A Biometric Evaluation of a Computerized Psychomotor Test for Motor Skill Training

Wenqi Ma, Wenjuan Zhang, Maicom Brandao, David Kaber, Manida Swangnetr, Michael Clamann

Edward P. Fitts Department of Industrial and Systems Engineering
North Carolina State University
Raleigh, NC, USA

Standardized psychomotor tests have been widely applied in laboratory research and clinical therapy as a tool to evaluate human motor and cognitive skills. A number of prior studies have developed computer-based versions of traditional tests by using virtual reality (VR) technology and haptically-enabled control devices. These systems provide the advantage of easy manipulation in administrating experiments and collecting data, as well as recording a broader range of human performance measures for researchers and therapists. However, many VR-based tests have not been validated in terms of human physiological responses. In this study, a VR-based computer simulation of the Block Design (BD) test (a standardized psychomotor task as part of an adult IQ test) was developed and compared with the physical version of the test. Performance was evaluated based on two types of muscle activation collected using electromyography (EMG). Results verified the VR-based task as physically comparable to the conventional BD test. The validated computerized psychomotor task may be applied for both experimental and clinical use in future studies.

Practitioner Summary: Standardized psychomotor tasks can be computerized for assessing human motor skill, including the use of VR systems with haptic interfaces. Some systems have been validated against conventional test methods in terms of performance. A system simulating block design reconstruction was validated in terms of human physiological responses (muscle activation). Results suggest such a system could be substituted with advantages over conventional testing.

Keywords: psychomotor test, virtual reality, motor skill training, electromyography

1. Introduction

Psychomotor tests have been commonly applied to evaluate human motor skills and cognitive performance in both laboratory experiment and clinical therapy training. Among various test batteries, the Block Design (BD) test, developed in the 1920s (Kohs, 1920), has been acknowledged as a powerful tool to measure intelligence and psychomotor performance, independent of specific language skills (Kohs, 1923; Goldstein & Scheerer, 1941). The task requires participants to reproduce a set of two-dimensional design patterns by matching the top surfaces of four or nine wooden blocks to a target stimulus pattern. All blocks are identical in shape and size but have sides colored in all “white”, “red”, or a cross-sectional pattern of both colors (see Figure 1). Recent studies have demonstrated a contemporary version of the BD test, embedded in the Wechsler Adult Intelligence Scale (WAIS; Wechsler, 1997), to have utility for assessing human motor control skills (Jeon et al., 2013; Clamann et al., 2013; Kaber et al., 2014).

A number of prior studies have demonstrated advantages of applying VR technologies in automating aspects of neuropsychological tests (Schultheis & Rizzo, 2001; Bouzit et al., 2002; Sveistrup, 2004), including capturing objective response measures that cannot be easily recorded in traditional testing (Riva & Davide, 2001; Jeon et al., 2013). Related to this, a previous research project (Jeon et al., 2013) applied advanced VR technology to the standardized WAIS-BD task. The VR-BD program maintained a record of block and control cursor trajectory data at a frequency of 10 Hz. With this data, the pattern of user behavior in reconstruction of any design can be played-back through the VR system and analyzed in terms of performance variables, kinematic responses, etc. In addition to superior data collection features, the use of haptic controls can facilitate motor performance by patients with impairments, such that real object manipulation is difficult.

The VR-BD program has been used in several follow-up studies (Clamann et al., 2013; Kaber et al., 2014) since development. These studies have demonstrated the program to be comparable to the physical
The BD task in terms of various measurements, including the BD test score obtained using the WAIS rules (The Psychological Corporation, 1999), task completion time, and a strategy index score (Clamann & Kaber, 2012). To further validate use of the VR-BD task for neuropsychological testing in terms of human physiological responses, electromyography (EMG) was applied in the present study. It was expected that the muscle activation measures would also support the application of the VR version of the BD test as a potential substitute for the conventional physical version.

Since the BD task involves simultaneous translational and rotational movements (i.e., moving a block to specific position while rotating it to reveal a desired top surface), investigation of arm muscle activation levels required by each type of movement is confounded. Furthermore, determining the degree of challenge experienced by participants in the different types of performance is also confounded. In a recent study (Stoelen & Akin, 2010), tasks combining translational and rotational movements were investigated by splitting the combined movements into pure translational movement and pure rotational movement. The experimental results showed that no significant increase in performance time was incurred by such splitting. Therefore, a similar method was applied in the present study where the original VR-BD program was modified to allow participants to perform block moving and block rotation in separate phases.

In summary, the specific aim of the present study was to validate the VR-based BD task as being comparable to the physical version of the task in terms of human muscle activation responses. Comparison of the two tasks was made in terms of defined phases of movement (transitional and rotational). It was expected that the computerized version of the BD test would provide comparable challenge to participants as posed by the physical task in either phase of movement and that muscle activation levels would be comparable across tasks.

2. Method

2.1 Participants

For this study, a total of 24 right-handed participants were recruited from the North Carolina State University and off-campus populations. Participant age ranged from 19 to 46 years old (mean = 26.4; standard deviation = 6.5). All participants were required to have 20/20 or corrected vision (if corrected, they were asked to wear their glasses or lens while performing the tasks) and to have neither current nor chronic wrist disorders (e.g., carpal tunnel syndrome). All criteria were confirmed in a screening step prior to scheduling an experiment session.

2.2 Tasks

All participants were required to perform one of the two versions of the BD task – the VR version presented on a computer display screen and controlled via a haptic interface or the native version with physical blocks. Under both conditions, administration of the BD test followed the Wechsler Abbreviated Scale of Intelligence.
Designs 4 through 9 of the WASI booklet were used as stimuli with all involving four blocks in construction of patterns. Participants were asked to repeat the same set of six designs three times, with a short break provided in between each replication. In both the native and VR conditions, a specific physical area was defined on a worktable (real or virtual) above which participants were required to perform any block rotation. This requirement divided the BD task into a “rotation” phase (blocks being rotated above the area without translational) and a translation or “honing” phase in which blocks were moved to a target position without any re-orientation. All participants were required to perform the task with their dominant hand so as to reduce any potential motor learning effects in block movement or haptic device use on the muscle activation responses.

For participants assigned to the VR condition, pre-test training was provided in order to ensure proficiency in using the haptic device to manipulate virtual blocks. The training program was developed in a prior study (Clamann et al., 2013) and was found to produce fluid control of the haptic device among novice users through a series of 40 trials (completed in approximately 15 minutes). In every trial of the training task, a single virtual die was placed near the center of a work surface with a two-dimensional stimulus design presented in a display area (see Figure 2). The goal of the task was to move the die to the target square as quickly and accurately as possible, with the top surface matching the given stimulus. In pilot testing, we did not observe an effect of participant fatigue through the device training on subsequent experiment testing; therefore, only participants under the VR condition were required to complete the pre-test training as part of the study.

Figure 2. An example of pre-test VR control device training task.

2.3 Apparatus

The VR interface was presented on a high performance PC integrated with a stereoscopic display using an NVIDIA® 3D Vision™ Kit, including 3D goggles and an emitter (see Figure 3). Stereoscopic rendering of the task simulation was supported by an OpenGL quad-buffered stereo, high-performance video card (NVIDIA® Quadro™). A SensAble Technologies PHANTOM Omni® Haptic Device was used as the haptic control platform and was integrated with the PC. The Omni includes a boom-mounted control that supports 6-degree-of-freedom (DOF) movement and 3-DOF force feedback. The interface automatically recorded participant movement behavior (rotations and translations) at a frequency of 10 Hz.

The VR-BD simulation presented a virtual tabletop divided into two parts – a display area and a work area (see Figure 4). The display area presented the stimulus design patterns to be replicated by a participant. The work area was used for arranging the virtual blocks. The work area and blocks were presented at approximately 70% of actual size to allow the design pattern and workspace to be viewed on a 21-inch stereo monitor. All block designs were constructed with the aid of a target grid, which appeared as a 2x2 collection of squares in the work area (see Figure 4). A shaded area was presented at the bottom of the simulation screen and was defined for participants as the block rotation area.
The Omni haptic device was used to manipulate a cursor (a small blue orb) appearing on the display during BD training. A customized block-shape control (see Figure 3) was developed to provide a more realistic simulation of actual block handling, as in the native task. Virtual blocks could be grasped by touching the cursor against them and pressing a button one side of the block-shaped control. A virtual block could be lifted from the virtual table surface and rotated about any axis using the haptic control. Haptic features were included in the simulation to represent the blocks and the table as solid objects.

A custom wooden worktable with a flat-screen monitor mounted horizontally into the table surface (at a cutaway) was used as a platform for performance of the native BD task (see Figure 5a). A graphical image was rendered on the flat-screen (see Figure 5b) identifying starting positions for blocks (in “green”) and presenting a rotation area (in “orange”) and block destination grid (in “blue”) for participants. All positions were consistent with those in the VR version of the task. At the start of each test trial, physical blocks were placed over the green squares at the surface of the flat-screen. Participants picked-up the blocks, rotated them over the orange area and then returned them to the surface of the flat-screen at the blue grid. In order to precisely capture and control participant performance, a Logitech® HD Webcam C525 was hung from the ceiling of our lab space, directly over the center of the flat-screen but above participant seated height. The camera recorded video of all participant motion behavior in order for subsequent classification of muscle activation responses as causing rotational or translational movement. The muscle activation levels (EMG signals) of participants were recorded during test trials with a BIOPAC® MP 150 system.
The study followed a between-subjects experiment design with each participant being randomly assigned to either the native or VR task condition (i.e., the task condition represented the independent variable). With respect to dependent variables, we captured EMG signals from two muscles, including the flexor pollicis brevis and pronator teres. The flexor pollicis brevis controls the thumb while gripping a block (or the block-shaped control device) and the pronator teres activates forearm rotation in order to achieve a desired block orientation. The Biopac EMG system was to a sampling rate of 1000 Hz. All signal samples were processed with a fourth-order Butterworth filter (high-pass filter set as 20 Hz and low-pass filter set as 450 Hz) and a notch filter of 60 Hz. The screened data was then rectified and averaged across every 51 data points. Prior to formal experiment testing, maximum voluntary muscular contractions (MVC) were required of each participant in order to identify the maximum force that could generated with each muscle. Individual MVC data was subsequently used to normalize the EMG responses collected during test trials (i.e., task EMG was normalized as a percentage of participant MVC responses). Statistical analyses were conducted on the post-processed EMG responses.

3. Results

Table 1 presents descriptive statistics on the muscle activation levels, grouped by phase of movement in the BD task (i.e., rotation vs. honing) as well as the task condition (native vs. VR). Both maximum and mean normalized EMG responses were determined. As can be seen in the data table and in Figure 6 (max responses) and Figure 7 (mean responses), muscle activation was greater in the rotation phase as compared to honing under either task condition. The flexor pollicis brevis muscle (CH1) showed higher levels of response under the native task condition as compared to the VR condition across both phases of movement. However, the pronator teres (CH2) showed similar levels of activation under the two task conditions and across the phases of movement. These trends were consistent among the max and mean EMG responses.

<table>
<thead>
<tr>
<th>CH*</th>
<th>Honing (Max)</th>
<th>VR (Max)</th>
<th>Rotation (Max)</th>
<th>VR (Max)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Native</td>
<td>VR</td>
<td>Native</td>
<td>VR</td>
</tr>
<tr>
<td>Max</td>
<td>1</td>
<td>21.92</td>
<td>15.87</td>
<td>38.42</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>4.11</td>
<td>5.27</td>
<td>5.08</td>
</tr>
<tr>
<td>Mean (SD)</td>
<td>1</td>
<td>4.97</td>
<td>2.23</td>
<td>11.06</td>
</tr>
<tr>
<td></td>
<td>(6.24)</td>
<td>(1.53)</td>
<td>(9.78)</td>
<td>(3.82)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.83</td>
<td>0.90</td>
<td>1.92</td>
</tr>
<tr>
<td></td>
<td>(0.53)</td>
<td>(0.59)</td>
<td>(1.51)</td>
<td>(1.19)</td>
</tr>
</tbody>
</table>

* CH1 – Flexor pollicis brevis  CH2 – Pronator teres
To further analyze the muscle response data, a multivariate analysis of variance (MANOVA) was conducted to identify any statistically significant differences in muscle activation levels among phases of movement in the BD task as well as significant differences among task types within phase of movement. Table 2 presents MANOVA test results on comparison of the EMG responses (max and mean for both CH1 and CH2) between the phases of movement. The MANOVA revealed significant differences between rotation and honing for both maximum EMG and mean EMG level.

Table 2. MANOVA results on EMG responses among phases of movement (rotation vs. honing).

<table>
<thead>
<tr>
<th></th>
<th>Wilks' Lambda</th>
<th>F value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMG max</td>
<td>0.9552</td>
<td>F(1, 286) = 13.41</td>
<td>0.0003*</td>
</tr>
<tr>
<td>EMG mean</td>
<td>0.9007</td>
<td>F(1, 286) = 31.52</td>
<td>&lt; 0.0001*</td>
</tr>
</tbody>
</table>

* Statistical significance level was set as α = 0.05.

Figure 6. Max EMG responses for phases of movement and task conditions.

Figure 7. Mean EMG responses for phases of movement and task conditions.
On the basis of the above results, responses collected during the two phases of movement were separated into two data sets for analysis of any task condition affect. Separate MANOVAs were conducted to identify differences between the VR and native conditions. As shown in Table 3, no significant differences were detected between the task conditions within either phase of movement. Such results were consistent with the research hypothesis, which posited that comparable levels of muscle activation would occur under the two task conditions based on the design of the VR simulation and haptic control interface.

Table 3. MANOVA results on EMG responses among task conditions (VR and native) within phase of movement.

<table>
<thead>
<tr>
<th></th>
<th>Wilks’ Lambda</th>
<th>F value</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Honing</td>
<td>EMG max</td>
<td>F(1, 142) = 1.20</td>
<td>0.2744</td>
</tr>
<tr>
<td>Phase</td>
<td>EMG mean</td>
<td>F(1, 142) = 5.04</td>
<td>0.0663</td>
</tr>
<tr>
<td>Rotation</td>
<td>EMG max</td>
<td>F(1, 142) = 1.38</td>
<td>0.2424</td>
</tr>
<tr>
<td>Phase</td>
<td>EMG mean</td>
<td>F(1, 142) = 2.17</td>
<td>0.1428</td>
</tr>
</tbody>
</table>

4. Discussion

The specific aim of the present study to validate a computerized-version of the BD task as being comparable to the conventional physical form of the task in terms of human physiological responses. Based on the design of the VR visual interface and haptic control interface, it was expected that forearm muscle activation levels in the VR task would be comparable to those observed under native task conditions. Our results supported the research hypothesis. No significant difference was observed in mean and max EMG responses among the task conditions across different types of movement in real and virtual block handling. In general, muscle activation levels were similar in magnitude during performance of the BD task in physical form or with the VR workstation. Such results support the notion that the computerized BD task could pose a similar degree of physical challenge for users as the conventional task. Considering these findings together with the results of previous studies on the computerized BD task (Leon et al., 2013; Clamann et al., 2013; Kaber et al., 2014), the VR setup appears to be valid in terms of both performance and physiological response measures. It is suggested that the VR-BD test could be applied as a substitute for the conventional BD task in clinical therapy or laboratory research with the advantages of ease of manipulation, automatic data collection, etc.

With respect to the specific muscle activation responses, we found the flexor pollicis brevis to yield greater responses than the pronator teres under both task conditions. These results suggested that gripping and holding blocks (or the block-shaped haptic interface) with the thumb required greater effort relative to maximum muscle force output as compared to rotation of blocks with the forearm.

Although the two task conditions were found to be statistically comparable in terms of muscle activation levels, the pattern of muscle activation for the experiment revealed the pronator teres response to be slightly higher under the VR vs. native condition. However, the flexor pollicis brevis showed exactly the opposite pattern, with relatively stronger activation level under the native task condition. This difference in activation pattern suggested that participants might rely more on the thumb in reconstruction of block designs under the native condition vs. the VR condition. When directly manipulating physical blocks with the hand, one can easily maintain control of a block with only the fingers while keeping the elbow still. However, when manipulating virtual blocks in the VR task condition by using the haptic device, participants often rotated the forearm to achieve a desired movement. Due to such differences in physical behavior, it is possible that the pronator teres muscle was more active under the VR condition and, to some extent, reduced participant reliance on the flexor pollicis brevis, as in the native task condition.

5. Conclusions

Many computerized versions of standardized psychomotor tasks have been developed for motor skill assessment and training. Some have been validated through comparison of performance results with results for actual physical tasks. However, few computer tests have been validated in terms of biometrics or human physiological responses. In this study, we focused on assessment of the validity of a computer-based (VR) simulation of the well-known BD task in terms of user muscle activation required by specific movements in task performance. In general, the objective of such assessment is to determine whether the VR-based task
simulation can be used as a comparable alternative to the native/physical task in order to take advantages of benefits including ease of task administration, condition manipulation and recording of user performance data. We conducted a between-subjects experiment in order to capture EMG responses from two upper-extremity muscles and to make comparison across task conditions (VR vs. native) as well as types of movements. Our findings indicated comparable levels of muscle activation, which support the potential application of the VR-BD task in terms of clinical testing and therapy.

Limitations of this research include examination of only two muscle responses in the BD task. It would be interesting to examine additional arm muscles in future study in order to develop a more complete “picture” of any implications of the haptic interface on activation levels divergent from the physical task. Data on a larger set of muscles might allow for identification of other interdependencies among muscle or reveal a more elaborate pattern of activation, providing additional information for future enhancement of the VR simulation. In addition, future research should analyze different types of measures, including performance and physiological responses, in the same study. Consistent results generated from a single sample of participants would provide for more robust validation of the VR-BD task.

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References


