Methods for Transition Toward Computer Assisted Cognitive Examination

P. Jurica1; S. Valenzi1; Z. R. Struzik1; A. Cichocki1,2
1RIKEN Brain Science Institute, Wako-shi, Saitama, Japan;
2Systems Research Institute, Polish Academy of Sciences, Warsaw, Poland

Keywords
Cognitive test, cognitive impairment, health information exchange, health information database, open-source, software framework, Python programming language, computer-aided diagnosis

Summary
Introduction: We present a software framework which enables the extension of current methods for the assessment of cognitive fitness using recent technological advances. Background: Screening for cognitive impairment is becoming more important as the world’s population grows older. Current methods could be enhanced by use of computers. Introduction of new methods to clinics requires basic tools for collection and communication of collected data. Objectives: To develop tools that, with minimal interference, offer new opportunities for the enhancement of the current interview based cognitive examinations. Methods: We suggest methods and discuss process by which established cognitive tests can be adapted for data collection through digitization by pen enabled tablets. We discuss a number of methods for evaluation of collected data, which promise to increase the resolution and objectivity of the common scoring strategy based on visual inspection. By involving computers in the roles of both instructing and scoring, we aim to increase the precision and reproducibility of cognitive examination. Results: The tools provided in Python framework CogExTools available at http://bsp.brain.riken.jp/cogextools/ enable the design, application and evaluation of screening tests for assessment of cognitive impairment. The toolbox is a research platform; it represents a foundation for further collaborative development by the wider research community and enthusiasts. It is free to download and use, and open-source. Conclusion: We introduce a set of open-source tools that facilitate the design and development of new cognitive tests for modern technology. We provide these tools in order to enable the adaptation of technology for cognitive examination in clinical settings. The tools provide the first step in a possible transition toward standardized mental state examination using computers.

1. Introduction
Numerous screening tests exist that quantitatively assess the onset and progress of cognitive impairment [1–12]. A specific subset of such tests is based on an interview between an examiner and a subject [1]. Interviews require no setting up, only basic training, and their usefulness has been approved by their continuous use for more than 40 years [1, 2]. The methods work well, in spite of the unpredictability of subjects, who usually come from the elderly population and have a high variability in the level of cognitive and physical abilities. For these reasons interviews retain their popularity.

A radical change in this process will likely be met with scepticism [3–5, 13, 14]. However, interview based cognitive examination was developed before the age of computing and data mining, and we believe it is now time to adapt cognitive examination to the age of computing. We identify two areas in which the established methods could be improved without drastic intervention. We discuss here methods which, with minimal changes to current protocols (regular interview examinations), allow: 1) collection and storage of large amounts of data for future analysis, 2) enhancement of the objectivity and precision of grading of the cognitive performance of subjects, and 3) retrospective analysis of data collected during repeated testing of subjects with the progress of disorders.

Recent studies suggested that signatures of cognitive decline may be hidden in process variables related to the planning and execution of movement [15–21]. Handwriting, for which visual integration, motor planning and memory are essential, attracts attention of researchers due to accessibility of high precision measurement tools [15, 17, 18]. Data from subjects is collected using pen tracking and handwriting digitization. It has been already shown that the analysis of handwriting and involuntary hand movements aid in the diagnosis of cognitive disorders [15–22]. Handwriting has also been studied during execution of variants of known cognitive examination tasks [16, 22]. These discoveries need more
support from further research, but more importantly from clinics, where data can be collected from real patients in real world setting.

Our contribution to this promising new path of study of cognitive examination is a framework and a set of tools, freely available to researchers and clinicians, which could facilitate the exchange of data and guidelines for adapting examinations to modern computer hardware.

2. Approach

The main goal of the framework presented here is to enable the transition of cognitive examinations to the most recent methods of data collection and analysis. This should be done with minimal intervention to current procedures.

The transition will require computerization of the established processes. The use of computers and computer aided methods for mental and physical fitness examination [3–5, 14] and monitoring [23, 24] is motivated by their objectivity. Computers perform examinations in a controlled manner, which can be replicated independently of the human medical examiner. Acquisition of data by computers also enables the analysis of recorded data by the most recently available statistical tools. This, as opposed to evaluation by humans, means that subjectivity and personal biases are not introduced into the scores.

It is important that computerization does not disrupt established procedures for examiners and their subjects. For this reason we focus on cognitive examinations which involve written or drawn responses. Responses in such tests are recorded through pen input digitizers, obtained by simply replacing a regular pen with a pen that records the motion of subject’s hand [15–21] (Figure 1). Such devices are portable and can be easily installed in a doctor’s surgery.

Collection of data through computers will increase objectivity and precision. At the moment, most cognitive assessment suites use a rough scoring table [1, 2, 6–12], which classifies subjects into a few categories (i.e. normal, mild cognitive impairment or MCI, severe impairment). Cognitive assessment is performed mostly on elderly subjects, and is initiated following complaints about the subject’s cognitive ability. The current tests are therefore designed to test the severity of already existing cognitive impairment. For example, in the Mini-Mental State Exam (MMSE) scores range from 0 to 30 [2, 6], but the scale devotes only 3 points (10%) to subjects who are considered normal. In our opinion, this is the part of the scale that could be used to estimate the onset of impairment and its progress in the near future. Although we want to preserve the applicability of the test to the rating of cognitive impairment, we would like to steer the development toward tools that will allow us to understand how such a subject’s score changes over time (c.f. [25]). Thus, we would like to gain insight into the time course of the impairment, into when and how it appears and how it develops. Such observations require a better sensitivity (or resolution) to usually slowly declining cognitive function.

Computerized cognitive examination will provide more data about subjects. So far, cognitive examination has been used for occasional and immediate evaluation of cognitive state. However, data recorded from computerized examinations can be stored, and enables retrospective studies and re-analysis as new methods emerge. One prominent example of retrospective study [25] recently delivered promising results in the context of memory impairment detection from a review of subject’s long term records.

Hence, if the outlined approach is successful we expect the most benefit in early detection of cognitive impairment, of its onset and its progress. Targeting this group will also minimize the expected interference from adjustment of established procedures and introduction of new measurement devices.

3. Methods

3.1 Handwriting Digitization

To solve the task, we take advantage of the fact that parts of cognitive examinations are based on written or drawn responses. Examinations relying on pen input can be adapted to a variety of devices [15, 16]. Wacom tablets offer very high precision in space and time (Table 1). It is, however, also possible to use other, consumer level, touch enabled tablets (Figure 1B). Such tablets do not offer high precision of recordings, but offer the possibility to reach many subjects and allow collection of data remotely, even over the Internet (c.f. [5]).

3.2 Tasks

Automated analysis of pen input in the context of mental health evaluation is very new and untested. The best chance of getting applicable results is by adopting tasks from established examinations. We have made an extensive search among popular tests [1–12] and selected a number of tasks that either rely on drawing or writing, or can be easily adapted for pen input.
Data could be analyzed by engineers, but it is more desirable to rely on the experience of clinicians in judging the validity and meaning of the data. Examinations performed using Wacom tablets (Figure 1A) obtain results on a sheet of paper, as until now. On top of that, our toolkit provides tools for plotting collected digital data. These tools can reproduce the traditional hand-filled sheets through visualization (plotting) and printing of digital data. This approach works also with data collected on other tablets (Figure 1B). The framework also allows the enhancement, or annotation, of collected drawings (Figure 2B–C). We hope the options of known and new methods will facilitate the acceptance of the technology, and spark interest in alternative methods of data evaluation. Such methods will most likely come from collaborations between researchers and clinicians, enabled through a common framework.

## 4. Results

### 4.1 Open-source Toolbox

We have developed tools that allow: 1) the design of an examination procedure, 2) presentation and control of the examination and data collection, and 3) data analysis. The development of different parts of this framework requires expertise in different backgrounds, ranging from psychology to computer science. We have built the system with the goal of ensuring that the presentation and data collection can be reliably performed by laboratory technicians or nurses without any technical background. All the tools we suggest are open-source and freely available and can be easily installed on a modern PC using any major operating system. The tools described here are available through project’s web-page at http://bsp.brain.riken.jp/cogextools/.

### 4.2 Examination Design for Tablet Data Collection

The sheets used in our experiments are designed in an open-source and free desktop publishing tool called Inkscape (www.inkscape.org). The reason for this choice is the large amount of data collected using input digitizers has to be translated for interpretation by examiners. The interpretation presents another possible source of interference with established procedures.

### 3.3 Examination and Evaluation

The control of examination stays in the hands of an examiner. This is one measure which mitigates the interference from novelty. The computer aids the examiner in controlling the process of the examination. However, we would rely on the experience of clinicians in order to find a good balance between tasks which provide data and tasks which keep subjects comfortable. When appropriate, interview can be guided by the doctor. Instructions provided by the examiner are more natural and the whole process is similar to a regular doctor’s visit. Such an approach might be suitable for testing subjects with MCI or more severe impairments. Whenever possible, instructions in a more controlled manner should be provided by either a pre-recorded video or a sequence of images on a computer.

Computer aided execution of the mental fitness test will ensure that the order and precise timing is controlled and replaceable. For the sake of analysis, it is important to design tasks which maximize the amount of data obtained for analysis. A convenient example, inspired by handwriting studies [17–21], is a task composed of the repetitive drawing of simple shapes. An example instruction could be: “Please draw five circles anticlockwise”. The analysis of data then concentrates on the precision, speed and correctness of motion according to the instructions [17–22]. Beside the kinematics, the digitized results can be inspected for correctness; in the context of our example instruction: Was the circle drawn the correct number of times? Was it drawn in the correct direction? Was the speed of execution uniform? Finally, digitized handwriting contains information on the timing of stroke execution and the subjects’ reaction times.

The sheets used in our experiments are designed in an open-source and free desktop publishing tool called Inkscape (www.inkscape.org). The reason for this choice is

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tablet specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model name</td>
<td>Wacom Intuos5</td>
</tr>
<tr>
<td>Movement resolution</td>
<td>5080 lpi (lines per inch)</td>
</tr>
<tr>
<td>Accuracy</td>
<td>± 0.01 in (± 0.254 mm)</td>
</tr>
<tr>
<td>Pressure levels</td>
<td>2048</td>
</tr>
<tr>
<td>Sampling frequency</td>
<td>Up to 250 Hz</td>
</tr>
<tr>
<td>Active area</td>
<td>12.8 x 8 in (~32.5 x 20.3 cm)</td>
</tr>
<tr>
<td></td>
<td>10.6 x 5.7 in (~25.7 x 14.4 cm)</td>
</tr>
</tbody>
</table>

Figure 2 shows examples of three such cognitive tasks (used in MoCA [8], MMSE). Figure 2A shows a simple questionnaire adapted for pen input digitizer. Responses in verbal interviews can be also recorded through forms, e.g. by circling answers or filling check boxes. Interviews adapted this way provide additional data, which could be analyzed for correctness, precision and speed of their completion. Figure 2B shows data collected from the Clock Drawing Test (CDT) [12, 22], and Figure 2C illustrates a spiral drawing test [15]. The tasks were selected in order to test specific aspects of mental fitness, such as memory, attention or motivation, and adapted in order to maximize the amount of data captured by the sensors in the tablet’s pen. Test sheets for tasks described can be obtained with the tools through a website created for this project at http://bsp.brain.riken.jp/cogextools/.

Many popular cognitive examinations put high emphasis on verbal exchange. Such tests alone do not provide many opportunities for digitization of responses. Digital data can be collected in such cases through questionnaires (Figure 2A), or by means of alternative tasks. Questions in verbal interviews are designed in order to perturb and test specific cognitive functions; often tasks with similar intent, yet designed for drawing, either exist or can be developed.

## Table 1

Pen input digitizer specifications. The table shows a comparison of two tablets used for the recorded data presented.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tablet specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model name</td>
<td>Wacom Intuos5</td>
</tr>
<tr>
<td>Movement resolution</td>
<td>5080 lpi (lines per inch)</td>
</tr>
<tr>
<td>Accuracy</td>
<td>± 0.01 in (± 0.254 mm)</td>
</tr>
<tr>
<td>Pressure levels</td>
<td>2048</td>
</tr>
<tr>
<td>Sampling frequency</td>
<td>Up to 250 Hz</td>
</tr>
<tr>
<td>Active area</td>
<td>12.8 x 8 in (~32.5 x 20.3 cm)</td>
</tr>
</tbody>
</table>

Figure 1A shows a simple questionnaire adapted for pen input digitizer. Responses in verbal interviews can be also recorded through forms, e.g. by circling answers or filling check boxes. Interviews adapted this way provide additional data, which could be analyzed for correctness, precision and speed of their completion. Figure 1B shows data collected from the Clock Drawing Test (CDT) [12, 22], and Figure 1C illustrates a spiral drawing test [15]. The tasks were selected in order to test specific aspects of mental fitness, such as memory, attention or motivation, and adapted in order to maximize the amount of data captured by the sensors in the tablet’s pen. Test sheets for tasks described can be obtained with the tools through a website created for this project at http://bsp.brain.riken.jp/cogextools/.

Many popular cognitive examinations put high emphasis on verbal exchange. Such tests alone do not provide many opportunities for digitization of responses. Digital data can be collected in such cases through questionnaires (Figure 2A), or by means of alternative tasks. Questions in verbal interviews are designed in order to perturb and test specific cognitive functions; often tasks with similar intent, yet designed for drawing, either exist or can be developed.

## Table 1

Pen input digitizer specifications. The table shows a comparison of two tablets used for the recorded data presented.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tablet specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model name</td>
<td>Wacom Intuos5</td>
</tr>
<tr>
<td>Movement resolution</td>
<td>5080 lpi (lines per inch)</td>
</tr>
<tr>
<td>Accuracy</td>
<td>± 0.01 in (± 0.254 mm)</td>
</tr>
<tr>
<td>Pressure levels</td>
<td>2048</td>
</tr>
<tr>
<td>Sampling frequency</td>
<td>Up to 250 Hz</td>
</tr>
<tr>
<td>Active area</td>
<td>12.8 x 8 in (~32.5 x 20.3 cm)</td>
</tr>
</tbody>
</table>

Figure 1A shows a simple questionnaire adapted for pen input digitizer. Responses in verbal interviews can be also recorded through forms, e.g. by circling answers or filling check boxes. Interviews adapted this way provide additional data, which could be analyzed for correctness, precision and speed of their completion. Figure 1B shows data collected from the Clock Drawing Test (CDT) [12, 22], and Figure 1C illustrates a spiral drawing test [15]. The tasks were selected in order to test specific aspects of mental fitness, such as memory, attention or motivation, and adapted in order to maximize the amount of data captured by the sensors in the tablet’s pen. Test sheets for tasks described can be obtained with the tools through a website created for this project at http://bsp.brain.riken.jp/cogextools/.

Many popular cognitive examinations put high emphasis on verbal exchange. Such tests alone do not provide many opportunities for digitization of responses. Digital data can be collected in such cases through questionnaires (Figure 2A), or by means of alternative tasks. Questions in verbal interviews are designed in order to perturb and test specific cognitive functions; often tasks with similar intent, yet designed for drawing, either exist or can be developed.

## Table 1

Pen input digitizer specifications. The table shows a comparison of two tablets used for the recorded data presented.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tablet specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model name</td>
<td>Wacom Intuos5</td>
</tr>
<tr>
<td>Movement resolution</td>
<td>5080 lpi (lines per inch)</td>
</tr>
<tr>
<td>Accuracy</td>
<td>± 0.01 in (± 0.254 mm)</td>
</tr>
<tr>
<td>Pressure levels</td>
<td>2048</td>
</tr>
<tr>
<td>Sampling frequency</td>
<td>Up to 250 Hz</td>
</tr>
<tr>
<td>Active area</td>
<td>12.8 x 8 in (~32.5 x 20.3 cm)</td>
</tr>
</tbody>
</table>

Figure 1A shows a simple questionnaire adapted for pen input digitizer. Responses in verbal interviews can be also recorded through forms, e.g. by circling answers or filling check boxes. Interviews adapted this way provide additional data, which could be analyzed for correctness, precision and speed of their completion. Figure 1B shows data collected from the Clock Drawing Test (CDT) [12, 22], and Figure 1C illustrates a spiral drawing test [15]. The tasks were selected in order to test specific aspects of mental fitness, such as memory, attention or motivation, and adapted in order to maximize the amount of data captured by the sensors in the tablet’s pen. Test sheets for tasks described can be obtained with the tools through a website created for this project at http://bsp.brain.riken.jp/cogextools/.

Many popular cognitive examinations put high emphasis on verbal exchange. Such tests alone do not provide many opportunities for digitization of responses. Digital data can be collected in such cases through questionnaires (Figure 2A), or by means of alternative tasks. Questions in verbal interviews are designed in order to perturb and test specific cognitive functions; often tasks with similar intent, yet designed for drawing, either exist or can be developed.

## Table 1

Pen input digitizer specifications. The table shows a comparison of two tablets used for the recorded data presented.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Tablet specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model name</td>
<td>Wacom Intuos5</td>
</tr>
<tr>
<td>Movement resolution</td>
<td>5080 lpi (lines per inch)</td>
</tr>
<tr>
<td>Accuracy</td>
<td>± 0.01 in (± 0.254 mm)</td>
</tr>
<tr>
<td>Pressure levels</td>
<td>2048</td>
</tr>
<tr>
<td>Sampling frequency</td>
<td>Up to 250 Hz</td>
</tr>
<tr>
<td>Active area</td>
<td>12.8 x 8 in (~32.5 x 20.3 cm)</td>
</tr>
</tbody>
</table>
the accessibility of this software and the fact that it is built around an open SVG format for storing designs. Other tools for design of vector graphics (i.e. Corel Draw, Adobe Illustrator) could be adopted as well if they support the export of designs to SVG format.

The Inkscape application is useful in a number of additional tasks. Inkscape allows easy automated export of designs to PDFs for printing, or raster images. The SVG format is a human-readable mark-up format similar to HTML. Design elements and their coordinates can be accessed from data analysis programs in order to enable automated evaluation of recorded input. Text of instructions is stored in its raw form, which means that sheets can be easily translated into other spoken languages even without the use of a graphical editor.

4.3 Data Collection

We have developed two methods for the presentation and data collection of pen input data. Both methods come in the form of an executable application in the CogExTools package. The first method allows collection of data using a modified pen, when responses are filled in on ordinary paper. The examination sheets (example in Figure 2A) are printed on a sheet of paper and placed on a surface that digitizes pen input (Figure 1A). The second method allows the collection of data on numerous consumer level devices such as tablets and touch enabled notebooks and monitors, some of which come with a pen (Figure 1B). The same sheets used for examination using pen and paper, stored in SVG format, are displayed on the screen and input is enabled by the tablet’s pen or even the touch of a finger.

4.4 Data Analysis

We discuss three approaches to the analysis of the data collected, but more are possible.

The first method of evaluation, and the one which requires the least explanation, is the established method by visual inspection and instruction guided scoring [1]. Even this evaluation method can benefit from tools provided in our toolbox. The recorded digitized pen input can be plotted while emphasizing certain properties of handwriting. We show such depictions in Figure 3B–C. The pen digitizer used in the experiment recorded stroke pressure. The pressure during handwriting is variable; such changes are visible to the naked eye only if the changes are substantial. We can amplify and visualize the pressure as the width and colour of the pen stroke (Figure 3B–C). Precision recording also allows us to draw each separate stroke in a different colour. Both these enhancements can be implemented for post hoc and on-line analysis, and for real-time evaluation.

Figure 2 Tools for the evaluation of properties of handwriting. A) Example of interview questions adapted for pen input (red ellipses mark correct choice). B) Results of clock drawing test, with each stroke automatically plotted in a different colour. The local pressure is emphasized using circular markers of different size. The thin red line shows pen’s in-air trajectory between strokes. C) Pressure visualization using markers displaying the location every 25 ms. D) Visualization of parameters recorded during execution of spiral drawing task. From top: speed, pressure, angle from tablet normal. Right: Phase of circular motion (computed relative to the centre of the spiral) as a function of the radius. The dashed line shows linear regression of the data. The inset shows the normalized histogram of errors (difference of radius and value on the regression line.)
scoring. We take advantage of the fact that the SVG format allows inclusion of invisible layers. We use such invisible layers in order to store the “correct” solution templates (red elements in Figure 2A). Each sheet requires the design of an algorithm that translates collected data into scores. Such algorithms have to be developed and tuned following scoring instructions for the existing cognitive examination task [16, 22]. This scoring will help in immediate automated evaluation. However, we should keep in mind that with retrospective analysis, it might be possible to revise all scoring analysis as more data is collected and experience in the analysis of such data is accumulated.

The last method of scoring we demonstrate is the evaluation of the dynamics and kinematics of the subject’s handwriting [17–21]. On paper, circles are circles; however there may be infinite ways of drawing them. Post hoc analysis of the trajectory of the pen allows us to see the direction, number of strokes, the speed and the precision of the subject’s pen during the execution of a task. In Figure 2D, we show the temporal course of some parameters recorded during the execution of a spiral drawing task.

The methods of evaluation described so far are examples created in order to test the application of our toolset for cognitive examination. Our hope is that over time and with increasing use of the described platform, the data collected in many experiments with a variety of subject categories will allow us to select analysis methods that are the most efficient in the classification of subjects with different conditions. A growing body of data will allow us to use more complex statistical analyses that are employed in other branches of science. Algorithms need to be designed by data researchers and engineers, but useful outcomes will most likely come only with the critical evaluation from experienced clinicians.

5. Discussion

We have developed a toolbox that facilitates the extension of the current interview based cognitive evaluation in the age of computing and big data mining. We have presented a number of examples of how mental examination scoring can be improved in resolution and possibly in accuracy, and definitely in objectivity. All the tasks we suggest here result in data that are anonymous, collected by non-invasive methods. The tasks were designed with privacy and feasibility of application by non-engineers in mind.

The common approach to mental state evaluation is an interview with a doctor, possibly in the presence of a nurse. The adjustments suggested here preserve this possibility. The operation of the tools provided in this package does not require extensive training or the introduction and explanation of specialized machinery. The examination requires none or minimal setup of a tablet, and it does not have to be tied to a specific location. The approach we adopt allows us to collect more data in a controlled manner while preserving the general structure of examination.

Any introduction of a new tool into established procedure faces a major issue of possible interference. Technology may disrupt tested procedures acquired by examiners or it can distract subjects. We chose the hand-written input digitizing tablets with these concerns in mind. Tablets are now ubiquitous and those used by professionals, such as Wacom (Figure 1A), appear as a slightly bulky writing pad. It is possible that digitizing tablets are already present in some clinics.

The first iteration of our toolkit targets specific devices, but the toolkit is open and created for extensibility. Our framework can serve as a standardizing platform. All our analysis tools can be applied to data collected from any device if the data is stored in format chosen by us.

The analysis tools we provided were designed to provide output familiar to clinicians. We chose this approach to ease the transition toward new methods of evaluation. Experienced clinicians can view collected data in the traditional form, but they can extend their horizons through a variety of new views of the data (Figure 2B–D). Our framework provides examples of analysis methods used previously [15–19, 26, 27]. It would be beneficial if those examples and other attempts for automated evaluation of figure drawing [16, 22] were developed for data collected on a standard platform. Adoption of a common framework, such as the one we provide, will make this possible.

Our toolkit in its current form presents an initial step toward a standardized computerized cognitive examination. It offers a platform for collecting and analyzing performance of subjects during cognitive examinations. We have suggested a number of methods of automatic scoring on the very limited data available to us. In order to evaluate other possible approaches, we will need to wait until data from larger and sufficiently diverse populations are available. The future of this research depends on the brave individuals among clinicians that are willing to try out the software and explore the new opportunities that pen input digitizers offer. We hope new methods of performance analysis will emerge as more data becomes available. The most likely future of scoring algorithms for digitized handwriting is the use of machine learning techniques very popular among data scientists. Modern algorithms can search for similarities between subjects’ results in extremely large datasets. A highly positive outcome of such search will be the crucial elements of cognitive and physical ability that enable the diagnosis of cognitive decline.

References


