries Association (CTIA) has also grown significantly from $18.7 billion in 2006 to $193.1 billion in 2011 (Martin, 2012). Accompanying the increase in SMS service consumption and in phone ownership is the decrease in cellular bandwidth cost. According to MobiThinking (2012), the cost of 1MB of data transfer on average worldwide in US dollars was $0.10 in 2010 but decreased to $0.03 in 2012.
The third significant area of improvement is increased smartphone consumption. According to Statista (2012), global market penetration of smartphones has been steadily increasing by about 5% per year as a fraction of total handsets sold from 2008 to 2013. In 2010, smartphones accounted for 20% of total market sales of phones. In 2012, sales of smartphones increased to 35.5% of total sales (MarketingCharts, 2013). ZenithOptimedia predicted that by 2015 smartphones will constitute 71% of sales in the cellular phone market (MarketingCharts, 2013).

The advent of smartphone technologies is transforming many aspects of health care. Health care providers can leverage the extensibilities of smartphones to create applications for medical education, test result notification, medical records, disease monitoring, and telemedicine data collection (Qiang et al., 2011). Furthermore, patients and consumers can benefit from apps for chronic disease management, first aid care, and medical adherence aid (Qiang et al., 2011).

B. Rise of mHealth Consumerism

The second important factor for rapid mhealth adoption is the rise in mhealth consumerism. The growing mhealth market offers vast venues of products and services and encompasses a wide range of companies that specialize in health-related technologies and services (Health Research Institute, 2010). In 2013, more than 97,000 medical, health care, and fitness-related applications exist for smartphones and other devices (Jahns, 2013). The Health Research Institute (HRI) predicted that the annual consumer market for remote and mobile monitoring devices generates somewhere between $7.7 billion to $43 billion in revenue per year (Health Research Institute, 2010).
To date, several mhealth products and services are built around the model of consumer-centered care. In particular, these services cater to the “quantified self” movement, a recently popular movement that incorporates technologies to measure various health metrics for consumers (Wolf, 2013). Recent advances in sensor technologies and in mobile integrations of these sensors resulted in an increase of health metrics technologies, such as Nike+FuelBand, Fitbit trackers, and Pebble. Dr. Yan Chow, the director of Innovation and Advanced Technology Group at Kaiser Permanente, stated that “For consumers, mobile is a synonym for independence.”

Currently, most of the services targeting the consumer market gravitate toward the philosophy of providing clear, accessible and meaningful information for patients and for mhealth consumers (Health Research Institute, 2010).

Additionally, the consumer-centered care model has also produced two new types of mhealth consumer services. First, businesses are taking advantage of this model to deliver care information that they are already hosting online. For instance, several mobile services, such as UPMC Health Plan and myCigna, offer patients claim checks and electronic physician notes.

Second, businesses are targeting consumers with chronic illnesses and are seeking to improve patient-provider interaction and communication. One example is the iMPak’s Health Journal for Pain created by Palliative Care Physicians in New Jersey in conjunction with Meridian Health System¹ (Health Research Institute, 2010). This interactive journaling smartphone application enables patients to record responses to daily health-related questions. Physicians can then download these data to patients’ health records and web portals to better monitor care. In doing so, physicians are alerted to changes in patients’ health and can change medication dosage for patients. This collaborative technology is specifically marketed for

¹ Meridian Health System is a five-hospital health system in New Jersey consisting of 1,600 private practice physicians, with half in private practices.
consumers because of its affordability. The combination of clinical expertise of Meridian Health and of technological expertise from Cypak\(^2\) enabled the production an affordable mhealth application for cancer management (Health Research Institute, 2010).

C. New Operational and Service Models of Patient Care

The third factor for mhealth adoption is the development of new clinical and operational models of patient care and health care. According to a survey conducted by the Health Research Institute (HRI) in 2010, one-third of the physicians surveyed responded that they would benefit from mobile devices that provided access to more accurate data in real-time (Health Research Institute, 2010). Furthermore, 40\% of the physicians surveyed responded that they think they could eliminate 11\% to 30\% percent of their patients’ office visits through the use of mobile-enhanced remote monitoring systems, e-mails, and texting services (Health Research Institute, 2010).

The two potential improvements in patient care through mhealth technologies are the increase in patient-provider interactions and the reduction in hospital costs and expenses (HIMSS, 2011). Because mobile technologies offer the potential for sharing of real-time information among health care professionals, the first resulting improvement is in the quality of care. The integration of mhealth technologies with electronic health records (EHR) in medical systems can lead to more informed diagnoses for physicians. Additionally, because mhealth technologies offer the potential for real-time integration of patients’ health metrics and diagnostics, providers can then spend more time interacting with patients and providing a more informed diagnosis rather than collecting patients’ health data.

\(^2\) Cypak is a consumer tool developer company and retailing capacity in Best Buy retail stores.
In 2012, Qualcomm Life surveyed a group of physicians to evaluate areas of patient care that can be improved with mhealth technologies. Among the top ranked areas noted for improvements are pharmacy management (medication reminders and reconciliation), care continuum (remote patient monitoring), resource utilization (access to supplies), preventative support care (wellness management and disease surveillance) and pharma research validation (clinical trial recruitment) (Qualcomm Life, 2012).

The second resulting improvement is in the reduction of provider expenses, particularly in the area of chronic disease management. To date, several studies have pointed to the possibilities of high efficiencies in care and reductions in hospital cost resulting from applying mhealth technologies. The Cleveland Clinic piloted a chronic disease management program in which patients sent in information to their electronic health records from their wireless vital stats transmitters (Cleveland Clinic, 2010). Physicians in this program observed on average a 71% increase in the number of days between office visits. In another study, the Trans-European-Network-Home-Care Management System remotely monitored patients who received implantable cardiac defibrillators (Stachura, Elena & Khasanshina, 2007). This program resulted in a 35% drop in in-patient stays at hospitals, a 10% reduction in office visits and a 65% drop in in-home visits by physicians (Stachura, Elena & Khasanshina, 2007).

III. Challenges for mHealth Technologies

Although mhealth services and products offer the advantages of accessibility, integration, and the ability to improve patient care, there are several issues for health care providers to consider. According to the same 2012 Qualcomm Life survey, the top ranked areas of concern for practicing physicians are privacy and security of patient data, speed of accessing data, ability
of existing IT services to support medical devices (Qualcomm Life, 2013). To date, the three
major challenges for mHealth are lack of infrastructural support for mhealth integration in
hospitals, uncertainties in Food and Drug Administration (FDA) regulations of mHealth products
and services, and challenges in information security and in HIPAA\(^3\) compliance.

A. Lack of Infrastructural Support for mHealth Integration In Hospitals

The first and foremost challenge for mhealth integration is a lack of mhealth support in
hospitals. In many ways, the availability of mhealth services in health care settings is dependent
on the presence of supporting infrastructures for mobile technologies in care settings, such as the
support for mobile integration with existing medical devices and the presence of hospital mobile
broadband networks. In a 2011 survey conducted by Health Research Institute (HRI), 30% of
physicians responded that their hospital settings did not support any m-health integration.
Similarly, PricewarehouseCoopers Health Industries reported that 42% of the CIO’s at major
hospitals reported that they were underprepared to handle mhealth integration because their
device connectivity vendors did not consider hospitals’ interoperability needs (Health Research
Institute, 2010).

The lack of interoperability between medical devices is a serious problem at many
hospitals (Milliard, 2013). According to the West Health Institute (WHI), hospitals today use a
variety of medical devices produced by many manufacturers (Milliard, 2013). A typical intensive
care unit might use up to a dozen medical devices, such defibrillators, electrocardiographs, vital
sign monitor, and infusion pumps, all of which may have their own sets of intercommunication
protocols and drivers. The integration of these various devices would require a complex and an

\(^3\) Health Insurance Portability and Accountability Act
expensive IT infrastructure and can result in potential communication errors. Dr. Joseph M. Smith, the chief medical and science officer at WHI, stated “today’s hospitals are filled with medical devices that are unable to share critical data, creating potential dangers to patients, as well as inefficiencies that put a tremendous financial burden on our health care system” (Milliard, 2013). In a hearing before the House Energy and Commerce Subcommittee in March 2013, Dr. Smith estimated that the adoption of interoperability standards in the health care industry can lead to more than $30 billion of savings a year (West Health Institute, 2013). Until a more accessible interoperability standard is adopted, integration of mhealth technologies to existing medical devices in hospital settings can still be a formidable challenge.

Additionally, many hospitals today still support outdated wireless systems (Health Research Institute, 2010). Without a robust wireless or a broadband infrastructure in place, providers cannot utilize mobile technologies effectively. However, recent infusion of businesses into infrastructural supports for health care mobile networks does offer a glimmer of hope. For instance, Sprint Nextel has partnered with Calgary Scientific to create a more robust broadband network for Calgary Scientific’s RsMD app, a mobile application that relies on high bandwidth networks to transfer medical data, such as 3D brain scans, between providers and patients (Health Research Institute, 2010).

B. Uncertainties in FDA Regulations of mHealth Products and Services

The second challenge for mhealth products and services is the issue of mhealth regulation. One of the many foreseeable challenges to the mhealth space headed into 2014 is the mobile application approval process through the FDA. On the one hand, mhealth products and services offer a tremendous amount of innovations and of potentials to improve care quality and
consumer health. On the other hand, oversight needs to exist to regulate and correct possible inaccuracies and malfunctions in medical apps. Currently, the FDA has yet to provide a finalized guideline for overseeing the myriad of health apps in the mhealth space (Horowitz, 2013).

Currently, there exist two challenges to the FDA regulation of mhealth applications. First, it is unclear the extent to which mobile devices should be regulated. According to the mHealth Regulatory Coalition, there are many complicated issues that the FDA still needs to address (Thompson, Kendall, Brooke & Stout, 2010). As 2013, any medical device that is sold to end-users is not exempt from FDA approval or clearance (Thompson, 2010). However, it is unclear whether smartphones and mobile technologies that collect and transmit data from biomedical devices should be considered medical devices and thus be regulated. This issue is particularly relevant to mobile apps, such as the IBG gluometer, that have both a medical sensor component and a smartphone component. Additionally, other issues, such as whether wireless network carriers that are used for the transmission of health data should be subjected to regulation, are also unresolved (Thompson, Kendall, Brooke & Stout, 2010).

Second, it is also unclear the extent to which mobile health applications will be reviewed and be evaluated. According to Christy L. Foreman, the director of the FDA’s Office of Device Evaluation, medical apps that pose a low risk to consumers, such as medical resources apps and fitness apps, will not be regulated (Horowitz, 2013). However, many companies who building provider-facing apps worry that future FDA decisions may disrupt or impede mhealth products and services that are currently in use (Horowitz, 2013).

C. Challenges in Information Security and in HIPAA Compliance

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4 Provider-facing apps are mobile apps that can directly interact with providers and that can influence care decisions.
The third challenge for mhealth solutions is information privacy. To date, many mhealth apps, such as FitBit, exist in the market to help consumers track their health-related statistics and share these information socially. These consumer-generated information are not private health information (PHI) unless they are shared with covered entities—physicians, insurers, hospital staffs and other health care providers. Increasingly, a number of mhealth apps, such as AliveCor’s mobile heart monitor, cater to providers and may contain PHI (Lee, 2013). One of the biggest challenges to clinical mhealth applications is information security. According to the Health Research Institute, 41% of specialist physicians and 33% of non-specialists list security as the primary barrier to using mobile health technologies in clinical settings (Health Research Institute, 2010).

Although mobile health solutions interfacing with providers have to face security issues, there are many ways of achieving the escalation in security under HIPAA (Greene, 2011). First, covered entities that use a provider-facing mhealth application must comply to the HIPAA privacy agreement of nondisclosure for that particular app. Second, provider-facing applications need to submit an analysis of their users’ overall HIPAA Security risks and identify possible threats and vulnerabilities associated with stored private health information (PHI). In particular, two important areas of HIPAA evaluations are user authentication and data encryption (Greene, 2011). Third, all providers using the approved app must report breaches of PHI, and all business associates of the covered entities must also comply with HIPAA Privacy Rule and Security Rule (Greene, 2011).


Despite these security measures, there are still many security challenges to mhealth applications. Kotz (2011) identified three areas of threats: secure transmission, device presence, and device compromise. Secure transmission is the secure transfer of health information between a cellular node and a secure data point. Even with encrypted data, it is possible for a smart adversary to examine traffic patterns and determine the types of transmitted sensor data or the types of mobile devices transmitting the data (Wright, Monrose, & Masson, 2006). Additionally, in wireless networks, an adversary can inject synchronized packets of data to interfere with transmitted wireless frames and trick devices into revealing private information (Halperin, Kohno & Maisel, 2008).

Another threat is device presence, the identification of a particular mhealth device to a particular medical function. For instance, a patient may not want her employer to know that she is wearing a fetal monitor. Currently, there is no mhealth research that addresses the possible visible identification of patient information from mhealth device usage. A third possible threat is device compromise, the unauthorized access to devices through either remote access or theft. In this type of threat, an adversary may learn about patient’s information and use that information to access a patient’s previous, current, and future information. It is also possible for the adversary to inject false data or decrypt any of the patient’s information. Device compromise is still an open problem for mhealth security (Kotz, 2011).

IV. mHealth Application to Minimal Hepatic Encephalopathy

To date, one exciting area of provider-facing mhealth research is the use of mhealth technologies to improve standard paper diagnostics. This thesis explores whether a diagnostic test taken on a mobile device, such as an iPad or a similar tablet device, could improve the
quality of assessment as compared to a paper test. Specifically, it will focus on the conversion of the paper version of the standard PSE-syndrome test, a neuropsychological diagnostic assessment, to its computerized equivalent on the iPad.

The goals of this thesis are threefold: to explore whether the computerized version of the PSE-syndrome test can replicate the testing objectives of the original PSE-syndrome test, to explore whether the mobile-enabled PSE-syndrome test can automatically capture patient performance data that would require professional proctoring on the paper test, and to investigate whether mobile technologies can automatically capture additional motion-based performances metrics not present in the original paper test. The following includes a discussion of minimal hepatic encephalopathy.

A. Classification of MHE and MHE Symptoms

Hepatic encephalopathy is a cognitive condition resulting from liver failure characterized by episodes of confusion, altered consciousness, and coma (Cash et al., 2010). Minimal hepatic encephalopathy is a form of hepatic encephalopathy that reflects alteration in cognitive functions in patients who exhibit normal mental state (R. Tanasescu (Ed.), 2012). It is commonly present in patients with cirrhosis, a condition characterized by excessive hepatic tissue replacements (Bajaj, 2010).

Although the true prevalence of minimal hepatic encephalopathy is unknown, various reports using various assessment tools estimated that MHE diagnosis is present in 30% to 84% of all cirrhotic cases (Dhiman & Chawla, 2009; Prasad et al., 2007). As a condition, MHE presents a range of cognitive impairments in information retention, information processing and psychomotor skills (R. Tanasescu (Ed.), 2012). Patients with MHE and cirrhosis often exhibit
significant impairment of daily activities (social interactions, hand-eye coordination, alertness, and emotional behaviors) in comparison with patients with cirrhosis but no MHE (Dhiman et al., 2010; Weissenborn et al., 2003).

B. Diagnosis of MHE

To date, three popular batteries of neuropsychological tests for assessing MHE are used: the porto-systemic encephalopathy (PSE)-syndrome test, the psychometric hepatic encephalopathy score (PHES), and the repeatable battery for the assessment of neuropsychological status (RBANS) (Weissenborn, 1999; Randolph et al., 2009). Although all three batteries of tests can provide valid differential diagnosis for MHE, this thesis will concentrate on the PSE-syndrome test because it was a main focus of MHE research at Duke Clinical Research Institute.

The PSE-syndrome test is a suite of neuropsychological tests developed in Germany and administered in several other European countries for MHE diagnosis (R. Tanasescu (Ed.), 2012). The PSE-Syndrome test is comprised six popular neuropsychological test components: number connection test A (NCT-A), the number connection test B (NCT-B), the block design test (BDT), the digit symbol test (DST), the line tracing test (LTT), and the serial dotting test (SDT).

C. PSE-Syndrome Test Components

The number connection test (NCT) is the mostly commonly administered neuropsychological test for MHE. The two versions of the number connection test, NCT-A and NCT-B, both test for visuospatial orientation and for psychomotor speed (Shomerus & Hamster, 1998). NCT-A (see Figure 1 below) contains a series of non-overlapping circles numbered 1-25
randomly presented on a sheet paper, while the NCT-B (see Figure 2 below) test contains a series of non-overlapping circles numbered “1” to “13” and “A” to “L” randomly presented on a sheet of paper. The objective of NCT-A is to connect the numbers in increasing order (NCT-A) as quickly as possible. The objective of NCT-B is to interleave the numbers and the letters in increasing order (NCT-B) as quickly as possible. The participant is assessed for the time of completion (Shomerus & Hamster, 1998).

Figure 1. In NCT-A, the participant starts at circle “1” and then proceeds to connect all the remaining circles in increasing order until he/she reaches circle “25.” Reprinted from Miscellanea on Encephalopathy — A Second Look (p. 8), 2012, Rijeka, Croatia: Intech. Copyright 2012 by Intech. Reprint with permission.
Figure 2. In NCT-B, the participant starts at circle “1” then draws a line to circle “A”, first followed by “2” and then by circle “B.” He or she is then asked to connect all the remaining circles increasing numerical or lexicographical order until he/she reaches circle “13.” Reprinted from *Miscellanea on Encephalopathy — A Second Look* (p. 8), 2012, Rijeka, Croatia: Intech. Copyright 2012 by Intech. Reprint with permission.

The block design test (BDT) assesses for visuospatial reasoning and for motor skills (see Figure 3 below) (Kugler et al., 1994). The objective of BDT is to use 3D wood blocks of red, white, and red/white patterns to recreate the patterns shown on a card. This participant is scored on the time of completion and on the accuracy of assembly (Kugler et al., 1994).
Figure 3. In BDT, the participant uses the blocks on the bottom to create given non-segmented and segmented patterns. Reprinted from *Miscellanea on Encephalopathy — A Second Look* (p. 9), by 2012, Rijeka, Croatia: Intech. Copyright 2012 by Intech. Reprint with permission.

The digit symbol test (DST) evaluates for effective memory association and for visuospatial construction (see below Figure 4) (Conn, 1977). In this test, the participant is given a series of paired boxes with numbers on the top boxes and symbols on the bottom boxes. The objective of DST is to use the provided digit-symbol associations to complete all the unpaired numerals. The participant is assessed for the number of correctly filled boxes within a completion time (Conn, 1977).

Figure 4. In DST, the participant uses the nine paired boxes on the top to draw the associated symbols in the test area. Reprinted from *Miscellanea on Encephalopathy — A Second Look* (p. 9), 2012, Rijeka, Croatia: Intech. Copyright 2012 by Intech. Reprint with permission.

The line tracing test (LTT) assesses for psychomotor skills and for fine motor accuracy (see Figure 5 below) (Conn, 1977). The objective of this test is to draw a continuous line from the start location to the end location while attempting to stay within the boundaries of two outer
lines. The participant is assessed for the number of mistakes (bound violations) and for the time of completion (Conn, 1977).

Figure 5. In LTT, the participant draws a continuous line from the start location (bottom right) to the end location (top left) while attempting to stay within the bounds of the two outer lines. Reprinted from Miscellanea on Encephalopathy — A Second Look (p. 10), 2012, Rijeka, Croatia: Intech. Copyright 2012 by Intech. Reprint with permission.

The serial dotting test (SDT), the simplest of the six test components, assess for pure motor speed (see Figure 6 below) (Conn, 1977). The participant dots each of the 100 circles on the sheet after he or she practices by dotting 20 circles at the top of the sheet first. The participant is assessed for the time of completion (Conn, 1977).
Figure 6. In SDT, the participant completes the first 20 circles in successive order from the left to right before dotting on the 100 test circles. Reprinted from Miscellanea on Encephalopathy — A Second Look (p. 11), 2012, Rijeka, Croatia: Intech. Copyright 2012 by Intech. Reprint with permission.

D. Rationales for Mobile-Enabled PSE-Syndrome Test Conversion

To date, the PSE-syndrome test is commonly administered in Germany, Italy, and France (Bajaj, 2008). As a paper test, the PSE-syndrome test has several limitations. First, it requires an examiner to administer and the assessment, to enforce testing protocols, and to scrutinize for performance errors. Second, it requires physicians to record and to evaluate patient performance. Third, the paper-based assessment does not offer any easy methods for providers to share performance metrics with other health care professionals other than manual distribution of test results.

Converting the standard paper test into an mhealth application offers several advantages. First, the computerized version of the assessment can overcome several of the limitations listed with the paper PSE-syndrome test. The computerized assessment can automatically provide in-
test practice tutorials and proctoring, can perform individualized timing for each test, and can record patient performance data. Second, the computerized test can also share patient data with health care professionals in a secure manner and can leverage the secure databases to provide aggregate statistics on patients’ performances. Third, the computerized version can capture additional motion-related metrics that offers the potential for aiding future diagnosis of MHE.

V. Methods

The PSE-syndrome test was chosen because it is one of the well-validated and mostly commonly used neuropsychological assessments in Europe (R. Tanasescu (Ed.), 2012). Mobile development was chosen instead of a traditional laptops or a desktop computer for considerations of portability and interactivity. The iPad, given its size and weight, is very portable in the clinical settings. Its interactive multi-touch screen display can simulate the traditional paper-and-pencil PSE-syndrome test better than traditional laptops and desktops using trackpad and mouse can.

The iPad version of the PSE-syndrome test was built using the integrated developer environment Xcode version 4.0 and the iOS framework version 5.0. All learning materials pertaining to iOS development were obtained from lynda.com. The courses, “iOS Essential Training” (2012) and “Objective-C Essential Training” (2012), by Simon Allardice were the main resources for learning iPad development. In total, I spent 30 hours learning about iOS development, and, in particular, iPad development, before I joined Dr. Jones, my mentor, on the electron PSE-syndrome test conversion project.

The development of each component in the computerized PSE-syndrome test was accomplished through an analysis of the difficulties of creating the computerized test. One of the
The biggest challenges involved in the development process is understanding the necessary graphics-related aspects of each test. For instance, the number connection test A (NCT-A) requires drawing non-overlapping circles, detecting the user’s hand movement and motion, and identifying when the user hand inside the circles. These challenges not only complicate the design process but force consideration of good code design. To complete some of the graphics challenges in the test components, I used a lot of troubleshooting articles from StackOverflow.com and reading online forms.

To prioritize the tests, I met with Dr. Lisa Jones every two weeks starting in August 2012. We agreed to implement the six components in the following order based on the programming difficulties: LTT, NCT-A, NCT-B, SDT, BDT, and DST. Each test component took on average about two weeks of implementation time. After each of two-week periods, I would present my iOS test component to Dr. Jones and then revise the tests based on her preferences. The six components of the computerized PSE-syndrome test were completed in December 2012. The six tutorials and the Beck Depression Inventory were completed also in December 2012.

From January 2013 to May 2013, I made many changes to the electronic PSE-syndrome test based on Dr. Jones and neurologists’ recommendations. Some of these changes were to the aesthetics of the test components while others of these changes were to certain interactivity features of the test components. These changes can be found in the Results section of this thesis.

The mobile-enabled version of the PSE-syndrome test attempted to emulate the six original paper test components: NCT-A, NCT-B, BDT, DST, LTT, and SDT. Additionally, the electronic tests incorporated the features of automatic error tracking for each test component along with features of timings, tutorials, and device communication with a centralized database at the Duke Clinical Research Institute.
The iPad PSE-syndrome test was revised twice on the basis of physician use and evaluation at Duke Clinical Research Institute. Changes were made to application UI features, to test component features, to test tutorials formats and wording, and to captured patient performance metrics for each test component.

VI. Results

The iPad version of the PSE-syndrome test is comprised of computerized remakes of all six original test components: NCT-A, NCT-B, BDT, DST, LTT, and SDT. Each computerized test component is presented on a 185.7 mm by 241.2 mm (7.31 in by 9.50 in) iPad screen and support user interactions through the iPad’s multi-touch display system. In addition to the six test components, the mobile-enabled iPad assessment also includes six tutorial screens for the six computerized test components, the patient information screen, the Beck Depression Inventory (BDI)\(^7\) assessment screen, the provider login screen, and the completion screen. Screenshots of the results the mobile applications can be found in Appendix A and Appendix B. The essential features and the supplementary features of the computerized PSE-syndrome test are found below.

A. Essential Features: Computerized Test Components

The six test components are designed to simulate the test objectives and conditions of the six original test components. Each of the six computerized tests is enforced with a strict 15 minutes time of completion limit. A participant completes each test by either fulfilling the testing objective or being prompted to move on after time expiration. When the participant moves from

\(^7\) The Beck Depression Inventory is a popular assessment for measuring severity of depression using 21-question multiple-choice questionnaire. It is incorporated into the computerized test to rule out cases of depression-related performance impairments.
the current test to the next test, a screenshot is taken and a list of test-specific errors and
performance metrics are recorded for each test. The ability to take screenshots is an iOS built-in
feature; this feature enables care providers to examine how the patients interacted with each
computerized test.

The six computerized test components capture both performance data that the original
tests capture and also new performance data. Like the original tests, the computerized number
connection test A and B capture the time of completion or the last circle number reached in the
case of incompletion. Additionally, the mobile-enabled number connection test A and B record
the number of wrong connections made and the time spent between two successive circles. The
computerized block design test captures the time of completion, gives a score for the number of
correctly matched blocks, and counts the number of tries to establish correct pairings. The
computerized digit symbol test captures time of completion, number of wrong pattern presses,
and number of correct digit-symbol matching’s. The computerized line tracing test captures both
time of completion and number of out-of-bound movements. The computerized serial dotting test
captures time of completion and number of incorrect taps. The screenshots of all computerized
PSE-syndrome test components are found in Appendix A.

In addition to capturing normal test metrics for each test, the computerized PSE-
syndrome also offers the feature of randomization, particularly in NCT-A, NCT-B, DST, and
BDT. NCT-A and NCT-B generate a random series of 25 non-overlapping circles on the iPad’s
multi-touch screen; DST generates a random sequence of numbers for the participant to match;
and BDT creates a random 9x9 tiled image for the user to recreate.

B. Supplemental Features: Patient Information, Tutorials, and BDI
The patient information screen is the very first screen of the computerize PSE-syndrome test. It is a form on which the providers can fill patient identification information: name, participant ID, age, gender, and education level (see Figure 7 below).

![Patient Information Screen](image)

Figure 7. Patient information screen.

After the presentation of the patient info screen, each of the six test components is presented in tandem with its respective tutorial screen. The six tutorial screens are presented before the six assessments. Each tutorial screen contains a test description and a partial test for practice. The test description is a concise message that informs the participant of each test component’s objective. Each description is worded to suit the comprehension of a person with a middle school education level or higher. The tutorial screen is intended to allow the participant to gain an initial exposure to the actual test.

Each tutorial is untimed and the participant can reset the practice tutorials as many times as needed to become comfortable with the testing formats. The practice screen for the block design test is shown below in Figure 8. The participant is asked to recreate a 2x2-tiled image based on the given 2x2-tiled image shown on the left by dragging any of the patterns from the
bottom of the screen. The tutorial will not indicate if the participant correctly recreated the given image but allow the user to reset the currently displayed image as he or she sees fit. Screenshots of all tutorials screens are found in Appendix B.

Figure 8. Tutorial screen for the block design test.

The Beck Depression Inventory (BDI) assessment is presented after the six tests to rule out cases of depression-related performance impairments. The participant’s information is recorded and saved along with his/her individual test component performance data. Figure 8 below shows a screen displaying a question from the Beck inventory. The participant can proceed to complete all the questions in questionnaire by using the hand swipe gesture on the multi-touch screen.
Figure 9. A question screen from Beck Depression Inventory assessment.

After the completion of the Beck Inventor, the completion screen is presented (shown in Figure 9 below). The patient’s performance data, personal person, and Beck Depression Inventory assessments response will all be saved to an XML file to be sent to a secure server at the Duke Clinical Research Institute. After this point, the test administrator then obtains consent form from the participant to relay the patient’s performance information to a secure database.

Figure 10. Test completion screen.

C. Revisions to the Computerized PSE-Syndrome Test
Two iterations of changes were made to the presentations and to the content of the m-health app in the process of developing the computerized test. In the first iteration of development, wordings of each description were changed to contain simpler dictons based on recommendations from a health care professional. Additionally, the countdown timer was hidden for each of the test to prevent timing from influencing test performance.

In the second iteration of development, the three revisions were made to the computerized version from the recommendations of my mentor and of a neurologist. First, because the iPad’s touch screen allows users to interact directly with the app via their digits, the certain spacing issues were redesigned, such as the minimal non-overlapping distances between circles in NCT-A and in NCT-B. Second, the first computerized version of the line tracing test did not capture the original test’s complexity in turns and in shapes. Test lines were redrawn and the boundary-checking algorithm was redesigned to better detect boundary collisions for turns. Third, other changes were made to the presentations of the test for readability. The locations of the “back” button and of the “forward” button on each test, the locations of patterns on the block design test, and the sizes of circles in the serial dotting test were all changed.

VII. Conclusion

The emergence of mobile technologies has pointed a new direction in health services, namely the use of m-health technologies to improve care. With yearly improvements in mobile hardwares and yearly increase in smartphone adoptions, m-health apps target consumers already increased in number to 97,000 in 2013 (Jahns, 2013). While the challenges in regulating of mhealth app, the concerns about data security, and the lack of support for mobile infrastructure in hospitals are all obstacles to mhealth integration, the benefits of provider-facing mhealth
solutions are can be readily observed. Currently, several mhealth products already serve at the interface between providers and patients; the iMPak’s Health Journal used at Meridian Health System and the wireless vital transmitter in Cleveland Clinic are two great examples of apps interfacing providers and patients (Health Research Institute, 2010; Cleveland Clinic, 2010). These mhealth products enable providers not only to keep track of patients’ health in real time but also to have more meaningful patient interactions.

To date, one area of m health that offers potential is the mobile technologies to improve existing care practices. This thesis focused on whether mobile technologies can replicate and augment clinical diagnoses. Specifically, the question, whether building a computerized version of the PSE-syndrome test can emulate or can improve the original paper test battery, was examined. In building the computerized PSE-syndrome test application, three areas of improvements were observed from using mobile technologies for administering the PSE-syndrome test.

First, the computerized battery automatically captures the original test component’s performance metrics without a test examiner. Performance metrics, such as time of completion and accuracy of completion, are recorded automatically as the participant completes the test. Second, the computerized battery captures performance metrics that the original test does not capture. Discrete time measurement of hand movement between different circles on NCT-A and NCT-B and number of association errors in DST are a few examples of the new types of data that are captured. The next step of this thesis will involves exploring how to creatively provide additional performance data for providers. Third, the computerized battery contains ways to share patients’ performance data with health care providers via data relay to database. This

8 For more examples of the new metrics captured, see Appendix A.
feature coupled with the powers of a database to collect aggregate statistics offer new ways of analyzing the PSE-syndrome test.

However, despite these advances, there are still several challenges facing this mobile application. First, further tests are still needed to validate the extent to which the computerized battery can maintain the integrity of the paper test. Because a touch-screen test medium is inherently different from a paper-based test medium, patient testing is required to assess the accuracy and integrity of the computerized battery. Already there are many questions about the paper test and the electronic test. For instance, the original block design test (BDT) uses wood blocks with different patterns on all three sides to simulate visuospatial testing. However, the computerized PSE-syndrome test only presents possible 2D patterns from the surfaces of the blocks. The next step in this thesis involves seeking institutional review board approval (IRB) from Duke Medical Center to start pilot testing. Once approval for pilot testing is obtained, physicians at DCRI will gain a better understanding of how well this application can replicate the original paper PSE-syndrome test.

Second, because the computerized test transmits patient information to providers on wireless networks, a heightened security measurement is needed in the future. Currently, no data encryption method exists to protect testing information before transmission. Similarly, no escalated security measures are in place as a clinical database to store patient information. However, one definite future direction for this project is to examine how escalation in security can be achieved this provider-facing mhealth application.

Overall, the computerized version of the PSE-syndrome test demonstrated that mobile health technologies offer the potentials not only to simulate paper diagnoses but also to improve those diagnoses. This thesis on computerized PSE-syndrome test hopefully showed with
cautioned optimism that researching mobile technologies as alternative diagnostic media for traditional paper-based assessments is a particularly effective avenue to improve care qualities for providers.
Appendix A

Appendix A contains a list of all test components found in the computerized PSE-syndrome test. The “reset” button is located on the top left of the screen. The “back” button is located on the bottom left of the screen and is temporarily present to allow physicians and app testers to move back to a previous screen. The “next” button is located on the bottom left of the screen.

Figure 11. The block design test (BDT). The participant is asked to recreate the 9x9-tiled image on the left side using the 4 pattern blocks located at the bottom of the screen. The participant is evaluated on 1) time of test completion, on 2) number of correctly paired blocks, and on 3) number of tries to establish correct pairings.

Figure 12. The digit symbol test (DST). The participant is asked to press the symbols on the bottom of the screen and to complete as many of the three rows of numerals as possible. The participant is evaluated on 1) number of correct pairings, on 2) time of test completion, and on 3) number of incorrect clicks in the bottom patterns.
Figure 13. The number connection test A,B (NCT-A,B). The participant is asked to connect the numbers or letters from “1” to “13” or from “1” to “25” depending which of the two tests is administered. The current circle from which the participant is asked to connect to the next one is colored in green. The participant is evaluated on 1) time of test completion, on 2) number of incorrect moves, and on 3) time spent between two successive circles.

Figure 14. The serial dotting test (SDT). The participant is asked to dot the circles serially from left to right and top to bottom, starting from the top left corner. The participant is assessed on 1) time of test completion and on 2) the number of redundant or incorrect taps.
Figure 15. The line tracing test (LTT). The participant is asked to connect the green area to the red area starting at the green area. The participant is assessed on 1) time of test completion and on 2) number of times the participant is out of bound.
Appendix B

Appendix B contains a list of all test tutorials found in the computerized PSE-syndrome test. The “reset” button is located on the top left of the screen. The “back” button is located on the bottom left of the screen and is temporarily present to allow physicians and app testers to move back to a previous screen. The “next” button is located on the bottom right of the screen.

Figure 16. The tutorial screen for the block design test. The participant is asked to read the test objective and then to recreate the 2x2-tiled image using the four patterns provided on the bottom of the screen.

Figure 17. The tutorial screen for the digit symbol test. The participant is asked to read the test objective and then to correctly pair 4 unpaired numerals on the top right. There is a flashing carrot, indicating the current numeral location of the participant. The participant can press the two patterns on the bottom of the screen to complete the tutorial.
Figure 18. The tutorial screen for number connection test A,B. The participant is asked to read the test objective and then to connect the circles in increasing order starting from circle “1.”

Figure 19. The tutorial screen for serial dotting test. The participant is asked to read the test objective and then to dot the three circles from left to right, starting from the leftmost one.

Figure 20. The tutorial screen for line tracing test. The participant is asked to read the test objective and then to connect create a line starting from the green area and ending in the red area.
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