Home-based Computerized Cognitive Assessment Tool for Dementia Screening

Hyungsin Kim\textsuperscript{a}, Chih-Pin Hsiao\textsuperscript{b}, Ellen Yi-Luen Do\textsuperscript{a,b}
\textsuperscript{a}School of Interactive Computing and GVU Center, Georgia Institute of Technology, GA 30332 USA
\textsuperscript{b}College of Architecture, Georgia Institute of Technology, GA 30332 USA
E-mail:{hyungsin, chsiao9, ellendo}@gatech.edu

Abstract. With a rapidly aging population worldwide, developing alternatives to enhance current cognitive screening practices is becoming increasingly important. The Clock Drawing Test, a paper-and-pencil test, has been used as one of the most popular cognitive screening tools for dementia. In this paper, we present our approach to developing a home-based computerized dementia screening tool, the ClockMe System, which we developed based on our observational study of the current practice of dementia screening at a clinic. The ClockMe System has two main parts: The ClockReader Application and the ClockAnalyzer Application. By using the ClockReader Application, older adults can self-administer dementia screening at home. The ClockAnalyzer Application enables medical practitioners to review and monitor screening results of their patients. We conclude our paper with preliminary user evaluation results and suggestions for future implementation. The study shows the potential of computing technologies that can advance the current practice of dementia screening.

Keywords: Keywords: Dementia screening, sketch recognition, cognitive impairment assessments, home-based screening system

1. Introduction

Technology plays a critical role in advancing telemedicine and health care. In particular, technology-enabled home care promotes a new approach to tackling various chronic health diseases as well as rising health care costs [15]. Home health technology empowers people to proactively care for themselves [12]. For example, people can monitor their blood pressure to prevent stroke without visiting the doctor’s office. People at risk of diabetes can also monitor their blood sugar levels daily with a simple finger prick test.

With fast growing older population, dementia is becoming one of the most common diseases in the United States [1,3]. Unlike other diseases that are physically visible, early detection of dementia is rarely easy. Older adults and their family members tend to consider early signs of dementia, such as memory loss and functional disabilities, as part of the normal process of aging [28]. The patient’s perception of the disease is one of the biggest barriers to identifying the early stages of dementia. In addition, primary care doctors tend to be reluctant to conduct dementia screening in their offices [13].

In brief, it is often difficult to detect the early stages of cognitive impairment because (1) it is hard to differentiate between cognitive impairment and normal cognitive degeneration due to aging; (2) there is limited opportunity for seniors to meet with specialists, such as neurologists or neuropsychologists, unless they have serious observable symptoms; and (3) the disease usually develops progressively; thus, early detection is challenging, as this normally requires continuous monitoring of everyday activities.

To support an independent life for older adults, we pose several questions: How can older adults proactively prevent any diseases due to age-related cognitive impairment? How can older adults determine whether they need to see a doctor due to frequent forgetfulness? Could an assessment tool enable older adults to conduct home-based cognitive screening?

We identified five issues that can be supported by technologies by conducting two focus group meetings with medical practitioners consists of neurologists and neuropsychologists. First, the
scoring process is long and tedious. Furthermore, different administrators of the test may have different scoring criteria. To reduce the tedious efforts of human scoring and to facilitate a consistent scoring practice and analysis, we have investigated how technology can enable better recording and analysis of the Clock Drawing Test.

Second, the pencil clock drawings made by the patients or participants are predominantly analyzed only at the end of the tests as a final product. With a computational tool, we would be able to capture time related information such as stroke sequence and spatial planning strategies.

Third, the medical technicians who administer the test are required to multi-task, such as measuring the time and observing the patient simultaneously, which may have inadvertently missed some critical details. A technology augmented instrument may reduce cognitive overload in test administration.

Fourth, the current practice of data collection and storage does not facilitate monitoring of progressing cognitive condition as the drawings were scanned and filed away after scoring and never retrieved later for comparison.

Lastly, most clinical dementia screening is conducted by technicians instead of medical practitioners. Patients only need in-depth examinations by clinicians for further analysis if the screening identifies some abnormal behavior patterns. Thus, if a screening tool can be situated at home, there is no need to have older adults visit a clinic just to conduct the test. Such home screening tool can potentially eliminate unnecessary trips and save medical expenses [3,10].

To make cognitive screening more accessible and effective, we present the design, implementation, and evaluation of a home-based computerized dementia-screening tool, the ClockMe System. In the following section, we first present related work of cognitive assessments. Second, we provide our ethnographical observation study of current dementia screening practice. Third, we provide an overview of the ClockMe System, its user interface and data structure design. The system includes two components – (1) ClockReader for patients to perform the Clock Drawing Test and (2) ClockAnalyzer for clinicians to monitor and diagnose cognitive impairments based on the CDT results. Then, we report the evaluation of the ClockReader Application in terms of sketch recognition rates and usability. After a discussion of the results, we close the paper with a summary conclusion and future research directions.

2. Background and Related Work

In this section, we briefly describe (1) the definition of Mild Cognitive Impairment (MCI), a symptom often considered a precursor of dementia, (2) the state of the art computerized cognitive assessments, (3) the Clock Drawing Test, one of the most popular MCI screening instruments, (4) handwriting recognition algorithms, and (5) other computerized Clock Drawing Tests.

2.1. Mild Cognitive Impairment

According to the American Academy of Neurology, individuals with MCI are defined as those who have a measurable memory deficit, but no dementia [26,29]. There are different types of MCI. Some people with MCI have impairment in multiple areas of cognitive function such as language or attention, in addition to memory. Others may have normal memory function but may be abnormal in other cognitive functions. All people with MCI have a high risk factor for Alzheimer’s disease. In order to delay the progress of Alzheimer’s disease, early detection is essential, and screening individuals with Mild Cognitive Impairment (MCI) is crucial. Simply put, MCI is considered an intermediate (or transitional) clinical state between normal aging and the earliest stage of Alzheimer’s disease [5]. Figure 1 shows a graph illustrating the progression of a person developing Alzheimer’s disease, reported by the National Institute of Aging [23].

![Fig. 1. Charting the Course of Healthy Aging, Mild Cognitive Impairment, and Alzheimer’s Disease. National Institute on Aging 2009 [23]](Image 312x169 to 526x331)
2.2. Computerized Cognitive Assessments

Much research in developing computerized psychological testing has been conducted since the advent of personal computers [6,7]. Studies have supported that the value of computerized assessments lies in their precision of measurement, automatic scoring, minimization of subjectivity, standardization, and the reduction of the impact that examiners may have on the participants [6,19,20,36].

The CANTAB (Cambridge Neuropsychological Test Automated Battery) is a computerized test for patients with dementia, Parkinson’s disease, depression, schizophrenia, HIV and for children with learning disabilities [4]. The battery consists of 13 sub-tests, such as motor skills, visual attention, memory, and working memory. The CANTAB test takes approximately 90 minutes to complete. Because of the lengthy time requirement, the CANTAB is not suitable as a quick screening tool. Moreover, it focuses only on memory testing [24].

CNSVS (Central Nervous System Vital Signs) is also a computerized neuropsychological test. CNSVS consists of seven conventional neurocognitive tests: verbal memory, visual memory, finger tapping, symbol digit coding, the Stroop test, a shifting attention test, and a continuous performance test [9,11]. One study on the reliability and validity of CNSVS shows that it is appropriate as a screening tool, but still not good enough to replace formal neuropsychological testing [11].

Besides CANTAB and CNSVS, there are more computerized tests that have been investigated and developed [7]. However, none of the tests include drawing tasks. Drawings have been used as a fundamental source for neuropsychologists to understand their patients [33]. Lezak argues that drawing tasks should take a central position in neuropsychological assessment because drawings are a rich source of information for understanding the presence (or absence) of cognitive abilities [20].

2.3. The Clock Drawing Test

The Clock Drawing Test (CDT) has been used for decades as a neuropsychological screening test [8]. The CDT is usually a part of the 7-Minute Screen, CAMCOG (Cambridge Cognitive Examination), and the Spatial-Quantitative Battery in the Boston Diagnostic Aphasia Examination [22].

The CDT focuses on visual-spatial, constructional, and higher-order cognitive abilities, including executive aspects [8]. The CDT accesses human cognitive domains from comprehension, planning, visual memory, visual-spatial ability, motor programming and execution, abstraction, concentration, and response inhibition [14,20,34]. The major value for clinicians to conduct this test is that the CDT can provide concrete visual reference points for a patient’s specific abilities. This provides good information for capturing cognitive dysfunction.

The Clock Drawing Test (CDT) is one of the simplest, but most commonly used screening tools to detect cognitive impairment in the elderly [33]. By simply asking people to draw a clock, it easily identifies people with dementia [38].

Clock drawings from people with cognitive impairment frequently show missing or extra numbers, or misplaced clock hands [8,26]. These drawings clearly show degradation of the patient’s cognition. Figure 2 shows examples of abnormal clock drawings from patients with Alzheimer’s disease and related disorders. The clock drawings from three patients illustrate their declining cognition [8].

![Fig. 2. Examples of clock drawings showing deterioration in dementia, adopted from Freedman’s example [8]](image-url)
clock drawing at 12 months is missing one hand as compared to the relatively intact clock at 6 months.

2.4. Handwriting Recognition Algorithms

The major advantage to adopting computational powers in CDT is that it automates the assessment process, and thus increases efficiency and saves costs. The key components to achieve assessment automation are the hand writing recognition algorithms. There are two elements that we need to recognize in a clock: the digits and the hands of the drawn clock. The recognition techniques that researchers have developed can be classified into two categories: offline recognition and online recognition. While offline recognition analyzes the sketches/characters after the drawing is complete, online recognition recognizes a stroke or character while users are drawing/writing it. In this sense, researchers often employ offline recognition to analyze raster images for pattern matching [21].

Online recognition techniques, on the other hand, not only provide the real time recognition results, but also help researchers capture various data that will help them make further analyses. Researchers have been developing online recognition techniques for decades. In recent years, the most notable recognition algorithms are the $l$ recognizer and the $N$ multi-stroke recognizer [2,37]. Both algorithms are lightweight and easy to deploy. While $l$ recognizer supports only one-stroke recognition, $N$ recognizer supports multi-stroke recognitions for characters and gestures [37]. However, their research has some limitations [2], and will not work for the practical conditions in a CDT drawing.

Since it’s hard to reach 100% recognition accuracy, Shilman et al. have developed an interface for users to correct the results on the fly [31]. Based on the corrections, the system will continuously evolve the recognized results. We have developed a Context-Bounded Filter Algorithm (CBFA) to enable the automatic corrections according to the contextual information surrounded by a character [16]. The CBFA algorithm adopts Microsoft Hand Written Recognition Engine to select the most probable character and uses the algorithm to correct the result. We have improved the CBFA by classifying the types of strokes and the distance between strokes that could be drawn in a clock drawing and thus improved the general recognition rates.

2.5. Other computerized Clock Drawing Tests

Several technology-supported GUI (graphical user interface) Clock Drawing Tests are commercially available. Both Automatic Clock Drawing Tests™ (www.clockdrawingtest.com) and ALZselftest, known as Computerized Self Test™ (CST), (http://alzselftest.com) include an Internet-based automatic clock drawing test using WIMP interface (i.e., windows, menus, icons, pointers) instead of digital pens. Automatic Clock Drawing Tests™ is used mainly for quick screening of cognitive impairment and as a driver’s assessment tool [39]. The purpose of Computerized Self Test™ is to identify cognitive impairment by assessing six major areas such as orientation, visuo-spatial ability, verbal fluency, memory, attention, and executive processing.

Similar to our ClockMe System, both systems have automatic scoring and reporting functions. However, these two tests require users to have computer experience, especially in using a mouse and a keyboard. Both tests employ the “drag and drop” method for number and clock hands placements to complete the Clock Drawing Test. In contrast, we deployed pen-based interaction when we designed the ClockMe System. By using a digital pen, a user experiences an environment much closer to that of an actual paper-and-pencil Clock Drawing Test. This is critical because our main target users are older adults who often do not have much computer usage experience.

Furthermore, the ClockMe System provides an exploratory investigation tool for medical practitioners to capture non-traditionally recorded data. For example, the real-time pen-interaction can collect novel behavioral data such as such as airtime (between strokes, digits and time setting), pausing tendency, pen pressure exerting patterns, and the drawing sequence (e.g., 12-3-6-9, or 1-2-3-4). These additional behavioral data may provide evidence for medical practitioners to make a differential diagnosis or test their hypothesis.

3. Formative Study: Understanding Technology Design Space

Before designing and implementing the system, we conducted a formative study to understand the technological potential in supporting cognitive impairment screening. We conducted ethnographical observation studies from March to July 2010 at the
Emory Alzheimer’s Disease Research Center (ADRC).

The main purpose of the study was to understand the screening process, the interactions between clinicians and patients in the screening process, and the handling of the test materials by observing how medical practitioners conducted and administered the Clock Drawing Test (CDT) in their screening routines.

We performed several research activities: (1) observations of 24-session cognitive screening clinical practices; (2) computer-familiarity surveys of the session participants, together with their biographical surveys; (3) a Tablet-PC based drawing task using a stylus; (4) a data analysis of the 50 Clock Drawing Test datasets previously collected by ADRC research; and (5) two focus group meetings with medical practitioners in Neurology and Neuropsychology.

Twenty-four older adult volunteers (with an average of 75 years) participated in the study from April to July in 2010. The participants consisted of 11 females and 13 males. Even though their average age was 75, the groups included 10 individuals who were older than 78. The oldest participant was 98 years old, and the youngest participant was 59. Their educational levels were diverse. Six participants had high school diplomas. Nine participants were college graduates. The last nine participants had a graduate-level education.

Considering the participants’ ages, it is not surprising to see the results of the computer familiarity survey. Most participants considered themselves as having low computer literacy, with limited or no experience. However, unlike their self-reported computer usage, the results of their drawing tasks using a stylus on a Tablet PC surface were very positive. All of the participants completed the drawing tasks without any difficulties. As for the tasks, we asked the participants to draw anything they liked to draw, such as a house or a flower.

With these results, we confirmed that older adults can use pen-based computing applications to interact with a computer. These novice computer users considered the use of a stylus to draw on top of the tablet screen similar to paper-and-pencil writing. Since pen-based interaction is easily accessible to people with little or no experience with computers, it shows good potential to be deployed in neuropsychological assessment tools.

At Emory ADRC, medical technicians conduct the dementia screening. The medical technicians are trained to administer neuropsychological testing to patients, to interpret these test results, and to prepare the final reports. The current practice is to administer the CDT with traditional analog media. Patients are asked to draw a clock by using a pencil on a given sheet of paper with a pre-drawn circle. The instructions are, “Pretend the circle is like a clock face. Put in all the numbers and set the hands at ten after eleven.”

Table 1. An Evaluation Criteria of the Clock Drawing Test adopted by Freedman et al. [8]

<table>
<thead>
<tr>
<th>Numbers</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Only numbers 1 – 12 are present (without adding extra numbers or omitting any)</td>
</tr>
<tr>
<td>2. Only Arabic numbers are used (no spelling, e.g., “one, two,” no Roman numerals)</td>
</tr>
<tr>
<td>3. Numbers are in the correct order (regardless of how many numbers there are)</td>
</tr>
<tr>
<td>4. Numbers are drawn without rotating the paper</td>
</tr>
<tr>
<td>5. Numbers are in the correct position (fairly close to their quadrants &amp; within the pre-drawn circle)</td>
</tr>
<tr>
<td>6. Numbers are all inside the circle</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Depiction of Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>7. Two hands are present (can be wedges or straight lines; Only 2 are present)</td>
</tr>
<tr>
<td>8. The hour target number is indicated (somehow indicated, either by hands, arrows, lines, etc.)</td>
</tr>
<tr>
<td>9. The minute target number is indicated (somehow indicated, either by hands, arrows, lines, etc.)</td>
</tr>
<tr>
<td>10. The hands are in correct proportion (if the subject indicates which one is which after “finishing,” have him/her fix the proportion until he/she feels they are correct)</td>
</tr>
<tr>
<td>11. There are no superfluous markings (extra numbers or errors on the clock that were corrected, but not completely erased, are not superfluous markings)</td>
</tr>
<tr>
<td>12. The hands are relatively joined (within 12mm; this does not need to happen in the middle of the circle)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Center</th>
</tr>
</thead>
<tbody>
<tr>
<td>13. A Center (of the pre-drawn circle) is present (drawn or inferred) at the joining of the hands</td>
</tr>
</tbody>
</table>

Afterward, the medical technicians need to spend time analyzing and scoring the tests. To score the tests, the technicians at Emory ADRC use the 13-point evaluation criteria developed by Freedman et al. [8]. Having a full score of 13 indicates that the drawing is intact and that the patient has no cognitive
impairment. Table 2 shows the 13 critical items for clock evaluation. The 13 items can be grouped with respect to numbers (6 items), hands (6 items), and the center (1 item) [20].

First, the technicians examine the drawings to see whether all the numbers are present with only Arabic numbers. Then, they look at whether the numbers are in the correct order, together with the correct position. Lastly, they see whether the numbers are all inside the circle. As for the items with respect to the hands, it is all about the description of time. The drawing is examined to determine whether two hands are present and the two hands are indicated based on the instructions, such as ten after 11 with the correct proportion. Also, there should not be any superfluous markings. The center where the two hands join should be marked or easily identifiable.

From the data analysis we collected from ADRC, one of the most common error patterns was related to setting the time at ten after eleven. Figure 3 shows six different clock drawings, from drawers who were asked to set the time at 11:10.

Only the first clock drawing on the top left column shows the correct time set. The five others clocks show different time-setting errors. For example, patients with Alzheimer’s disease frequently set the time at 10 to 11. Freedman et al. argues that the time setting requirement is difficult for people with Alzheimer’s disease [8]. Research shows that stimulus-bound responses are more common among Alzheimer’s disease patients, compared to responses from normal elderly individuals and patients with frontal lobe dementia [8, 27, 32]. Furthermore, several studies investigated the co-relationship between this error pattern and the sub-types of dementia [17, 18, 30]. Researchers advocated that when a patient’s drawing shows this time-setting error pattern, clinicians should pay special attention in examinations of the patient’s symptoms and other examination results.

4. The ClockMe System

4.1. The ClockMe System Overview

The overarching goal of the ClockMe System is to develop an automated analysis of the Clock Drawing Test. First, the system records and recognizes a patient’s freehand drawing data. Then based on the scoring criteria, the system automatically analyzes the drawing and reports the score. The system can reduce the extensive labor needed for manual scoring. Furthermore, capturing and monitoring data through computerization provides additional dimensions (such as pressure, air time, and the drawing sequence) for the understanding of cognitive impairment for medical practitioners.

The ClockMe System includes two main parts: the ClockReader Application for patients to draw a clock and the ClockAnalyzer Application for clinicians to make appropriate diagnoses. Figure 4 shows the overview of the ClockMe System. Each application has a different User Interface, which can also run independently as a separate application. However, the ClockAnalyzer shares all the data collected from the ClockReader.
4.2. The ClockReader Application: Patient Side

4.2.1. User Interface of the ClockReader

We developed the ClockReader Application by implementing it on a Tablet PC platform to replace the traditional pen-paper style of testing. The design goal of the ClockReader User Interface (UI) is to provide older adults with an environment that is similar to the paper-and-pencil based testing. As with a paper-based CDT, a user sees a circle in the middle of the Tablet PC screen. The bottom part of the UI includes two radio buttons and three submit buttons. The radio buttons provide input options such as “Pen” and “Eraser”. The default setting is “Pen”. If users want to erase a part of their drawing, they can select the “Eraser” radio button, in which case the stylus works as an eraser.

The three submit buttons are “Start”, “Complete”, and “ClearAll”. When a user begins to conduct the test, they press the “Start” button, which records the beginning time of the test by sending time-stamped data to a server. The “Complete” button (1) records the ending time of the test, (2) initiates running the sketch recognition algorithm, and (3) sends all the data to a server. Lastly, the “ClearAll” button deletes all of the strokes in the drawing area. If a user wants to restart the test, they need to press the “ClearAll” button. Figure 5 shows a screen shot of the ClockReader Application.

Patients will be asked to draw a clock with a stylus on the running program. When they start to draw a clock, they will be asked to press the “Start” button. Once they finish drawing a clock, they will be asked to press the “Complete” button at the bottom. Then through the sketch recognition algorithms, the drawing will be collected and recorded in a proper data structure. The character recognition method using a Tablet PC collects dynamic process data from each stroke level and the overall sequence of the drawing and arrangements for analysis.

4.2.2. Sketch Recognition Algorithm

The ClockReader Application with the sketch recognition algorithm is developed in C# programming language and is supported by the “Microsoft Windows 7 Software Development Kit.” The running environment of the program is limited to the Microsoft Windows platform, equivalent to or better than the “Windows 7” with the “Microsoft.Net Framework 4.0 Service Pack 1.” The architecture of the ClockReader Application consists of three components: a GUI for drawing a clock, a character recognition engine, and a data storing utility.

A test participant (patient) starts the entire data flow of the system using a Tablet PC. Once the patient draws the clock as requested, the handwriting recognizer will analyze each number stroke along the inside of the circumference of the given circle and returns the best-matched character. Two clock hands that start from near the central point of the circle will have their validity determined by calculating the distance and internal angle between them. It will also
collect every end point, intersected point, Bezier point, pressure value and timestamp in each packet point, and airtime of the stroke for the successive possible analysis afterwards. The collected data will be transmitted to database storage and to the hard disk of the Tablet PC simultaneously, just in case the communication is interrupted for any reason. The following list shows the sequence of how the ClockReader Application works.

- **Sketch Input:** The participant is asked to draw a clock and set the time (e.g., at 10 after 11. Every coordinate of the cusps and every intersection of each stroke (even if it represents a character) will be stored in the memory.

- **Generic Recognition Engine:** The processor captures a rectangle-shape dynamic recognition region for the strokes and recognizes them as the best-matched characters by the Microsoft Handwritten Recognition Engine. The two clock hands will be identified by their relative locations, angles, and the size of the strokes.

- **Additional Refinement Filter:** After the first recognition result is generated, an additional refinement filter enhances recognition accuracy by correcting misrecognized characters. The most frequent errors are misclassifications of numerical digits as alphabet characters. We implemented the Context-Bounded Filter Algorithm (CBFA) [31] to convert the recognized characters into appropriate numeric digits using constraint predicates.

- **Final Output:** When the recognition process is over, the program analyzes the relative position between each number and scores, and stores them into a database with given schemas.

The most important elements in a computerized clock drawing are the recognized numbers. This is also the first challenge we faced when implementing the system. A stroke is a computerized drawing element composed of a series of packet points from a tablet computer when users put down the stylus on the screen until they lift it up. Figure 6 shows that there are three categories for strokes to represent the numbers in a clock drawing: one stroke for a single digit, multiple strokes for a single digit (Figures 6-A and 6-C), and two single-digit characters for a double-digit character (Figure 6-B).

These categories are determined by whether they are close to each other and by the contextual information in the clock. According to the location and the size of the strokes in each category, we create bounding rectangles as the recognition region for the generic recognition engine to make the best decisions. However, the recognition engine cannot always give us accurate results because it excludes the contextual understanding of handwritten data. For example, it would misrecognize 6 as 9 or 1 as l. For these cases, the Context-Bounded Filter Algorithm (CBFA) comes in and helps refine the results [16]. The CBFA uses the relative locations between each number and the clock circle to decide whether the results from the generic recognition engine are correct.

In order to calculate the relative locations, we also need to convert the ink coordinate system used in the Ink Serial Format (ISF) file to the pixel coordinate system in which the circle is drawn. This conversion also benefits the calculation of the scores in the ClockAnalyzer Application.

4.2.3. **Data Structure**

These relative locations, relations between strokes, and recognition results are stored in a separate database, along with the original ISF file after a user presses the “recognize” button in the ClockMe Application. The goal is to represent the contextual information and collect the data in a clock when the participant is drawing a clock for the ClockReader Application to analyze and visualize.

In the database, the Clock_Stroke entity, which contains each packet point, bounding rectangles, and the properties, such as timestamps, is the most rudimentary object in this database. However, compared to the Stroke object in the ISF file, it has the relationship attributes to indicate the strokes related with it. For example, when two strokes compose the single digit “4,” such as Figure 6-A, we add the id key of the second stroke in 4 to the “MergeTo” attribute of the first stroke. Likewise, we also add the id key of the
first stroke to the “MergeTo” attribute of the second stroke. In the case of a two-digit number, we simply add the id of the associated stroke(s) in one digit to the “CombineTo” attribute of the stroke in the other. With these relationships, the bounding rectangles of multiple strokes for one digit and two digits for one number can be calculated from the bounding rectangle of one single stroke when analyzing and visualizing in the ClockReader Application. Figure 7 shows the structure of the database.

![Database Diagram](image)

**Fig. 7. Database for storing the contextual information relating to the circle**

4.3. **The ClockAnalyzer Application: Clinician Side**

4.3.1. **User Interface of the ClockAnalyzer**

The ClockAnalyzer Application is a tool for medical practitioners. The ClockAnalyzer is designed to support the medical practitioner’s decision-making by performing several different analyses of the automated data collection. For example, the ClockAnalyzer will help doctors analyze the data by automatically scoring the criteria, as well as by creating graphs from the existing data. The goal of the ClockAnalyzer UI design is to provide medical practitioners with a data analysis and an interpretation effectively through multiple visualization methods.

![User Interface](image)

**As can be seen in Figure 8, the user interface of the ClockAnalyzer Application consists of three main parts: the Drawing Output area, the Analysis area, and the Monitoring panel. The drawing output area is in the top left window. We provide two different drawing outputs: static drawing and active animated drawing. When a user opens a patient’s file, the user sees the static clock drawing from the CDT. The static drawing becomes an animation when a user clicks the “Arrow” button at the bottom of the window. The “Arrow” button plays the role of a video playback button. To reset the animation to its initial status, a user needs to click the “Clean” button.**

![User Interface](image)

**Fig. 9. The User Interface of the ClockAnalyzer: Scoring Tab**

As can be seen in Figure 9, the Analysis area is in the top right area of the UI. The Analysis area in-
cludes three different tabs: Scoring, Graph, and Monitoring. Each tab shows different information. The Scoring Tab shows two types of data: Scores and Sequences. The CDT results are evaluated by Freedman et al.’s 13-point CDT criteria. If a patient’s CDT drawing applies each criterion, the green-color check is shown. The Sequences show how a user constructs a clock with a specific sequence. The timestamps of each stroke for each number can help clinicians inspect the patient’s drawing strategies. While a patient without dementia could use a strategic way to draw a clock (e.g., 12, 3, 6, 9, or 1, 2, 3, 4), a patient with dementia may exhibit a haphazard manner of arranging the numbers properly. For example, in Figure 9, a user drew a clock by first writing 12, 3, 6, 9, and then filled out the remaining numbers.

Fig. 10. User Interface of the ClockAnalyzer: Graph Tab

The Graph Tab shown in Figure 10 shows two different graphs: Millisecond Airtime vs. Recognized Characters and Pressure vs. Recognized Characters. The airtime and pressure data are two novel types of data that the computerized system can provide. The Airtime is measured by the sensor to calculate how many milliseconds a pen is up in the air versus how long the pen is on the screen. The pressure is also measured by the pressure sensor embedded in the Tablet PC. For more information about using novel data for clinical purposes, please refer to the next section: Features of the ClockMe System as Automated Novel Data Collection.

The third tab, the Monitoring Tab, relates to the bottom panel. This bottom panel shows the Monitoring Panel, which includes multiple clock drawings of a patient collected over time (e.g., weeks, months or multiple years) for easy comparison. The Monitoring tab will show a graph of historical CDT results, which provide a quick overview of the patient’s cognitive condition.

4.3.2. Features of the ClockAnalyzer

The ClockAnalyzer application is an application for medical practitioners to retrieve a particular participant’s data for analysis. The application needs to provide practitioners with visualized data in an efficient way. There are three types of data that the computerized ClockReader application can provide: clock drawings, scores, and analytical charts from associated data. Clock drawings from patients are the most important one. Because the spatial and temporal data of each stroke are captured in the first place, the application can reconstruct the drawing accurately. In addition to static drawings, the animated drawings provide a new way for doctors to understand how a clock was constructed. Capturing the drawing process is not a new concept. In 1988, Kaplan, a leading neuropsychologist, argued that the best way to understand a patient’s performance was based on a process-oriented approach [14]. Despite the importance of the concept, it has been hard to utilize this approach in current clinical practice.

The timestamps of each stroke in each number character can also help doctors inspect the patients’ drawing strategies. While a patient without cognitive impairment could use a strategic way to draw a clock (e.g., 12, 3, 6, 9, or 1, 2, 3, 4), a patient with dementia may not be able to arrange the numbers properly. Besides showing the drawing sequences, the application also highlights the numbers in the drawing when practitioners move their mouse cursors over these sequence numbers in the UI.

The scoring criteria also provide a standard way to evaluate the patients’ conditions. When the application loads the clocks in the database, it will calculate these criteria automatically and will save a tremendous amount of time for practitioners. However, there are still a few cases when the recognition engine incorrectly recognizes the number. In these cases, the application allows practitioners to correct the numbers and recalculate the scores automatically.

In addition to a single clock drawing, multiple drawing data will be organized sequentially so that doctors can monitor the history of the participant. In addition, doctors will be able to see the data represented by a chart or graph throughout the application. The airtime and pressure charts are two novel ways that a computerized system can provide data in addi-
tion to a clock drawing. When drawing a clock, at a certain time in the drawing process, the patient may hesitate and pause, perhaps due to memory problems. Or perhaps they may experience difficulty in recalling a specific number on the clock face. When this happens, the airtime charts will indicate significant changes as a useful indicator for clinicians to identify a particular problem.

Figure 11 shows the current visualization scheme for displaying airtime. The x-axis indicates the sequential order of numbers when a patient drew a clock. The y-axis indicates the airtime between each stroke. We note that regular people would have longer airtime in the first few strokes because they are trying to arrange the space for each number. However, in a dementia or Alzheimer patient’s drawing, we would see a different pattern. In general, there are two critical moments in which they spend longer time thinking before drawing something: drawing initiation and time setting.

Even though we do not have a concrete theory to support whether pressure charts can provide evidence for diagnosis purposes, these alternative data can give clinicians additional information about the drawing behaviors, such as when a patient’s hand is shaking.

In short, the computerized testing system makes it possible to gather novel behavioral data, such as airtime, the tendency to pause, patterns of exerting pressure, and the drawing sequence. Thus, we are in collaboration with research specialists on Alzheimer’s disease at Emory Hospital to investigate how these additional behavioral data can be applied for better diagnosis and treatment, or how they can be used as a tool to verify clinical hypotheses.

5. Preliminary User Evaluation

We evaluated the recognition accuracy and usability of the Tablet PC-based ClockReader System with twenty people. We are interested in finding out whether ClockReader results more accurate measurement than the paper-based system. For example, we asked questions such as, “How accurate is the recognition rate with our filtering algorithm? And, “Does our Tablet-PC based ClockReader System yield the same results as the traditional paper-and-pencil-based Clock Drawing Test?” In this section, we first report our study participants’ background information and then describe the recognition accuracy and usability results.

5.1. Study Participants

The participants were recruited from the HONOR Research Registry in Clinical Research in Neurology (CRIN) at the Emory Alzheimer’s Disease Research Center in Atlanta. In order to enroll in HONOR, participants must either be over 70 with no memory problems or of any age with mild cognitive impairment, very mild memory or thinking problems, or mild to moderate Alzheimer’s disease.

The twenty participants consisted of 12 females and 8 males. The average age of the participants was 75 years old. The age distribution was somewhat different than the average. Ten participants were older than 78. The oldest participant was a 98-year-old, and the youngest participant was a 59-year-old. Their educational levels were diverse. Six participants had high school diplomas. Seven participants were college graduates. The last seven participants had a graduate-level education. Their computer literacy levels were also mixed. Three people had never used a computer before. On the other hand, some of them regularly used computers as a daily routine.

5.2. Recognition Accuracy

We asked our study participants to draw a clock in order to understand the handwritten digit accuracy rates of the system. The entire process is captured by the ClockReader system as well as by the Camtasia Studio desktop recording program. The external recording program helped us investigate several unexpected errors. With the movie generated by the program, we were able to observe the in-depth context of an individual patient’s drawing activity.
Figure 12 shows the recognition rates of the twenty participants. The x-axis indicates the individual user’s ID number. The y-axis indicates the recognized rates per individual user. Four of the participants, namely u4, u12, u13, and u20, showed 100% recognition accuracy. Seven participants, namely u2, u3, u5, u7, u8, u14, and u17 showed 93% recognition accuracy. The remaining nine participants, namely u1, u6, u9, u10, u11, u15, u16, u18, and u19 showed 73% recognition accuracy.

Overall, the average recognition accuracy rate was 85%. The way we calculated the rate was by how many digits were correctly recognized out of 15 digits. Our digit recognition algorithm detects each digit individually within two-digit numbers, such as 10, 11, and 12. Thus, the total digits are 15 instead of 12. Most misrecognized numbers are either 7 or 8. They were recognized as 1 or 0 respectively.

Based on the results, we learned that we could add an additional filtering to track the order of strokes in each digit so as to find how many times the stroke changes its direction, and toward which direction the stroke changes. For example, the number 8 is often misrecognized as the number 0 due to the similarity in the shapes of both numbers. However, the system can algorithmically identify the two numbers not just by analyzing the general shape, but also by comparing the number of direction changes between those two numbers. We can see that the number 8 has 4 curved segments that are convex to the left, right, left, and right and that the number 0 has only 2 curved segments that are convex to the left and right in the order of sequence. These could be unique signatures for each number. We will apply this additional algorithm for the numbers 1, 7, 4, and 9, which are often misrecognized as other numbers in order to reduce the possibility of misrecognition.

5.3. Usability

We conducted a usability comparison study with the twenty HONOR research volunteers. The procedures of the usability test consisted of 1) a computer familiarity survey, 2) a drawing comparison, and 3) other free drawing tasks. Each user took less than 10 minutes to complete this task. The survey results of computer familiarity show that most participants considered themselves as having low computer literacy. This is not surprising, considering the participants’ average ages. However, unlike their self-reported computer literacy, the comparisons of drawings indicate that there were no critical difficulties for older adults when using a Tablet PC. Figure 13 shows how a user interacts with the system.
6. Conclusion and Future Work

In this paper, we have presented our approach to developing a sketch-based cognitive screening tool, the ClockMe System, by implementing online sketch-recognition algorithms. Among many other trials intended to cure neurodegenerative diseases, prevention through delay is currently proposed as the best way to tackle dementia. The Clock Drawing Test is a rapid and reliable instrument for the early detection of cognitive dysfunction. With the ClockReader System, a patient can self administer the Clock Drawing Test at home without the presence of a human evaluator.

For our next step, we will develop an interface that enables clinicians to integrate all of the data collected from the ClockReader Application. The automatically collected computer-generated data will likely assist medical practitioners in making timely and appropriate data-based decisions. The ultimate goal of the ClockMe System is to identify the early stages of dementia so that clinicians can help delay or prevent the progression of the disease and increase the quality of life for aging people. Lastly, this study may have a lasting impact on our society, showing the potential of a novel, quick-and-easy screening tool. Moreover, our study shows timely promise for computerized screening systems to get out of the research lab and become situated in the home environment.

7. Acknowledgments

This work is supported by a Health System Institute Seed Grant at the Georgia Institute of Technology, the feasibility study grant at the Korea Institute for the Advancement of Technology (KIAT)’s Global Industry Academia Cooperation Program, Emory ADRC (P50 AG025688) and ACTSI (supported in part by PHS Grant UL1 RR025008, KL2 RR025009 or TL1 RR025010 from the Clinical and Translation al Science Award program, National Institutes of Health, National Center for Research Resources).

This material is based upon work supported by the National Science Foundation under Grant No 1117665 (SHB). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

We thank our collaborating researchers and medical practitioners at the Emory Alzheimer’s Disease Research Center for their valuable feedback on the development of the ClockReader System. We also appreciate the volunteers who participated in our usability testing.

References

Molecular Genetics and Metabolism 102(2) (2011), 210-213.


