SIG-Blocks: Tangible Game Technology for Automated Cognitive Assessment

Abstract

This paper presents the SIG-Blocks system developed for automated cognitive assessment via tangible geometric games (TAG-Games). Computerized game administration and real-time cognitive and behavior assessments were realized by wireless self-synchronization in communication, decentralized hybrid-sensing, assembly and motion detection, and graphical visualization. The measurable performance data included time and accuracy at each manipulation step, overall speed of manipulative motions, and the total number of rotational motions. For preliminary evaluation, three types of TAG-Games were designed: TAG-Game^A for assembly, TAG-Game^S for shape matching, and TAG-Game^M for memory. As a part of the game design, a computational measure of play complexity was defined for each TAG-Game based on the geometric properties and the number of blocks in the item. An evaluation with 86 participants assessed both reliability of the TAG-Game items using split-half and test-retest reliability tests and validity of the proposed complexity measures by comparing the results with three subtests of the Wechsler Adults Intelligence Scale 4th Edition (WAIS-IV), i.e. Block Design (BD), Matrix Reasoning (MR), and Digit Span (DS). The high reliability coefficients show that TAG-Games are reliable. Regarding validity, correlations were found between TAG-Game^A and BD and between TAG-Game^S and MR. Behavioral analysis also showed that the TAG-Game performance was positively correlated with the manipulation speed, but not correlated with the total number of rotations applied to the blocks.

Keywords: Sensor-embedded blocks, Tangible user interface, Wireless sensor network, Cognitive assessment

Figure 1: Overview of SIG-Blocks and TAG-Games. A player is given a set of SIG-Blocks and plays computerized TAG-Games while the game items are displayed on a computer screen. The administrator administers the tet and monitors the player’s performance in real time. The administrator may administer the games from a remote location.

1. Introduction

Skilled cognitive performance is a highly complex process that involves perception, memory, reasoning, problem solving, and executive functions (Sparrow & Davis, 2000). Cognitive skills work in concert to produce general intellectual and learning capabilities (Kulp, 1999; Short & Weissberg-Benchell, 1989; Schweikardt, 2006). The ability to measure these components efficiently is essential for better understanding of the cognitive impairments associated with many disorders, including brain injuries, intellectual disabilities, dementia, psychiatric/mental disabilities, and other neurological and age-related conditions (Tatemichi, Desmond, Stern, Paik, Sano, & Bagiella, 1994; Christensen, Griffiths, MacKinnon, & Jacomb, 1997; Petersen, Smith, Waring, Ivnik, Kokmen, & Tangelos, 1997). Cognitive assessment has evolved into a widely diversified subject. The Wechsler tests are among the earliest and most widely accepted instruments of cognitive assessments (Silverman, Mizejeski, Ryan, Zigman, Krinsky-McHale, & Urv, 2010; Strauss, Sherman, & Spreen, 2006). The Raven’s Progressive Matrices (RPM) is another widely used test, which is often accepted when verbal constraints are in place or the clinician chooses to test non-verbal intelligence (Raven & Court, 1998). RPM relies on a series of perceptual and analytical reasoning problems presented in a matrix format (Bors & Stokes, 1998).

Sometimes, cognitive assessments use physical objects in order to track motor responses as well as cognitive processing (Lezak, 2004). Geometric blocks are employed in many such assessments because they are a benchmark

24 for observing manipulation patterns and developmental transformations. As
 25 such, they are often employed as an evaluation tool for understanding how
 26 children develop spatial cognition and fine motor skills (Pehoski, Henderson,
 27 & Tickle-Degnen, 1997). For example, the Block Design subtest in the Wech-
 28 sler tests employs a set of cubes to examine how quickly and accurately the
 29 examinee assembles the cubes to match the item configuration. Achievement
 30 of certain developmental milestones can be captured by performance on ma-
 31 nipulative tasks, such as piling and assembling blocks and inserting objects
 32 in holes (Lockman, 2000; Polatajko & Cantin, 2005). Object manipulation
 33 tasks using geometric blocks can also be used for cognitive rehabilitation of
 34 patients with cognitive and/or fine-motor skill deficiencies caused by trau-
 35 matic brain injury (TBI), stroke, cerebral palsy, Huntington’s disease, and
 36 dementia (Millis, Rosenthal, Novack, Sherer, Nick, Kreutzer, High, & Ricker,
 37 2001; Fork, Bartels, Ebert, Grubich, Synowitz, & Wallesch, 2005; Lund &
 38 Nielsen, 2011; Wright, Rosenbaum, Goldsmith, Law, & Fehlings, 2008; Will-
 39 ingham, Koroshetz, & Peterson, 1996). Using geometric blocks in cognitive
 40 assessment, or using any other physical objects, requires the administrator
 41 to closely observe the examinee’s performance while administering the test
 42 and recording measurable data (e.g. accuracy and speed for each test item).
 43 Compared to a paper-pencil test, this process can be more labor-intensive
 44 and error-prone.

45 This paper presents *SIG-Blocks* (Sensor-Integrated Geometric Blocks),
 46 developed for tangible, computerized assessments of cognitive skills using
 47 physical blocks (Fig. 1). The computer-based games using SIG-Blocks are
 48 called *TAG-Games* (Tangible Geometric Games). Each SIG-Block detects
 49 the overall manipulative motions applied by the player and the assemblies
 50 made with neighboring blocks. The system, involving a set of SIG-Blocks
 51 and a host computer, features independent wireless communication between
 52 each SIG-Block and the computer using radio frequency, and block-to-block
 53 communication using infrared (IR) signals. For reliable and efficient block-
 54 to-computer (global) and block-to-block (local) communications, distributed
 55 wireless sensor network (DWSN) algorithms, including self-synchronization
 56 and hybrid-sensing techniques, were implemented. Further, computational
 57 measures of play complexity were incorporated in TAG-Games to quantify
 58 the difficulty associated with game items. This feature, once fully validated,
 59 can be used to personalize the test items to address individual/group dif-
 60 ferences. SIG-Blocks and TAG-Games were designed for *automated*, *real-*
 61 *time*, and *remote* assessment of cognitive skills, as well as hand-eye coordi-

nation skills. These were aimed at addressing the following limitations that are common in traditional assessment methods: 1) high cost due to clinician/administrator time, 2) limited amounts and types of measurable data by a human administrator, 3) subjectivity and human measurement errors, 4) limited accessibility to professional services for people living in hard-to-reach areas, and 5) difficulty in addressing individual differences in cognitive skills, age, and developmental status, because of lack of flexibility in test items.

As a first step in evaluating the clinical utility of this technology and establishing the reliability and validity of the outcome measures, we designed three types of TAG-Games, each aimed at measuring specific domains of cognitive skills via tangible object manipulation: TAG-Game^A for assembling multiple blocks to match the given assembly configuration, TAG-Game^S for identifying a missing block in assembly configurations, and TAG-Game^M for memorizing a sequence of block images. For each TAG-Game, we defined a computational measure of play complexity, C , to quantify difficulty associated with each game, based on geometric complexity and the number of blocks. This measure, once fully evaluated, can be used for personalizing the test items tailored for each individual. Our evaluation study focused on testing the following two *hypotheses*: **H1**. Performances in TAG-Games are correlated to the scores from standardized cognitive assessment tests, and **H2**. Computational measures of play complexity defined for TAG-Games properly reflect the difficulty of the test items. To evaluate our hypotheses, we used the Wechsler Adult Intelligent Scale - 4th Edition (WAIS-IV), which is the most widely used instrument for cognitive assessment. In particular, we selected three subtests in WAIS-IV: Block Design (BD), Matrix Reasoning (MR), and Digit Span (DS). Each of these subtests is considered to be closely related to a TAG-Game by test design and target measures.

2. Related Work

Several technology-embedded block systems have been developed for a broad range of education, entertainment, and research purposes. Table 1 lists these systems and compares them with SIG-Blocks, in terms of communication capabilities, embedded sensors, measurable data, and data display methods. One such system, AlgoBlock was developed for children to learn programming via tangible manipulation of the blocks (Suzuki & Kato, 1995). The AlgoBlocks facilitate interactive learning of computer programming by

98 allowing users to write their own problems. This is accomplished by giving
 99 each AlgoBlock its own special semantics. Tangible Programming Bricks
 100 with a built-in microprocessor were developed for children to learn programming
 101 language via tangible manipulation of bricks (McNerney, 1999). Electronic
 102 Blocks, a similar system that allows the user to build simple computer
 103 programs by stacking blocks with embedded electronic circuits, was also designed
 104 for young children (Wyeth & Wyeth, 2011). Cognitive Cubes is another system
 105 developed for cognitive and constructional assessment (Sharlin, Itoh, Watson,
 106 Kitamura, Sutphen, & Liu, 2002). These cubic blocks are equipped with male-female
 107 connectors for forming a 3-D assembly and network topology with a base cube that
 108 is wired to the host computer. The roBlock system, which teaches advanced engineering
 109 concepts such as kinematics, feedback, and distributed control, also employs blocks
 110 to teach the user (Schweikardt & Gross, 2006). The working principle of roBlocks
 111 is similar to that of Electronic Blocks. Cubelets is a modular robotic kit consisting
 112 of sensor, logic, and actuator blocks (www.modrobotics.com). By assembling
 113 different types of Cubelets, a user can build a robot with the desired communication
 114 and sensing capabilities. Learning Cube is a digitally augmented block system,
 115 enriched with LED displays and an internal speaker (Terrenghi, Kranz, Holleis,
 116 & Schmidt, 2006). It is capable of gesture recognition by using an accelerometer
 117 in creating an interactive learning interface. Sifteo is another sensor-embedded
 118 block system with a small liquid-crystal display (LCD) screen on its top face
 119 (Merrill, Sun, & Kalanithi, 2012). The Sifteo blocks can sense and communicate
 120 with each other and detect tilt and shake motions. Lastly, the Multi-Agent System
 121 supports educational games for children with autism (Alers & Barakova, 2009).
 122 It displays its active state through color and light intensity by detecting the
 123 status of neighboring blocks with infrared (IR) communication.

126 In considering the effectiveness of each block system for automated, real-time
 127 assessment of cognitive skills, three criteria are considered: sensibility, scalability,
 128 and communicability. The blocks must be equipped with sensors that can detect
 129 the physical motions applied to each of them and the assembly configurations
 130 among multiple blocks. The number of blocks used in the test/game must be
 131 scalable to support 2-dimensional (2D) and 3-dimensional (3D) assemblies with
 132 varying difficulty. Bi-directional communication between the blocks and a
 133 host computer and among the blocks will support real-time sensor data acquisition,
 134 as well as assembly detection among the assembled blocks. The SIG-Blocks system
 135 has some unique features that

136 satisfy all of these criteria. Only Cognitive Cubes and Sifteo support both
 137 block-to-computer and block-to-block communications, but neither of them
 138 supports block-to-computer wireless communication. The SIG-Blocks sys-
 139 tem was operated in a fully decentralized manner without any hierarchi-
 140 cal or master-slave structure, such as that used in Cognitive Cubes, and is
 141 therefore fault-tolerant. In addition, most existing systems were designed for
 142 tangible gaming or educational purposes, but they lack the necessary record-
 143 ing functions, which are essential for assessment function. SIG-Blocks with
 144 TAG-Games were specifically designed to provide feedback on the player’s
 145 performance and behavior via real-time, wireless, and bidirectional communi-
 146 cations. Only Learning Cube demonstrates block-to-computer wireless com-
 147 munication capability based on radio frequency (RF) (Terrenghi et al., 2006).

148 Among the existing systems, Sifteo has the most features comparable to
 149 those of SIG-Blocks in terms of sensing and communication capabilities. Sif-
 150 teo adopts a gateway called Sifteo-base, a special block which is connected to
 151 a host computer using a USB cable for downloading new games. In addition,
 152 this base is responsible for wireless communication with the rest of the Sifteo
 153 blocks. The SIG-Blocks system differs from Sifteo in the following ways: 1)
 154 the low-cost infrared (IR) communication method for block-to-block com-
 155 munication, 2) direct wireless communication between each block and a host
 156 computer without requiring a gateway, 3) continuous sensor-data collection
 157 from each block, and 4) applicability for both 2D and 3D construction tasks.
 158 First, while Sifteo adopts four IrDA transceivers, SIG-Block uses six pairs of
 159 IR LEDs and a photo transistor. Second, bi-directional wireless communi-
 160 cation exists between each SIG-Block and a host computer. The computer
 161 can wirelessly control the mode of the blocks for different games and each
 162 block sends the collected sensor data, including orientation and assembly
 163 information, to the computer. Third, continuous data can be collected for
 164 assessment. Lastly, the cube design of SIG-Blocks enables 3D construction
 165 games. However, Sifteo may still be more suitable for games under some
 166 circumstances. Although the LCD display on Sifteo limits its workspace to
 167 2D, it renders Sifteo more suitable for entertainment and educational applica-
 168 tions than the plane images used in SIG-Blocks. As the current version of the
 169 SIG-blocks was designed for cognitive assessment, clear geometric patterns
 170 were selected.

Figure 2: SIG-Blocks with improved hardware design. The programming port and charging port can be easily accessed by detaching the covers. The outer cover is made with mat-board (non-toxic, light, and durable against impact).

171 3. SIG-Blocks

172 SIG-Blocks are interactive creation blocks designed to be used as a tangi-
 173 ble and computerized interface for various games (i.e. TAG-Games) that in-
 174 involve tangible manipulations of the blocks. This section describes the design
 175 considerations, technical specifications, and wireless communication strate-
 176 gies embedded in the blocks.

177 3.1. Design Considerations

178 *Sensibility*

179 One of the main considerations is the measurable data. When geometric
 180 blocks are used in an educational or clinical test, the administrator records
 181 the time and accuracy of the tasks completed by the player. Therefore, the
 182 quantity and quality of the measurable data are limited by the human ca-
 183 pability. To automate the measurement process, while potentially improving
 184 the quantity and quality of the data, the blocks must be capable of sensing the
 185 player's action applied to them as well as synthesizing the actions. To do so,
 186 the block must be capable of sensing the orientation and the accelerations ap-
 187 plied while being manipulated by hands, and of detecting neighboring blocks
 188 when assembled. Various sensors can realize these functions. For example,
 189 accelerometers, gyroscopic sensors, liquid tilt sensors, and/or magnetometers
 190 can provide the block's orientation state. In addition, simple optical sensors
 191 or mechanical contact sensors may be sufficient for face-to-face interaction
 192 among the blocks.

193 *Scalability*

194 SIG-Blocks are intended to be used for creating universal 2-D and 3-D
 195 shapes, and therefore should be scalable to form a large structurally stable

196 configuration when assembled. Among the various 3-D shapes, such as cubes,
197 cylinders, spheres, cones, and tetrahedrons, cubic structures enable efficient
198 and stable stacking and provide an adequate number of degrees of freedom
199 without any additional docking support. With respect to perception, recog-
200 nizing the rotations of a cube is intuitive, because the axes of the coordinate
201 system that represents the cube are orthogonal to the faces, and therefore,
202 the orientation of the cube is easily understood when the top and bottom
203 faces are parallel to the tabletop. With this universal design, a number of
204 tasks would be available by reprogramming the functions to interact with
205 new task environments. Identical cubes would be more desirable because of
206 their common geometric properties and shared communication protocols and
207 electronics. Homogeneity in block design also allows for replacement of any
208 broken block by a new one.

209 *Communicability*

210 The blocks should perform data measurement on board, wirelessly com-
211 municate with other blocks to detect assembly, and transfer data with the
212 remote data storage, i.e. the host computer. When multiple blocks are used
213 in a wireless sensor network (WSN), the communication subsystem is the
214 main infrastructure on which the WSN is constructed, and hence the com-
215 munication protocols affect the overall sensing accuracy and reliability. To
216 ensure a large and reliable communication subsystem, several technical is-
217 sues need to be addressed. Such issues may include synchronization, data
218 traffic, and non-deterministic lag time between the transmitter and the re-
219 ceiver. Without utilizing the master and slave mechanism, synchronization
220 becomes challenging; therefore, the self-synchronization method, which con-
221 tinuously transmits and receives data and shifts bits by a given rule at each
222 phase, must be implemented. This leads to a rapid massive data collection
223 which generates significant data traffic when the host computer collects the
224 data through a single receiver. Therefore, the data should be optimized in
225 terms of size without loss of meaningful information and sent efficiently by
226 an event-driven method. Also, the non-deterministic lag time during wireless
227 data transmission should avoid data collision in fast data transfer.

228 *3.2. Technical Description*

229 *3.2.1. Design and specifications*

230 SIG-Blocks feature 1) block-to-block communication using infrared (IR)
231 optical sensors, 2) bidirectional block-to-computer communication using an

232 XBee module, and 3) light and compact packaging (Fig. 2). Compared to
 233 the previous prototype presented in (Jeong, Kerici, & Lee, 2010), the block's
 234 size was reduced from 2.7 inches to 2.05 inches in length along each side, and
 235 the weight from 355g to 82g. Each block contains a triaxial accelerometer
 236 (ADXL335), a microprocessor (ATmega328), six reflective optical sensors,
 237 and an XBee wireless module. It is powered by two 3.7 Volt, 350mAh polymer
 238 lithium-ion batteries, which are rechargeable through a USB connector. It
 239 takes less than 30 minutes to recharge each block and the operating time is
 240 approximately 3.5 hours.

241 Core electronic components were embedded in three stacks of printed
 242 circuit board (PCB) layers and were encased in a cubic block made of mat-
 243 board. The outer surfaces were covered by six distinctive geometric images,
 244 shown in Fig. 3. These images were selected to represent 1-, 2-, and 4-fold
 245 rotational symmetry, where each pair had the same shape, but with reversed
 246 colors (Jeong et al., 2010). Retaining the core module intact, cover lay-
 247 ers can be customized for different purposes. The reflective optical sensor
 248 installed at the center of each block's surface detects the reflected IR sig-
 249 nal. By combining the data from the optical sensors and the accelerometer,
 250 assembly configurations of the blocks can be reconstructed for real-time feed-
 251 back. Also, local communication between the assembled blocks was enabled
 252 through these optical sensors with protocols proposed in Section 3.3. These
 253 optical sensors may require periodic replacement. Female sockets were used
 254 for positioning these optical sensors to facilitate replacement.

Figure 3: Six distinctive images with 1-, 2-, and 4- fold rotational symmetry.

255 3.2.2. Measurable data and sensing capability

256 Each block can detect its relative position, orientation, and elapsed time
 257 after each assembly made by the player. When used in geometric games,
 258 such as matching an assembly configuration or identifying a missing piece
 259 in a puzzle, the blocks can also determine whether they are placed correctly
 260 or incorrectly. Six embedded optical sensors, a triaxial accelerometer, and a

261 timer in the microprocessor were used to determine the accuracy of manipu-
 262 lation, the time for each manipulation step, and possibly behavioral charac-
 263 teristics such as impulsive or repetitive motion. Each block sends ten packets
 264 of data to a host computer wirelessly. The first packet is the ID of the block
 265 and the next six packets are binary optical sensor data corresponding to the
 266 assembly status of each block’s surface. The last three packets correspond to
 267 acceleration data along x , y , and z directions and their values range between
 268 $-1.0g$ to $1.0g$.

269 3.3. Wireless Communication Strategies

270 The SIG-Blocks system features the following communication capabili-
 271 ties: IR-based inter-block (local) communication and bidirectional block-to-
 272 computer (global) communication using an XBee module, based on the dis-
 273 tributed wireless sensor network (DWSN) scheme. To avoid resource conflict,
 274 deadlocking, and to establish reliable wireless communication, two strategies
 275 were adopted: 1) synchronization techniques (self-synchronization) to ini-
 276 tiate local communication, and 2) efficient network topology (decentralized
 277 hybrid-sensing network) with even-driven data input for optimal global com-
 278 munication.

279 3.3.1. Self-synchronization in local communication

SIG-Blocks utilize *self-synchronization* for initializing local communica-
 tion between two adjacent blocks. Two communication ports, **A** and **B**,
 are considered fully synchronized if **B** listens while **A** talks, and **A** listens
 while **B** talks. However, as shown in Fig. 4, signals transmitted by **A** and
B may mutually conflict when they both talk or listen at the same time.
 The self-synchronization method uses an internal clock, transmitted pulse,
 and received pulse to determine the port that needs to listen while the other
 talks. This bit-shift strategy was performed as follows, for port **A** (Jeong &
 Lee, 2016):

$$\begin{aligned} I_A &= [1, 2, 3, \dots, 30, 31, 32] \\ T_A &= [0, 0, \dots, 0, 0, 1, 1, \dots, 1, 1] \\ R_A &= [*, *, \dots, *, *, *, *, \dots, *, *] \end{aligned}$$

280 I_A is the 32-bits cyclic bit number index generated by the internal clock,
 281 T_A is the transmitted binary data, and R_A is the received signal from the
 282 other port. The pulse train from T_A is generated from the IR photo diode
 283 according to the bit number of the I_A . When the two ports, **A** and **B**, are

Figure 4: (a) Short-range communication mechanism used in the new SIG-Blocks via IR sensors and (b) self-synchronization scheme between the ports **A** and **B**. The gray bar indicates talking bytes while the white bar refers to listening bytes (Jeong & Lee, 2016).

284 within the local communication range, R_A receives data from T_B , as well as
 285 reflected signal from T_A . Due to the pull-up resistors attached to the photo
 286 transistors, R_A is set as 1 initially or when no IR signals are received, and it
 287 changes to 0 when IR input is detected. Decision for shifting, either forward
 288 or backward, for synchronization can be made stochastically; however, this
 289 process can take a long time. For every 31st bit of the 32 bits (4 bytes),
 290 the binary train moves one step forward or two steps forward depending on
 291 the received data. If $\sum_{n=bit1}^{bit8} R_A(n)$ is smaller than $\sum_{n=bit9}^{bit16} R_A(n)$, then the
 292 pulse train proceeds one step forward, but when it is bigger, the pulse train
 293 moves two steps forward. When the two transmitted signals are the same, a
 294 random shift is applied to each port, so that it makes partial synchronization.
 295 When the synchronization is completed, IR communication data packets are
 296 replaced in the last two bytes of T_A . Fig. 4 illustrates this process.

297 3.3.2. Decentralized hybrid-sensing network (DHSN)

298 To avoid data traffic when multiple blocks are used in the game, the sys-
 299 tem utilizes a DHSN. While low-power local communication is always on,
 300 the data transfer between each block and the host computer is triggered
 301 only when an *event* occurs. During play, most of the blocks will remain
 302 stationary excepting the few that are being manipulated at the time. The
 303 event-driven data transfer is triggered by the acceleration reaching a thresh-
 304 old value, which is determined by the noise density level of the accelerome-
 305 ter. Event-driven data transfer is more effective than periodic data transfer
 306 at preventing loss of any significant information. Also, static channel access
 307 control was utilized because dynamic control requires both linking and stabi-
 308 lizing time, which has the potential to cause significant time delay in wireless
 309 communication.

310 4. Algorithm Implementation

311 In this section, the proposed wireless communication algorithms are im-
 312 plemented for block assembly detection, motion detection, and visualization
 313 for real-time administration and monitoring of the user's performance and
 314 behavior.

315 4.1. Assembly Detection

Figure 5: A SIG-Block with six sides, each with a unique ID number, and an example of 2×2 assembly configuration seen from the top.

316 When two blocks are assembled, the assembly configuration is captured
 317 by a pulse train via local inter-block communication, using IR sensors. The

318 pulse train involves the following information: (ID1, SIDE1, TOP1, ID2,
 319 SIDE2, TOP2). ID1 and ID2 are the ID numbers of the two blocks assem-
 320 bled, SIDE1 and SIDE2 are the surfaces on the blocks facing each other, and
 321 TOP1 and TOP2 are the surfaces of each block that face upward. Consid-
 322 ering the low response and signal reading time in the photo transistor and
 323 the microcontroller’s input port, 1 millisecond per bit for the pulse train
 324 was selected. For detecting each assembly, the configuration matrix, A , was
 325 generated by labeling the block’s IDs and side IDs. For the example shown
 326 in Fig. 5, A is a 6×6 matrix consisting of four 3×3 matrix blocks where
 327 each matrix block contains the SIG-Block ID in the (2,2) entry and the four
 328 sides information in the (1,2), (2,1), (2,3), and (3,2) entries. Before and after
 329 assembly, the changes in A are as follows:

$$A := \begin{bmatrix} \star & 0 & \star & \star & 0 & \star \\ 0 & 1 & 0 & 0 & 2 & 0 \\ \star & 0 & \star & \star & 0 & \star \\ \star & 0 & \star & \star & 0 & \star \\ 0 & 4 & 0 & 0 & 3 & 0 \\ \star & 0 & \star & \star & 0 & \star \end{bmatrix} \rightarrow \begin{bmatrix} \star & 0 & \star & \star & 0 & \star \\ 0 & 1 & 3 & 1 & 2 & 0 \\ \star & 1 & \star & \star & 3 & \star \\ \star & 3 & \star & \star & 1 & \star \\ 0 & 4 & 1 & 3 & 3 & 0 \\ \star & 0 & \star & \star & 0 & \star \end{bmatrix}$$

330 For an $n \times m$ assembly configuration in 2-D, $A \in \mathcal{R}^{3n \times 3m}$ consists of $n \times m$
 331 matrix blocks. For 3-D assemblies, A can be defined as a 3-D matrix, or keep
 332 the same 2-D matrix format and store the assembly statuses of the top and
 333 bottom surfaces on empty spaces, indicated by $\star$ in the above matrix.

334 4.2. Motion Detection (Jeong et al., 2010)

Once the linear acceleration data is transferred from the SIG-Blocks, the
 data is processed in the host computer to be translated into rotational mo-
 tions applied to the blocks. To enable the use of a triaxial accelerometer in
 detecting angular displacements of each block, the noise caused by measure-
 ments of hand-operational movements will have to be filtered. The low-cost
 capacitive accelerometer used in this study featured signal conditioning, a
 1-pole low-pass filter, temperature compensation, and g-select which allows
 for selecting one of the four sensitivities: 1.5g, 2g, 4g, and 6g. The highest
 sensitivity of this accelerometer, 800mV/g, occurred when 1.5g was selected.
 Three output ports on the accelerometer provided analog acceleration sig-
 nals along x -, y -, and z -axes. These analog signals were then transformed to
 digital signals through the analog-to-digital converter in the microprocessor

Figure 6: Acceleration along the x -axis, x_{acc} , captured from the triaxial accelerometer versus time while rotating about the y -axis (Jeong et al., 2010).

(ATmega328). When the accelerometer is in static state, it can detect angular displacements by measuring static accelerations due to gravity, which range between $-g$ and $+g$. Using a triaxial accelerometer, tilting angles along the x -axis and y -axis can be calculated based on the acceleration data $(x_{acc}, y_{acc}, z_{acc})$ by (Wong & Wong, 2008):

$$\theta_{pitch} = \tan^{-1} \left(\frac{x_{acc}}{\sqrt{(y_{acc})^2 + (z_{acc})^2}} \right); \quad \theta_{roll} = \tan^{-1} \left(\frac{y_{acc}}{\sqrt{(x_{acc})^2 + (z_{acc})^2}} \right).$$

335 Detecting tilting angles of a moving accelerometer is challenging. To an-
 336 alyze the effect of dynamic acceleration, we conducted a simple block test by
 337 manually rotating a SIG-Block 90° and -90° about the x -axis repeatedly at
 338 different frequencies. Fig. 6a was generated by rotating the block 5 cycles
 339 per 50 seconds (0.1 Hz). Figures 6b-d show the results when the block was
 340 rotated at 0.5 Hz (5 cycles per 10 seconds), 1.0 Hz (10 cycles per 10 sec-
 341 onds), and 2.0 Hz (20 cycles per 10 seconds), respectively. The results show

Figure 7: Frequency spectrum of the rotating motions in four different frequencies (Jeong et al., 2010).

342 that the overall influence of dynamic acceleration is trivial for slow motions
 343 (≤ 1.0 Hz), while the error increases at higher frequency domains. This
 344 is corroborated by Bernmark’s finding that shows that the accelerometer is
 345 not influenced by dynamic motion less than 0.75 Hz (Bernmark & Wiktorin,
 346 2002). For fast motions, shown in Fig. 6d, the x_{acc} exceeds $\pm 1g$ corre-
 347 sponding to $\pm 90^\circ$ in the block’s orientation because of dynamic acceleration
 348 influencing the data. Although every user behaves uniquely and may have
 349 different frequency responses, humans have a limited speed and range of mo-
 350 tions for manipulating rigid objects as shown in Fig. 7. Therefore, since the
 351 SIG-Blocks are expected to be used within low frequency ranges, they can
 352 successfully retrieve their rotational information and provide reliable data on
 353 how they are manipulated by a player.

354 4.3. Graphical User Interface (GUI)

355 The GUI was developed based on Microsoft Visual C# with an open
 356 graphics library (OpenGL) for graphical visualization. Tangible games for

Figure 8: The administrator's GUI that displays test item, measurable data, and block status in real time. The player's GUI simply displays the test item.

cognitive assessment using SIG-Blocks require two GUIs. One of these GUIs serves as a game display for the player, and the other allows the administrator to administer the game and monitor the player's performance in real-time. This monitoring may be conducted remotely, if necessary. The administrator's GUI displays the test/game item, current configuration of the blocks, time and accuracy at each manipulation step, communication status of the blocks used in the game, and triaxial accelerations in real time (Fig. 8). The player's GUI simply displays the test item and/or the current block configuration depending on the game type.

5. TAG-Games

Three types of TAG-Games were developed for preliminary evaluation of the SIG-Blocks technology for automated cognitive assessment. The three games are TAG-Game^A for block assembly, TAG-Game^S for shape matching, and TAG-Game^M for sequence memory. Table 2 lists the cognitive skills that are hypothesized to be associated with each game. In addition, each TAG-Game item is assigned a value, C , that is a computational representation of its play complexity.

374 5.1. TAG-Game^A: Assembly

375 TAG-Game^A is an assembly construction game in which the user recreates
 376 a displayed image using the SIG-Blocks. The displayed image is an arrange-
 377 ment of the geometric shapes on SIG-Block surfaces. The user must rotate
 378 and rearrange the blocks to create the displayed pattern. The difficulty and
 379 novelty of this task are reflected in the manipulation of the blocks to find
 380 the correct face images, the size of the pattern, and the discriminability of
 381 the block surface images within the pattern image. The discriminability of
 382 the patterns can be decreased, making the task more difficult, by removing
 383 the separating lines between the pattern components. This change results
 384 in increasing the picture size and making it more prominent in the patterns
 385 than the picture of individual block face images. Fig. 9 shows 20 assembly
 386 items.

Figure 9: 20 TAG-Game^A items. The lines separating 4 or 9 individual shapes can be removed to potentially increase difficulty. Images as presented in this figure were used in our human-subject evaluation.

387 5.2. TAG-Game^S: Shape-Matching

388 As shown in Fig. 10, TAG-Game^S consists of 10 items for which an
 389 assembly pattern with a missing image is displayed and the participant is

390 prompted to fill in the missing image by placing a SIG-Block with the missing
 391 image face up. It was designed to assess fine-motor control, visuospatial
 392 reasoning, and problem-solving skills. Each of the patterns has a calculated
 393 play complexity value and patterns are arranged in the order of increasing
 394 complexity. The system records the time taken by the player to complete
 395 each pattern and whether it is completed correctly. The game requires the
 396 participant to determine the relationship among individual images in each
 397 pattern and complete the relationship by supplying the missing piece. As in
 398 the case of TAG-Game^A, fine-motor control is reflected in the coordination
 399 with the block being manipulated. Visuospatial reasoning is reflected in the
 400 participant's ability to see the relationships between block rotations and face
 401 images. Problem-solving skills are reflected in the participant's ability to find
 the relations within the pattern and to predict the missing image.

Figure 10: 10 TAG-Game^S items.

402

403 5.3. TAG-Game^M: Memory

404 This test requires the player to remember a sequence of images and repeat
 405 it using a SIG-Block. The images within the sequence are flashed one after
 406 the other on the screen. The user plays the sequence back by placing the
 407 SIG-Block with the correct images facing up in the order they appeared on
 408 the screen. As shown in Fig. 11, two different sets of images are used to make
 409 up the sequences: 1) a set of 6 different colored squares and 2) a set of images
 410 of the same black and white geometric shapes that were used in the other two
 411 games. These two sets of images were used to ascertain if the complexities
 412 of the images within the sequence affect the difficulty in remembering the
 413 sequence. This game assesses the participant's fine motor control, working
 414 memory, and attention span. Fine motor control is reflected in the speed

415 and accuracy with which the participant can rotate the block to find the
416 correct face image. Working memory is reflected in how well the participant
417 remembers the sequence of images. Finally, attention span is reflected in the
418 participant's ability to maintain focus when the sequences become longer.

Figure 11: 8 TAG-Game^M items.

419 5.4. Computational Complexity Measures

420 Difficulty is a relative attribute that can vary depending on a person's
421 developmental status, age, and health conditions. For an assessment test to
422 produce reliable and sensitive assays, it must be neither too difficult nor too
423 easy. For TAG-Games to be potentially useful as a dynamic assessment tool,
424 it was necessary that a computational measure of play complexity, C , be de-
425 fined. This value, associated with each TAG-Game, allows the administrator
426 to personalize each task to the test subject. Fig. 12 shows the complexity
427 values calculated for the items in each TAG-Game.

428 5.4.1. Complexity measure of TAG-Game^A

Based on an information-theoretic approach and adopting the concept of
the parts entropy (Sanderson, 1984; Lee, Moses, & Chirikjian, 2008), the
play complexity associated with TAG-Game^A is defined by the change in
configurational entropy:

$$C^A = H^{initial} - H^{final} \quad (1)$$

Figure 12: Calculated complexity values for all items in each TAG-Game, i.e., C^A , C^S , and C^M .

where $H^{initial}$ indicates the amount of randomness/uncertainty for the set of geometric blocks used in play and H^{final} is the remaining randomness/uncertainty after successfully accomplishing a given task (e.g. assembling the blocks to form a specific assembly configuration), measured by the discrete entropy. Therefore, the difference between $H^{initial}$ and H^{final} indicates the amount of uncertainty that is reduced by the person assembling the blocks.

5.4.2. Complexity measure of TAG-Game^S

The play complexity of TAG-Game^S takes into account the variety of pattern properties that increase or decrease the complexity of the item. The factors that increase the complexity are the total number of blocks, the number of unique blocks, and the length of the embedded pattern. The factors that decrease the complexity are the number of times the pattern repeats and the number of symmetry axes contained in the pattern. The play complexity of TAG-Game^S is calculated as

$$C^S = \frac{N \cdot N_d \cdot L}{R \cdot (S + 1)} \quad (2)$$

where N is the total number of blocks, N_d is the number of face images used in the pattern, L is the pattern length, R is the number of pattern repeats, and S is the number of symmetry axes.

439 5.4.3. Complexity measure of TAG-Game^M

The difficulty in remembering a sequence of images depends on the complexity of the employed images, the number of images, and the number of elements repeated within the sequence. The complexity measure is defined by the configurational entropy of the entire sequence, computed by

$$C^M = \log_2 Q + \log_2 L \quad (3)$$

440 where Q is the number of all possible arrangements for the given images and
441 L is the sequence length. For example, if the sequence involves four colors,
442 the number of their possible arrangements in four distinctive locations is
443 $Q = 4! = 24$ and the corresponding $C^M = \log_2 24 + \log_2 4 = 6.585$. If
444 the sequence item uses the same colored image four times, $Q = 4!/4! = 1$,
445 such that $C^M = \log_2 1 + \log_2 4 = 2$. If the geometric images used in TAG-
446 Game^A and TAG-Game^S are used, the total number of possible arrangements
447 is multiplied by the number of distinctive orientations for each image so that
448 the complexity of the geometric pattern is taken into account.

449 6. Evaluation Methods

450 The human-subject study focused on evaluating the two hypotheses stated
451 in Section 1. To do so, the study design was aimed at testing 1) preliminary
452 reliability and consistency of TAG-Games data, 2) the computational com-
453 plexity measures, and 3) preliminary validity of TAG-Games measures on
454 measuring target cognitive skills. This study was reviewed and approved by
455 Case Western Reserve University’s Institutional Review Board (IRB).

456 6.1. Participants

457 Eighty-six students (42 males) aged 18 to 30 years (Mean = 21.6, SD =
458 3.1) were recruited and participated in the study via convenience sampling,
459 where the participants were selected because of their convenient accessibility
460 and proximity to the researchers. 47 (31 males, 66%) were from the Engineer-
461 ing School and 39 (11 males, 28%) were from the School of Arts and Science.
462 There was a significant relationship between gender and school where there
463 were more males from the Engineering School ($\chi^2_1 = 12.16$, $p < 0.01$). The
464 proportion of males and females in our sample from the School of Engineering
465 match with the demographics of the school (68% male population). The per-
466 centage of male participants from the School of Arts and Science (28%) was

467 lower than the demographics of the school (43%) because several students
468 participated in this study for course credit, and the majority of students en-
469 rolled in this course were female. Participants were recruited from the Case
470 Western Reserve University campus, where emails and flyers were used to
471 find volunteers. Participants were compensated with either a gift card or
472 course credit.

473 All 86 participants were administered the three types of TAG-Games. 48
474 out of 86 took two subtests of the Wechsler Adult Intelligence Scale - 4th
475 Edition (WAIS-IV) (i.e. Block Design (BD) and Matrix Reasoning (MR))
476 in addition to the three TAG-Games, and 25 out of 48 were administered
477 the Digit Span (DS) subtest in addition to BD and MR of WAIS-IV and
478 the three TAG-Games. Among 48 participants who took the three TAG-
479 Games and BD and MR subtests of the WAIS-IV, 9 (7 males) were from
480 the Engineering School and 39 (11 males) were from the Arts and Science.
481 Among 25 participants who were administered all six tests, 2 (1 male) were
482 from the Engineering and 23 (7 males) were from the Arts and Science. The
483 demographics of the study participants is summarized in Table 3.

484 6.2. Protocol

485 Three types of TAG-Games and three subtests of WAIS-IV (i.e., BD,
486 MR, and DS) were administered in the order shown in Table 4. The three
487 subtests of WAIS-IV were selected to assess cognitive skills similar to those
488 tested by TAG-Games. Each participant was given a brief oral presentation
489 at the beginning of each TAG-Game with a sample item. The three WAIS-IV
490 subtests were administered using the standardized protocol (i.e. instruction,
491 prompts, time limits, and discontinuation rules), outlined in the WAIS-IV
492 manual. They were administered in the order BD→MR→DS, immediately
493 following the TAG-Games. BD involves 14 items requiring the participants
494 to manipulate a given set of blocks to match the assembly configuration
495 presented in a booklet. It discontinues with two consecutive scores of 0.
496 MD contains 26 items of colored matrix or visual patterns requiring the
497 participants to guess and select the missing item in the pattern among 5
498 possible answers. The test discontinues after 3 consecutive scores of 0. DS
499 consists of three parts: Digit Span Forward (DSF), Digit Span Backward
500 (DSB), and Digit Span Sequencing (DSS); they contain 48 items in total, with
501 16 items in each. The sets of digits were presented verbally to the participants
502 and they recited them in forward, backward, and increasing orders. The
503 participants were given two trials for each length of digit sequence, and the

504 test was discontinued when both trials scored zeros. The entire assessment
505 took approximately 60 minutes.

506 6.3. Scoring Methods

507 Scoring of TAG-Game^A was similar to the method used in the WAIS-IV
508 BD subtest, addressing accuracy, item complexity, and speed (i.e. time taken
509 to complete the item). Since TAG-Games are not standardized tests, the
510 participants' performance was analyzed to determine the score distribution
511 in a fashion similar to that of WAIS-IV. For items 1-10, 50% of the correct
512 answers were made within 10 seconds, resulting in 3 points. The other 50% of
513 the correct answers, which took more than 10 seconds, yielded 2 points. For
514 items 11-20, one third of the correct answers were made within 20 seconds
515 resulting in 7 points, another one third between 20 and 24 seconds resulting
516 in 5 points, and the rest took more than 24 seconds, yielding 3 points. For
517 every item, incorrect assembly resulted in zero points. The total available
518 score for TAG-Game^A is 100.

519 Scoring for TAG-Game^S also takes into consideration both accuracy and
520 speed. For items 1-5, 50% of correct answers were recorded within 4 seconds,
521 resulting in 3 points. Correct answers made after 4 seconds resulted in 2
522 points. For items 6-10, one third of correct answers were made within 8
523 seconds, resulting in 7 points, another one third between 8 and 12 seconds
524 resulting in 5 points, and the rest took more than 12 seconds yielding 3
525 points. For every item, incorrect shape matching resulted in zero points.
526 The total available score for TAG-Game^S is 50.

527 Scoring for TAG-Game^M was based solely on the correctness of memory;
528 completion time was not factored into the score. The total possible score of
529 56 was derived from 2 sets of blocks of 4 possible lengths (i.e. 4, 6, 8, and 10).
530 More specifically, the color and geometric pattern sequences yielded scores
531 of 28 each, accounting for a total of 56 points.

532 6.4. Data Analysis

533 The data analysis strategy focused on establishing the preliminary psy-
534 chometric integrity of the measure. To achieve this purpose, split-half and
535 test-retest reliability were conducted using Spearman's correlations with $\alpha =$
536 0.05. Once the reliability of the measure was established, the validity of
537 the TAG-Games was examined by correlations with WAIS-IV. Finally, ex-
538 ploratory behavior analysis was carried out by estimating the number of

539 rotational motions applied to the blocks and speed. The analysis was re-
540 stricted to TAG-Game^A data only, because TAG-Game^S and TAG-Game^M
541 use only one SIG-Block and are therefore not ideal to observe behavioral
542 differences. The algorithm for estimating the rotational motions was based
543 on the threshold value and the local maxima and minima in the acceleration
544 data. The accelerations caused by the user manipulation were different from
545 those obtained from the impact of the block assembly.

546 7. Evaluation Results

547 7.1. Split-Half and Test-Retest Reliability

548 In an effort to provide preliminary data on the psychometric property of
549 TAG-Game, split-half and test-retest reliability tests were conducted using
550 Spearman correlations for each of the games. Since the items varied on C ,
551 it was necessary to equate the sets on this variable before conducting the
552 split-half reliability. Our first split was based on an odd and even strategy;
553 unfortunately the sets differed significantly in C (i.e. 29.94 vs. 31.83 in
554 TAG-Game^A; 22.50 vs. 42.54 in TAG-Game^S; and 114.14 vs. 261.74 in
555 TAG-Game^M). Given the knowledge of the play complexity of each set, we
556 then moved items strategically across the sets to equate them on complexity.
557 As a result, the TAG-Game^A items were divided into $\{1, 3, 5, 8, 9, 12, 14,$
558 $16, 17, 19\}$ and $\{2, 4, 6, 7, 10, 11, 13, 15, 18, 20\}$, the TAG-Game^S items
559 into $\{1, 2, 6, 7, 10\}$ and $\{3, 4, 5, 8, 9\}$, and the TAG-Game^M items into
560 $\{1, 5, 6, 8\}$ and $\{2, 3, 4, 7\}$. Using Spearman's correlation coefficient, the
561 split-half reliability coefficients were found to be $r(10) = 0.73$ ($p = 0.016$)
562 for TAG-Game^A, $r(5) = 0.98$ ($p = 0.005$) for TAG-Game^S, and $r(4) = 1.0$
563 ($p < 0.001$) for TAG-Game^M. Of the 86 participants, 10 were administered
564 TAG-Games at two different times, approximately two weeks apart. The test-
565 retest reliability was found to be $r(10) = 0.72$ ($p = 0.19$) for TAG-Game^A,
566 $r(10) = 0.62$ ($p = 0.05$) for TAG-Game^S, and $r(10) = 0.75$ ($p = 0.013$) for
567 TAG-Game^M.

568 7.2. Validity of Complexity Measures

569 To evaluate the computational complexity measures, we investigated the
570 correlation between the participants' performance and the complexity value
571 of each item. For this, the mean time required for completing TAG-Game^A
572 was taken as the index of performance and used to examine the impact
573 of C^A on performance. For TAG-Game^S, incorrectness was computed by

the normalized number of total incorrect answers for each item, and for TAG-Game^M it was computed by the normalized number of total images that the player could not memorize, or could memorize only incorrectly, in each sequence item. Time for completion in TAG-Game^A was highly correlated with C^A where $r(20) = 0.91$ ($p < 0.001$), indicating that the more complex the assembly task, the longer the participants took to complete the design. Correctness on TAG-Game^S was also highly correlated with C^S where $r(10) = 0.95$ ($p < 0.001$). As regards TAG-Game^M, eight sequence items were examined and high correlation was found between the correctness and play complexity, $r(8) = 0.83$ ($p = 0.01$). For all the three TAG-Games, the selected performance measures fitted well to a linear function with the corresponding R^2 close to 1.

7.3. Relationship between TAG-Games and WAIS-IV Subtests

Of the 86 participants who completed the three TAG-Games, 48 completed two subtests of WAIS-IV, BD and MR, and 25 also completed the DS subtest. The number of participants in the WAIS-IV subtests was smaller than the total number of participants, because the study was initially focused on evaluating the preliminary reliability of the TAG-Games and validity of complexity measures and only later became focused on the preliminary validity evaluation of target measures. We first began with two subtests, BD and MR, and later added DS for correlational analysis. Correlations between the three TAG-Games and the three subtests of WAIS-IV are provided in Table 5. TAG-Game^A and the BD subtest scores were correlated by $r(48) = 0.48$ ($p = 0.001$), and TAG-Game^S and the MR subtest by $r(48) = 0.45$ ($p = 0.001$). Correlations were also found between TAG-Game^S and BD ($r(48) = 0.39$, $p = 0.006$), TAG-Game^M and DS ($r(25) = 0.33$, .108), and TAG-Game^M and BD ($r(48) = 0.28$, $p = 0.05$). Weak correlations were found between TAG-Games^A and TAG-Games^S ($r = 0.25$, $p = 0.023$) and between TAG-Games^A and TAG-Games^M ($r(86) = 0.22$, $p = 0.42$). BD and MR were also correlated by $r(48) = 0.38$, $p = 0.007$.

7.4. Exploratory Behavioral Analysis

We performed additional analysis to explore the potential of the SIG-Blocks system for behavioral assessment. The noisy acceleration data was filtered and processed into the discrete rotational motions applied to each block. For this exploratory analysis, TAG-Game^A was selected because it involves multiple block manipulations while the other two games use only a

single block, making them inappropriate for observing behavioral differences. The participants were divided into three groups based on their scores in TAG-Game^A: the high-score, middle-score, and low-score groups. Five individuals from each of these three groups of TAG-Game^A were randomly selected. For each, the speed of manipulative behavior and the total number of rotations applied to the blocks were automatically measured by an embedded algorithm. Fig. 13 shows an interesting finding. Although there were individual differences within the group, a positive correlation was found between the TAG-Game^A score and the manipulation speed ($r(15) = 0.81, p < 0.001$) (See Fig. 13a). On the other hand, as shown in Fig. 13b, no significant group difference was observed in the total number of rotations applied to the blocks during play ($r(15) = 0.22, p = 0.424$).

Figure 13: Speed of rotations for three groups (a) and total number of rotations (b). Fast decision and movement were recorded in the high-score group of TAG-Game^A.

7.5. Discussion

The present investigation suggests TAG-Games has the potential to be used as a cognitive assessment tool; however, the data here should be viewed with caution. The study was a first step towards establishing the reliability and validity of this measure. Small sample size, convenience sampling, and the use of the single administration order (i.e. three TAG-Games always followed by the WAIS-IV subtests) do not allow for generalization of the results and complete evaluation of this technology-based cognitive assessment method. Extended evaluation studies addressing these limitations

631 must follow. In addition, while the presented technology aims to be a fully
632 autonomous and remote assessment tool, the evaluation study involved an
633 administrator to ensure proper use of the hardware, which is a lab-made
634 prototype, and record sensor errors. The accuracy of the automated mea-
635 surement of the time and accuracy at each manipulation step by the SIG-
636 Blocks was over 98%. It was determined that the technical errors were mostly
637 related to the contact failure in the optical sensors. Replacement of these
638 connectors would significantly improve measurement accuracy.

639 With these caveats in mind, the SIG-Blocks technology is technically ad-
640 vanced and produces data which could not be captured in traditional human-
641 administered approaches. The blocks’ unique communication strategies and
642 real-time wireless assessment capabilities surpass the existing systems for
643 the use in cognitive assessment. The SIG-Blocks system can also capture
644 behavioral data in addition to the speed and accuracy for each test item, as
645 described in Section 7.4. Further investigation will be required for using this
646 technology for additional behavioral assessment. To assess behavior, objec-
647 tive and accurate measurement of target behavioral data is essential and the
648 presented technology forms the technical groundwork by enabling such data
649 collection in an objective and fully automated manner.

650 8. Conclusion and Future Work

651 A new tangible game interface technology, SIG-Blocks, and the comput-
652 erized TAG-Games using the SIG-Blocks, TAG-Games, were developed and
653 tested for their usefulness in cognitive assessment. The technology realizes
654 wireless and real-time assessment of cognitive skills by employing a set of
655 SIG-Blocks with embedded motion sensors. Three types of TAG-Games were
656 developed for preliminary technical and human subject evaluations. Relia-
657 bility of the TAG-Game items was assessed using split-half and test-retest
658 reliability tests for evaluating internal consistency and stability over time.
659 The results show high correlations in the evaluations by both of the tests.
660 The defined measures of play complexity are also highly correlated with the
661 participants’ performance in each game, implying that the computational
662 measures are potentially useful for generating dynamic test items meeting
663 each player’s performance and cognitive level. For preliminary assessment
664 of the validity of TAG-Games for measuring target cognitive skills, we com-
665 pared the TAG-Games data with widely accepted standardized measures
666 (i.e. the BD, MR, and DS subtests of WAIS-IV). Moderate correlation was

667 found between TAG-Game^A and BD and TAG-Game^S. TAG-Game^S and BD
 668 and TAG-Game^M and DS were also correlated. Weak correlations were also
 669 found among the TAG-Games, such that $r = 0.25$ between TAG-Games^A
 670 and TAG-Games^S, and $r = 0.22$ between TAG-Games^A and TAG-Games^M.
 671 Among the WAIS-IV subtests, a correlation ($r = 0.38$) was found between
 672 BD and MR.

673 Building on the results presented in this paper, extended human subject
 674 studies will be performed for further validation of the TAG-Game measures.
 675 The future studies will consider (1) broadening of the ages of the participants,
 676 (2) randomizing participants if possible, and (3) randomizing the test order.
 677 There are also a few technical improvements to be made. Although the cur-
 678 rent GUI supports only 2-D assembly, modification to 3-D game expansion
 679 would broaden the scope of our research to cover various applications. In
 680 addition, the cover images on the blocks can be changed or the blocks may
 681 be equipped with liquid crystal display (LCD) or light emitting diode (LED)
 682 displays for generating diverse visual feedback. The three TAG-Games pre-
 683 sented in this paper do not incorporate augmented visual graphics or ani-
 684 mated features, which may be important for making these games more fun
 685 and engaging.

686 Once fully evaluated, the SIG-Blocks technology will have the potential
 687 to provide advanced instrumentation for various research, clinical, and ed-
 688 ucational applications. Such applications can be so diverse as to include
 689 clinical psychology, early-childhood education, and cognitive and motor skill
 690 assessments with automated, objective, cumulative and real-time data col-
 691 lection that enables remote and continuous assessments. Technology-based
 692 approaches, such as the presented work, can also address limitations in the
 693 traditional assessment methods by i) reducing cost by automating the pro-
 694 cess and thus avoiding clinician/administrator time, ii) improving the quan-
 695 tity and quality of the measurable data, iii) enabling objective assessment,
 696 iv) enabling wireless, remote administration for hard-to-reach areas, and v)
 697 providing a dynamic test, tailored for each individual or group to increase
 698 sensitivity in assays.

699 References

- 700 [1] Alers, S. H. M., & Barakova, E. I. (2009). Multi-agent platform for
 701 development of educational games for children with autism. *IEEE ICE*
 702 *CIG, 2009*, 47-53.

- 703 [2] Bernmark, E., & Wiktorin, C. (2002). A triaxial accelerometer for mea-
704 suring arm movements. *Applied ergonomics*, 33(6), 541-547.
- 705 [3] Bors, D. A., & Stokes, T. L. (1998). Raven's Advanced Progressive Ma-
706 trices: Norms for first-year university students and the development of a
707 short form. *Educational and Psychological Measurement*, 58(3), 382-398.
- 708 [4] Chen, H. C., & Chang, L. Y. (2012). Design and implementation of
709 a ZigBee-based wireless automatic meter reading system. *PRZEGLAD*
710 *ELEKTROTECHNICZNY (Electrical Review)*, 88(1b), 64-68.
- 711 [5] Christensen, H., Griffiths, K., MacKinnon, A., & Jacomb, P. (1997).
712 A quantitative review of cognitive deficits in depression and Alzheimer-
713 type dementia. *Journal of the International Neuropsychological Society*,
714 3(06), 631-651.
- 715 [6] Cubelets. Retrieved from <http://www.modrobotics.com/>.
- 716 [7] Fork, M., Bartels, C., Ebert, A. D., Grubich, C., Synowitz, H., &
717 Wallesch, C. W. (2005). Neuropsychological sequelae of diffuse trau-
718 matic brain injury. *Brain injury*, 19(2), 101-108.
- 719 [8] Jeong, D., Kerci, E., & Lee, K. (2010, September). TaG-Games: tangible
720 geometric games for assessing cognitive problem-solving skills and fine
721 motor proficiency. In *Multisensor Fusion and Integration for Intelligent*
722 *Systems (MFI), 2010 IEEE Conference on* (pp. 32-37). IEEE.
- 723 [9] Jeong, D., & Lee, K. (2016). Distributed Communication and Localiza-
724 tion Algorithms for Homogeneous Robotic Swarm. In *Distributed Au-*
725 *tonomous Robotic Systems* (pp. 405-418). Springer Japan.
- 726 [10] Kulp, M. T. (1999). Relationship between visual motor integration skill
727 and academic performance in kindergarten through third grade. *Optom-*
728 *etry & Vision Science*, 76(3), 159-163.
- 729 [11] Lee, K., & Jeong, D. (2014, October). Memorix: A tangible memory
730 game using iSIG-Blocks. In *Games Media Entertainment (GEM), 2014*
731 *IEEE* (pp. 1-8). IEEE.
- 732 [12] Lee, K., Moses, M., & Chirikjian, G. S. (2008). Robotic self-replication
733 in structured environments: Physical demonstrations and complexity

- 734 measures. *The International Journal of Robotics Research*, 27(3-4), 387-
735 401.
- 736 [13] Lezak, M. D. (2004). *Neuropsychological assessment*. Oxford University
737 Press, USA.
- 738 [14] Lockman, J. J. (2000). A perception-action perspective on tool use de-
739 velopment. *Child development*, 71(1), 137-144.
- 740 [15] Lund, H. H., & Nielsen, C. B. (2011, November). Modularity for
741 modulating exercises and levels-observations from cardiac, stroke, and
742 COLD patients therapy. In *Ubiquitous Robots and Ambient Intelligence*
743 *(URAI), 2011 8th International Conference on* (pp. 253-258). IEEE.
- 744 [16] McNerney, T. S. (1999). *Tangible programming bricks: An approach to*
745 *making programming accessible to everyone* (Doctoral dissertation, Mas-
746 sachusetts Institute of Technology).
- 747 [17] Merrill, D., Sun, E., & Kalanithi, J. (2012, May). Sifteo cubes. In *CHI'12*
748 *Extended Abstracts on Human Factors in Computing Systems* (pp. 1015-
749 1018). ACM.
- 750 [18] Millis, S. R., Rosenthal, M., Novack, T. A., Sherer, M., Nick, T. G.,
751 Kreutzer, J. S., High, W. M., & Ricker, J. H. (2001). Longterm neu-
752ropsychological outcome after traumatic brain injury. *The Journal of*
753 *head trauma rehabilitation*, 16(4), 343-355.
- 754 [19] Pehoski, C., Henderson, A., & Tickle-Degnen, L. (1997). In-hand ma-
755 nipulation in young children: translation movements. *American Journal*
756 *of Occupational Therapy*, 51(9), 719-728.
- 757 [20] Petersen, R. C., Smith, G. E., Waring, S. C., Ivnik, R. J., Kokmen, E., &
758 Tangelos, E. G. (1997). Aging, memory, and mild cognitive impairment.
759 *International Psychogeriatrics*, 9(S1), 65-69.
- 760 [21] Polatajko, H. J., & Cantin, N. (2005, December). Developmental co-
761 ordination disorder (dyspraxia): an overview of the state of the art.
762 In *Seminars in pediatric neurology* (Vol. 12, No. 4, pp. 250-258). WB
763 Saunders.

- 764 [22] Raven, J. C., & Court, J. H. (1998). *Raven's progressive matrices and*
765 *vocabulary scales*. Oxford, UK: Oxford Psychologists Press.
- 766 [23] Sanderson, A. (1984, March). Parts entropy methods for robotic assem-
767 bly system design. In *Robotics and Automation*. Proceedings. 1984 IEEE
768 International Conference on (Vol. 1, pp. 600-608).
- 769 [24] Schoemaker, M. M., Niemeijer, A. S., Reynders, K., & Smits-Engelsman,
770 B. C. M. (2003). Effectiveness of neuromotor task training for children
771 with developmental coordination disorder: a pilot study. *Neural plastic-*
772 *ity*, 10(1-2), 155-163.
- 773 [25] Schweikardt, E., & Gross, M. D. (2006, November). roBlocks: a robotic
774 construction kit for mathematics and science education. In *Proceedings*
775 *of the 8th international conference on Multimodal interfaces* (pp. 72-75).
776 ACM.
- 777 [26] Sharlin, E., Itoh, Y., Watson, B., Kitamura, Y., Sutphen, S., & Liu, L.
778 (2002, April). Cognitive cubes: a tangible user interface for cognitive
779 assessment. In *Proceedings of the SIGCHI conference on Human factors*
780 *in computing systems* (pp. 347-354). ACM.
- 781 [27] Short, E. J., & Weissberg-Benchell, J. A. (1989). The triple alliance
782 for learning: Cognition, metacognition, and motivation. In *Cognitive*
783 *strategy research* (pp. 33-63). Springer New York.
- 784 [28] Silverman, W., Mizejeski, C., Ryan, R., Zigman, W., Krinsky-McHale,
785 S., & Urv, T. (2010). Stanford-Binet and WAIS IQ differences and their
786 implications for adults with intellectual disability (aka mental retarda-
787 tion). *Intelligence*, 38(2), 242-248.
- 788 [29] Sparrow, S. S., & Davis, S. M. (2000). Recent advances in the assessment
789 of intelligence and cognition. *Journal of Child Psychology and Psychia-*
790 *try*, 41(1), 117-131.
- 791 [30] Strauss, E., Sherman, E. M., & Spreen, O. (2006). *A compendium of neu-*
792 *ropsychological tests: Administration, norms, and commentary*. Ameri-
793 can Chemical Society.
- 794 [31] Suzuki, H., & Kato, H. (1995, October). Interaction-level support for
795 collaborative learning: AlgoBlockan open programming language. In

- 796 *The first international conference on Computer support for collabora-*
797 *tive learning* (pp. 349-355). L. Erlbaum Associates Inc.
- 798 [32] Tatemichi, T. K., Desmond, D. W., Stern, Y., Paik, M., Sano, M.,
799 & Bagiella, E. (1994). Cognitive impairment after stroke: frequency,
800 patterns, and relationship to functional abilities. *Journal of Neurology,*
801 *Neurosurgery & Psychiatry*, 57(2), 202-207.
- 802 [33] Terrenghi, L., Kranz, M., Holleis, P., & Schmidt, A. (2006). A cube to
803 learn: a tangible user interface for the design of a learning appliance.
804 *Personal and Ubiquitous Computing*, 10(2-3), 153-158.
- 805 [34] Willingham, D. B., Koroshetz, W. J., & Peterson, E. W. (1996). Motor
806 skills have diverse neural bases: Spared and impaired skill acquisition in
807 Huntington's disease. *Neuropsychology*, 10(3), 315.
- 808 [35] Wong, W. Y., & Wong, M. S. (2008). Detecting spinal posture change
809 in sitting positions with tri-axial accelerometers. *Gait & Posture*, 27(1),
810 168-171.
- 811 [36] Wright, F., Rosenbaum, P. L., Goldsmith, C. H., Law, M., & Fehlings,
812 D. L. (2008). How do changes in body functions and structures, activity,
813 and participation relate in children with cerebral palsy?. *Developmental*
814 *Medicine & Child Neurology*, 50(4), 283-289.
- 815 [37] Wyeth, P., & Wyeth, G. F. (2001). Electronic blocks: Tangible program-
816 ming elements for preschoolers. In *IFIP TC. 13 International Conference*
817 *on Human-Computer Interaction* (Vol. 1, pp. 496-503). IOC Press.

Table 1: Communication strategies, sensing capabilities, and homogeneity in the design of existing technology-embedded blocks and SIG-Blocks and their application domain.

Block systems (Year)	Block- computer com.	Block-block com.	Embedded sensor	Measurable data	Data display
AlgoBlock (1995) [31]	Wire	EM	-	Binary assembly detection	Online (PC)
Tangible Programming Bricks (2000) [16]	-	EM	Capacitive touch, infrared	Touch	Online (LED)
Electronic Blocks (2001) [37]	-	EM	Light, sound, movement	Light, sound, touch	Online (LED)
Cognitive Cubes (2002) [26]	Wire	EM	Ultrasonic, tactile, gyroscopes	Binary assembly detection	Online (PC)
roBlocks (2006) [25]	-	EM	Light, sound, touch, motion, distance	Light, sound, touch, motion, distance	Offline
Learning Cube (2006)[33]	Wireless (RF)	-	Accelerometer	Orientation	Offline
Multi-Agent System (2009) [1]	-	Optical	Infrared	Assembly detection	Online (LED)
Sifteo (2012) [17]	Wire	Optical	Accelerometer, infrared	Assembly, orientation	Online (LCD)
SIG-Blocks	Wireless (RF)	Optical	Triaxial accelerometer, infrared transistors	Triaxial accelerations, assembly, orientation	Online (PC)

Table 2: Three types of games and the cognitive skills expected to be associated with each game.

Type	Associated cognitive skills
TAG-Game ^A	Fine-motor proficiency, visual-motor integration, low-level working memory, attention span
TAG-Game ^S	Fine-motor proficiency, visual-motor integration, low-level working memory, cognitive problem solving, attention span
TAG-Game ^M	Fine-motor proficiency, visual-motor integration, high-level working memory, attention span

Table 3: Demographics of the participants for the three TAG-Games (TAG-Game^A (TA), TAG-Game^S (TS), and TAG-Game^M (TM)) and the three subtests of WAIS-IV. The table shows the number of participants, the number of female participants, and the average age with the standard deviation (SD).

TA	TS	TM	BD	MR	DS	No. Par.	No. Males	Ave. Age (SD)
○	○	○	×	×	×	86	38	21.6 (3.1)
○	○	○	○	○	×	48	18	20.9 (2.5)
○	○	○	○	○	○	25	8	20.4 (1.1)

Table 4: The test involves six subtests (60 min), including three TAG-Games and three subtests of WAIS-IV.

Order	Task	Time	No. Items
1	TAG-Game ^A (TA)	15 min	20
2	TAG-Game ^S (TS)	5 min	10
3	TAG-Game ^M (TM)	15 min	8
4	WAIS: BD	5 min	14
5	WAIS: MR	10 min	26
6	WAIS: DS	10 min	48

Table 5: Correlations among the three TAG-Games and WAIS-IV subtests (BD, MR, and DS).

	TA	TS	TM
BD	$r(48) = \mathbf{0.48}$ ($p = 0.001$)	$r(48) = 0.39$ ($p = 0.006$)	$r(48) = 0.28$ ($p = 0.05$)
MR	$r(48) = 0.03$ ($p = 0.825$)	$r(48) = \mathbf{0.45}$ ($p = 0.001$)	$r(48) = 0.09$ ($p = 0.556$)
DS	$r(25) = -0.19$ ($p = 0.365$)	$r(25) = 0.07$ ($p = 0.74$)	$r(25) = \mathbf{0.33}$ ($p = 0.108$)

SIG-Blocks: Tangible Game Technology for Automated Cognitive Assessment

Kiju Lee, Ph.D.

Corresponding Author

Assistant Professor in Mechanical and Aerospace Engineering

Case Western Reserve University

10900 Euclid Avenue, Cleveland, OH 44106

kiju.lee@case.edu

Tel: 216-368-2943

Fax: 216-368-3007

Donghwa Jeong, Ph.D.

Department of Mechanical and Aerospace Engineering

Case Western Reserve University

Donghwa.jeong@case.edu

Rachael C. Schindler, Ph.D. Candidate

Department of Psychological Sciences

Case Western Reserve University

Rdc55@case.edu

Elizabeth J. Short, Ph.D.

Professor in Psychological Sciences

Case Western Reserve University

Elizabeth.Short@case.edu