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Seethu M. Christopher[1(✉)], Corrie C. Urlings[2], Henri van den Bongarth[3], Karien M. Coppens[2], Petra P. M. Hurks[4], Lex Borghans[2], and Rico Möckel[1]

[1] Faculty of Science and Engineering, Maastricht University, Maastricht, The Netherlands
seethu.christopher@maastrichtuniversity.nl
[2] School of Business and Economics, Maastricht University, Maastricht, The Netherlands
[3] IDEE, Maastricht University, Maastricht, The Netherlands
[4] Faculty of Psychology and Neuroscience, Maastricht University, Maastricht, The Netherlands

Abstract. Standardized tests play an important role in assessing a child's cognitive capabilities. The results of such tests are used e.g. in schools and kindergartens to analyze and support the development of the tested child. Unfortunately, with classical standardized tests often only limited information on a child's behavior can be documented even by a professional observer. Obtaining detailed information would require automated data recording procedures. Also, standardized tests typically rely on well-controlled and thus rather artificial environments. As a result, young children age (e.g. with an age below 7) might not be able to fully understand the test instructions, feel uncomfortable being tested outside their natural environment, and thus test results become less relevant. Computer-based stealth-assessments that e.g. use a gaming environment to be fun and to hide the assessment from children might present a valid alternative. However, for children of lower age computer-based tests are not easily applicable due to technological boundaries. In this paper we thus explore an alternative approach: physical game devices with a look and feel similar to toys typically provided to children of their age group but that embed the electronics required for computer-based stealth testing. As a result, the game device – in our case a wooden tabletop maze – combines advantages of standardized computer-free and computer-based assessments. The device allows for stealth assessments in less structured environments without creating technological boundaries for the children.

Keywords: Intelligent games design · Digital toy · Cognitive assessments · Digital maze · Serious games

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1 Introduction

Cognitive assessments are useful to monitor a child's cognitive development [1, 2]. The field of psychology knows a variety of standardized tests targeting a variety of cognitive aspects. The Porteus Maze test [3] for instance is a nonverbal intelligence test developed to estimate psychological planning capacity and inhibition of a participant [4]. The Mazes subtest in WPPSI-R is another widely used test for assessing cognitive development of young children [5]. During these tests, children are confronted with mazes of varying complexity and instructed to solve as many mazes as possible within a given time. For this, children must trace through the mazes printed on paper with a pencil.

A key challenge with such standardized tests is that they rely on a professional observer to document the behavior of the participating children. A detailed recording of all potentially relevant behavioral information becomes not only impossible but also sometimes unreliable [6]. For instance to reach a high score in the Porteus Maze test, children are asked to solve mazes as efficiently as possible – by avoiding crossing maze lines, going into dead ends, without moving backwards, and lifting the pencil. The professional observer must record these features from the solved paper mazes by hand and calculate the final score. There might also be inconsistencies in the final score due to the complex scoring procedures, interrater reliability and administration difficulties [7]. Other potentially valuable information, like for instance at which maze position and for how long a child stopped drawing because the child planned the next actions, gets lost. Another criticism of standardized tests is that they require structured environments and are typically used under well-controlled conditions. Standardized tests thus can be stressful if the child has to leave his/her well-known environment or boring [8]. As a result, the child's motivation to participate in the test might drop and impact the test results [9].

To allow for maintaining high engagement of children during tests, to reduce the work load of testing professionals and to increase measurement accuracies, computer-based tests using game environments can present a valuable alternative to standardized pencil-and-paper tests [10]. Such computer-based tests have the additional advantage that they allow for collecting large amounts of detailed data in real-time. However, computer-based tests also always test a child's ability to adapt to and to handle the computer environment. In addition, computer-based tests cannot fully reassemble the interaction with and perception of natural environments. As a result, computer-based tests are often not suitable for young children for instance because of underdeveloped fine motor skills.

A better alternative might be to allow young children to play with tangible physical devices, as children naturally do during the continuous development of their skills [11]. Automated data collection then can be implemented e.g. by observing the participating child through computer vision. We for instance developed a setup where participants can play a game of Ludo using a physical game board. The game state was automatically captured through computer vision [12]. Digitized game moves could be assessed and processed automatically in a computer, but the participants would not be affected by the technology. However, reliable digitalization of game states through computer vision is susceptible to lighting conditions and occlusions, requiring optimal conditions and making it difficult to use in regular class room situations.

In this paper we thus explore the technology for yet another approach: we hide the required technology for digitalization and automated testing inside a physical game device. Inspired by the Porteus Maze test, a digital wooden maze device was developed that resembles those standard maze toys being used by children aged between 4 and 7. This digital wooden tabletop maze device is shown in Fig. 1(A). Inside the maze device, touch screen technology is hidden. The child moves a metal ball inside the wooden maze with a magnetic pen as shown in Fig. 1(C) without realizing that the pen and ball movements are automatically recorded, making it possible to do these tests in a less formal, child-oriented setting. In this paper we compare and analyze recordings automatically obtained by the wooden maze with recordings obtained from computer vision. For this, an overhead camera was installed as shown in Fig. 1(B).

From tests with children we show that the wooden maze can combine the advantages of both computer-based testing and classical standardized testing with physical objects. The digital wooden maze features automated data recording in real-time with high temporal and spatial resolution. Automated data analysis is performed offline on a standard PC. The maze is a physical object that fits on a table and is easy to use by young children who treat it like a standard toy without facing technological boundaries.

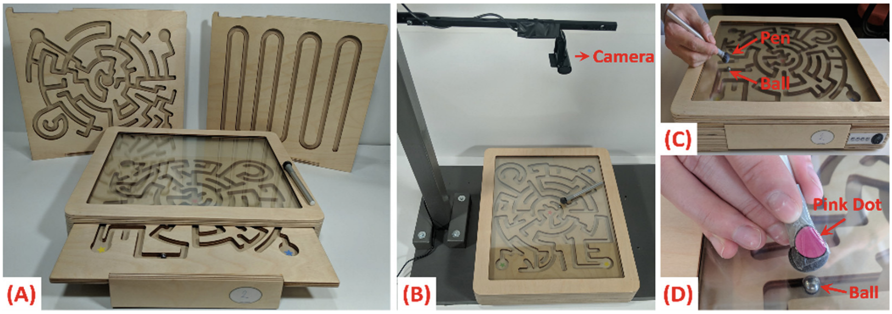

Fig. 1. **(A)**: Digital Wooden Maze device with the different interchangeable maze structures. **(B)**: Digital Maze setup with overhead camera for computer vision experiments; **(C)**: Digital maze with custom-made pen. **(D)**: Custom-made pen for controlling the magnetic ball. (Color figure online)

The remaining sections of this paper are organized as follows. Section 1 describes the digital wooden maze and data recording. Section 2 discusses the alternative approach of digitizing maze usage through computer vision. Section 3 and Sect. 4 present and discuss experimental results, respectively.

2 Digital Wooden Maze – Hardware and Data Processing

The digital wooden tabletop maze device (shown in Fig. 1(A)) weighs about 6.1 kg. Its material costs less than 600€. In low-volume fabrication a total price of less than 2500€ can be achieved. The maze device contains two separate touch screens placed back-to-back on top of each other. Screens are integrated into a wooden case as shown in the side view in Fig. 2(E). The wooden case and maze elements have been produced from sheets of Plywood that have been shaped through laser cutting and glued together. Inside the case and beneath the screens, the device contains a chamber that hosts the actual wooden maze structure. To allow for a variety of test items, we made the maze structures interchangeable. Figure 2(B–D) shows three existing wooden maze structures. The motor control structure (Fig. 2(D)) contains a single trace and was designed to gain insight into the base line (fine) motor capabilities of children. The assignment maze structure (Fig. 2(B)) allows testing children with three different maze solving tasks of increasing complexity. The exploration maze structure (shown in Fig. 2(C)) contains a free exploration maze pattern with which we want to gain insights into unstructured play behavior of children. The maze device contains four contact switches (Fig. 2(A)) that allow for automatic detection of the inserted maze structure due to different patterns milled into the top left corners of each maze structure (marked in red in Fig. 2(B–D)).

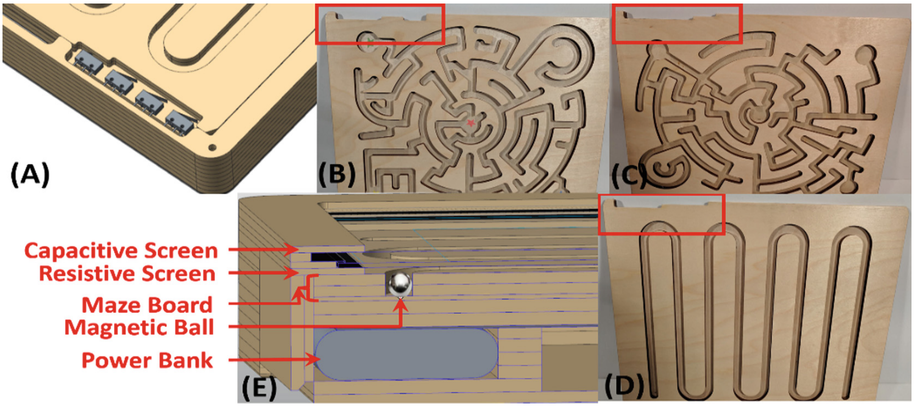

Fig. 2. **(A)**: Contact switches inside the digital wooden maze device allow the automatic detection of inserted maze structures: **(B)**: a maze structure with different assignments, **(C)**: a maze structure for free exploration, **(D)**: a maze structure for motor control tasks. **(E)**: CAD picture of a cross-section of the digital wooden maze device.

A magnetic ball is inserted into the maze structures when sliding the maze structures into the digital wooden maze device. Once the maze structure is inserted, this magnetic ball can move freely inside the maze structure underneath the bottom screen but cannot accidentally be removed from the device.

Children move the magnetic ball within the maze structure with the help of a custom-made conductive pen (shown in Fig. 1(C) and (D)). The pen was made from an anodized aluminum pipe of 12 cm height with conductive tip and designed, so that it activates the capacitive multi-touch screen (BI-TFT19-PCAP10-4-USB from A1touch with an active area of 376.32 mm × 301.06 mm and a touch resolution of 4096 × 4096 pixels) on top of the maze device. As a result, when touching the top screen, the pen position can be continuously recorded by the maze device. In addition, the pen contains a magnetic tip that when close enough to the magnetic ball, pulls the magnetic ball against the resistive screen (5WR1902FA5 from A1touch with an active area of 376 mm × 301 mm and a touch resolution of 4096 × 4096 pixels) beneath the capacitive screen. As a result, the resistive screen can record the ball position. A combination of a capacitive and a resistive screen was chosen, so that pen and ball position can be detected independently without affecting each other.

When calibrated correctly, by fusing the knowledge about the layout of the inserted maze structure with the pen and ball positions recorded by the capacitive and resistive screen, respectively, the position of the pen and ball with respect to each other and within the maze can be determined. In addition, it can be detected when the ball and pen are connected to each other and when a child moves the pen without the ball.

Figure 3 provides an overview of the main electronics of the digital wooden maze device: Data obtained from the capacitive and resistive touch screen is recorded and processed by an embedded STM32F429 processor board. For ease of use, this processor board can be controlled from a custom-made app via a Bluetooth wireless communication interface. To save data storage space and communication bandwidth, the processor board reads in the coordinate values of both the pen and the ball and stores these in a text file along with the time stamp following an event-based protocol. A new coordinate is registered if any of the following conditions is met:

- The X or Y coordinate of the pen changes by more than or equal to 2 mm.
- The state of the connection between pen and screen changes e.g. because the pen was disconnected from the screen.
- The state of the connection between pen and ball changes e.g. because the ball lost contact with the pen.

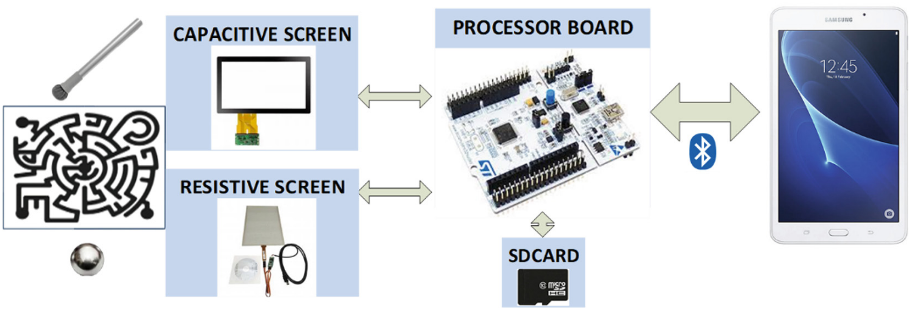

Fig. 3. Overview of main electronics inside the digital wooden maze.

Recorded data is stored in the following format: time since the startup of the maze in ms; id of the registered touch [0..10]; X coordinate of pen in mm; Y coordinate of pen in mm; a binary value that indicates if the pen touches the screen [0,1]; a binary value that indicates if ball and pen are connected [0,1]; the id of the inserted maze structure [0..3]; X coordinate of ball in mm; Y coordinate of ball in mm.

To avoid any loss of data e.g. during a loss of communication, all recorded data is stored on an SD memory card inside the maze device. All electronics are powered by a 10400 mAh power bank allowing for more than 7 h of continuous autonomous operation. The power bank is interchangeable so that the maze device can be kept operational during the charging process.

After recording, data is transferred to a PC for automated post-processing, feature extraction, and visualization. Figure 4 provides an overview of the processing steps. After the data acquisition step, we remove all data points that are not of interest to us. Such recorded points e.g. can be caused by the touch screen detecting contact by the hand or elbow of a child. Filtering of points consists of 3 steps:

(1) First, we remove all data points for which the ball and pen are not connected since for now we are only interested in movements where pen and ball move together.
(2) Secondly, we remove those data points where the distance between the consecutive x and y coordinates is above a given threshold. This step allows for removing data points caused by other touch events than the pen. The ideal threshold was found heuristically through extensive experimentation.
(3) Finally, we assign points according to the given tasks based on pre-defined start and end position on the maze as explained to the participating child.

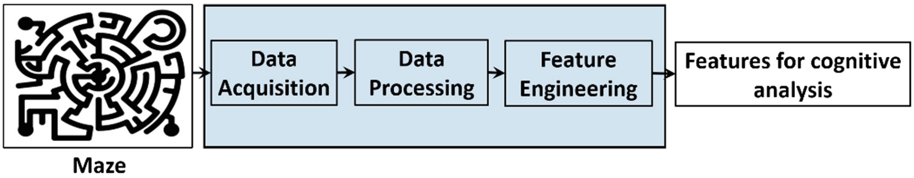

Fig. 4. Overview of data processing stages.

From the filtered valid points, we can extract a variety of features. This includes both those features required by the Porteus maze test (like crossing maze lines or going into dead ends) but also features that would be difficult to extract with a pencil-and-paper test like the position and duration that a child used to plan and rethink the applied maze-solving strategy. However, the evaluation and effect of these additional features for assessing cognitive abilities is beyond the scope of this paper. Here we focus on the presentation and evaluation of the new maze device mechatronics.

3 Digitalization of Pen Positions Through Computer Vision

We track the position of the pen with a camera to compare the processed outputs of the digital wooden maze device against data from camera tracking. The experimental setup for the tracking process is shown in Fig. 1(B). Tracking was accomplished through a HD720p webcam running at 30fps and an open-source object detection algorithm in OpenCV [13]. For ease of tracking the pen, a pink dot was added to the tip of the custom-made pen (see Fig. 1(D)) that is tracked during the experiments. Camera images are converted into HSV color space for better detection performance. The tracking algorithm detects the presence of the colored dot in the HSV camera images and saves the position to a text file. During the tracking process, the algorithm: (1) pre-processes the image frames (This step involves downsizing the image frame size and blurring the image to reduce high frequency noise.), (2) localizes all the regions in the image frame within the specified HSV range, (3) searches for the radii size of the pink dot in the localized regions found in the previous step, and (4) saves the coordinates along with a time stamp to a text file.

We adjusted color threshold parameters by hand to achieve a good detection performance. Still during experiments as expected from past studies [12] we experienced that detection performance was highly dependent on lighting conditions. To remove invalid point coordinates, we removed those data points where the distance between the consecutive x and y coordinates were above a given distance threshold. This step allows for removing falsely detected pen coordinates, similarly as for the data points directly obtained from the digital wooden maze device. Tracking ball positions was not possible with the camera setup due to occlusions and light reflections on the screen.

4 Experiments and Results

For an initial test of data recording quality, to compare data obtained from the screens and computer vision approach, and to generally demonstrate the feasibility of running tests with the digital wooden maze device, we invited 3 children of age 5 and one child of age 6 to test with us the device in two configurations. Children were asked to freely explore the maze equipped with the exploration maze structure and to run three assignments based on the colored stars printed on the assignment maze structure (see Fig. 5): Children always started at the center of the assignments maze structure and then got asked (1) to go to the yellow star and back, (2) to go to the green star and back, and (3) to go to the blue star and back.

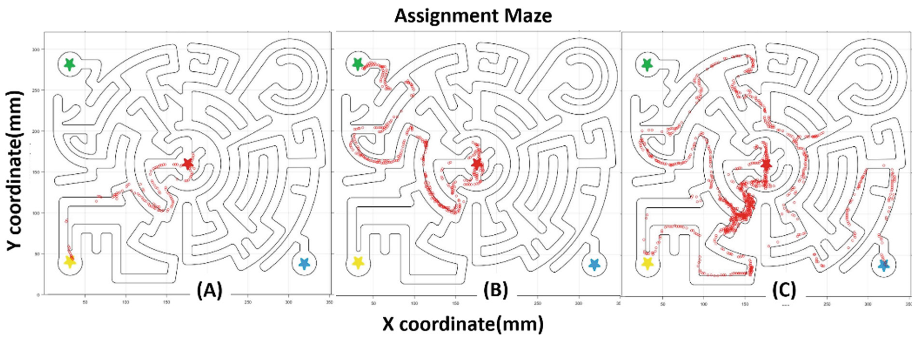

Fig. 5. Drawing of assignment maze structure overlayed with extracted data points for the three different assignments: **(A)** Assignment 1 (Go from red star int the middle to yellow star at the bottom left corner and back); **(B)** – Assignment 2 (Go from red star to green star in the top left corner and back); **(C)** – Assignment 3 (Go from red star to blue star in the bottom right corner and back). (Color figure online)

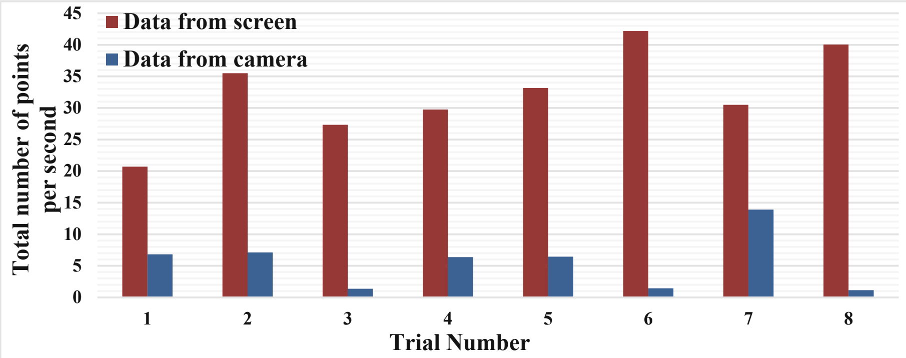

Fig. 6. Temporal resolution of screen and camera approach: total number of recorded points per second.

Table 1 presents the total number of collected and filtered (invalid) data points for the four individual participants and maze structure experiments. Numbers are given for both the data obtained through the maze's screen and through computer vision (camera). For the computer vision experiments we tried to create the best possible light conditions.

Table 1. Total number of data points collected and the invalid points from both Maze screen and Camera.

Trial No.	Maze structure	Participant No.	Maze screen			Camera		
			Total No. of points	No. of invalid points	Time (s)	Total No. of points	No. of invalid points	Time (s)
1	**Assignment**	1	9609	39	464.166	3232	27	473.677
2		2	4589	52	129.238	852	32	119.599
3		3	3326	37	121.65	145	25	105.327
4		4	3349	44	112.623	769	334	120.841
5	**Exploration**	1	7419	18	223.667	1365	19	211.976
6		2	2062	17	48.888	85	25	59.055
7		3	3930	24	128.831	1620	63	116.593
8		4	5935	48	148.261	169	80	149.499

To compare the performance of our approach (screen approach) with the camera approach, we plot for each trial and approach: in Fig. 6, the total number of points divided by the trial duration in seconds, in Fig. 7, the number of invalid points divided by the duration of the respective trial in seconds, and in Fig. 8, the number of invalid points divided by the total number of points in percent. The screen approach provides on average 82.79% more points per second, in the best case 96.58%, in the worst case

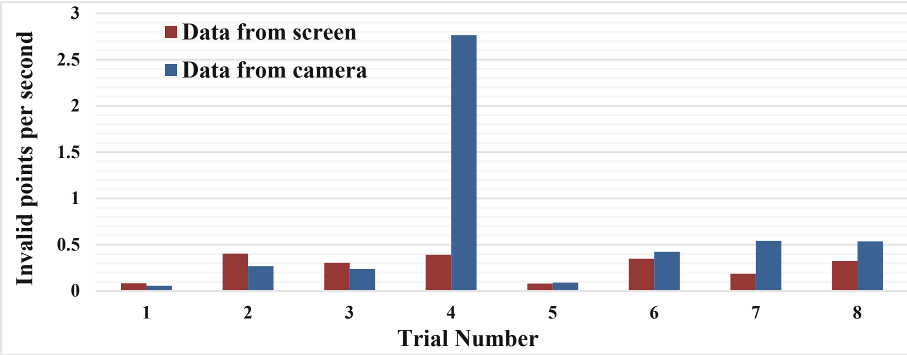

Fig. 7. Temporal resolution of screen and camera approach: number of invalid points per second

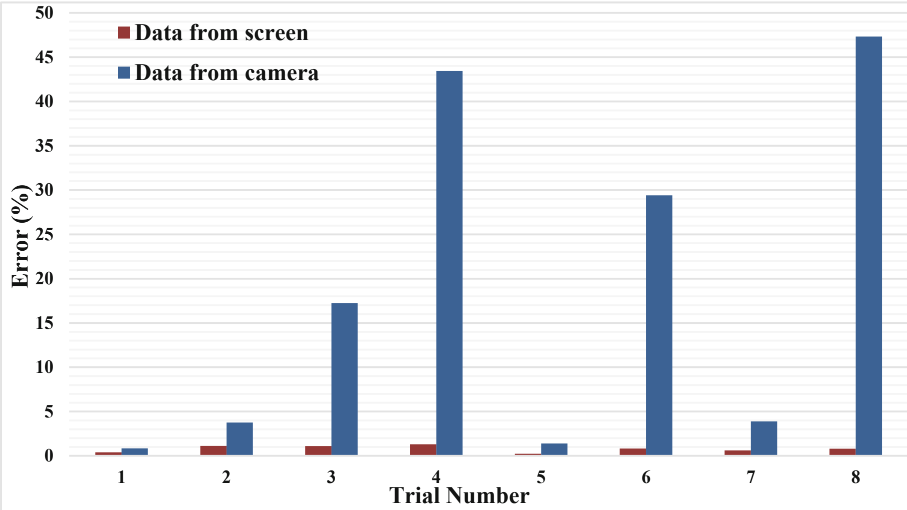

Fig. 8. Screen resolution of screen and camera approach: percentage of invalid (filtered) points with regard to total number of points.

54.45% and thus overall allows for a better temporal resolution. A reason is that the camera approach in contrast to the screen approach suffers from occlusions. So overall less points are detected in the camera images. In the screen method, inaccuracies are mostly generated when the pen loses contact with the ball. These usually occur if the pen is not held properly. As shown in Fig. 7, in three out of eight trials, the screen approach produced higher number of invalid points per second, on average 33.88%, and in the worst case 38.46%. This is partially caused by our definition of invalid points where we also filter situations where the ball is disconnected from the pen as invalid. This can also be caused by the fact that children sometimes rest their hands on the screen while playing, causing the top screen to detect both the hand and the pen. In the camera approach, the ball cannot even be detected. Thus, the data points being classified as valid in the screen approach are to be considered more reliable. The better screen resolution in terms of valid detected points also becomes visible when calculating an error value by normalizing the number of invalid points with regard to the total number of points as displayed in Fig. 8. On average the camera approach produces 95.62% more error than the screen approach, in the worst case 98.29% and in the best case 51.42%.

5 Discussion and Future Work

This paper presents a proof of concept for a digital wooden tabletop maze device designed for assessing cognitive abilities of young children. The novelty of the presented material lies in the approach and hardware. The maze device allows for stealth assessments inheriting advantages of computer-based testing like automated data acquisition and analysis but with a key advantage: The maze device looks like a normal wooden maze. Children can interact with the maze device in the way they are used to do with other tangible physical devices like toys. To proof the value of the maze device as a cognitive assessment tool, we are currently conducting a representative study with more children. So far, this paper presents only a pre-study with four children. However, the fact that the maze device allows for an extraction of similar features as the well-known Porteus maze test and mazes subtest from the WPPSI-R test is promising. Also, initial feedback from the four children who tested the device is very promising: all children showed great excitement when playing with the device and had no problems in handling the device. Also, their parents showed strong interest, making us hopeful that the maze device will be well-accepted by a general population.

Inspired by our experience with our camera-based digitalization approach of a board game for cognitive assessments, we compared the results obtained from the screens that have been integrated into the maze device with a camera-based tracking approach. Even under well-adjusted lighting conditions, the screen approach outperforms the camera-based approach. Due to its screen technology combining capacitive and resistance sensing, the digital maze is not susceptible to lighting conditions at all but can operate robustly in less-structured environments.

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