Using Cognitive Load Measurement and Spatial Ability Test to Identify Talented Students in Three-Dimensional Computer Graphics Programming

Farshid Anvari, Hien Minh Thi Tran, and Manolya Kavakli

***Abstract*—The aim of this paper is to identify talented students in three-dimensional computer graphics programming using cognitive load measurement and spatial ability test. Eleven students from the department of computing undertook a spatial ability test, a performance and a cognitive load test using task and performance-based techniques and, perception surveys. The results are supportive of previous research studies in building expertise. Students with high spatial ability who performed well in the task of generating three-dimensional computer graphics with low cognitive load measures were identified as talented students in three-dimensional computer graphics programming. This study suggests that people with higher abstract thinking have better ability to transfer skills from similar domains.**

***Index Terms*—Spatial ability, cognitive load measurement, three-dimensional computer graphics programmers, task and performance-based techniques, talented students, computer graphics education.**

I. Introduction

The performance of students in carrying out novel tasks will depend on their abilities and trainings in a similar domain, as well as their motivations [1]. Students exhibit different capabilities in learning new tasks or transferring learnt abilities from one domain to a similar domain [2]-[3]. While conducting tasks, students have to exert cognitive load. The cognitive load can be high when students are doing a task in a new domain as they have to learn new skills while performing the task [4].

A number of studies have demonstrated performance differences between the knowledge of experts and novices [5], innate talent and giftedness [2]-[3]. Studies of experts and novices have revealed that experts have lower cognitive load [5]. Students, who are gifted in one or more domains, have a strong drive and make discoveries independently [3]. Spatial ability is essential to be successful in a number of domains including architecture, engineering and programming [6].

In our study a group of eleven students from the Department of Computing at Macquarie University undertook a spatial ability test, task and performance-based tests, a cognitive load test, and perception surveys.

In the next section we review the human cognition, memory and performance literature. We outline the setup of the study to discover the traits of a talented student using cognitive load measurements and task and performance-based tests. In discussion and conclusion, we provide techniques to identify talented students in three-dimensional computer graphics programming (3DCGP). We propose further research to verify our findings.

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II. Related Work and Literature Review

The performances of students depend on their motivation, intelligence, memory and mental functionalities as well as their cognitive load. Considerable research has been conducted in the area of human memory and cognitive load. Cognitive Load Theory (CLT) explains knowledge and skill acquisition [7]. CLT is based on the cognitive architecture of human memory. Cognitive architecture consists of a sensory memory, a working or short-term memory and, a long-term memory. Visual or auditory stimuli have sensory memories which remember the stimuli for a very short duration of time, generally less than a second [8]. The view of working and long-term memories is similar to a computer architecture consisting of a central processing unit, temporary data buffers and long-term storages [9]. Human long-term memory is effectively limitless [10]. Squire [11] traced a long history of the idea that memory is composed of multiple separate systems which are grounded in biology. By placing memory within a biological framework, Squire [11] provides taxonomy of long-term memory in which memory is divided into two groups: declarative and non-declarative. Declarative memory deals with single events but non-declarative memory provides for the ‘ability to gradually extract the common elements from series of separate events’ [11].

The amount of working memory is limited [10]. The accepted limit of working memory is five to nine items with seven items often quoted [4]. In order to overcome the limitations of working memory, schemas [12] which help to “chunk” and systematically store and access information are created during the learning process. These schemata help us perform complex tasks many of which would otherwise be impossible, such as playing chess, reading and comprehending the written word [12], or computer programming [13]. Thus, developing schemata which can encapsulate large amounts of data is an essential part of learning. With further practice, schemata can be automated [14], which means they do not have to be processed in working memory at all. Automation occurs only for schemata

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that are very frequently utilised or practiced.

Kavakli *et al.* [15] who studied the performance of an expert and a novice architect found that the expert architect produced three times more drawings with richer contents than novices. This is due to expert's higher and more structured cognitive activity. An expert efficiently governs her performance as she structures clearly her cognitive actions and uses them in a more organised manner [5]. Cross [16] observed that experts in a domain can conceptualise abstract ideas and they have developed ability to access larger amount of information. These abilities allow the experts to recognise the underlying design principles when faced with a problem in the domain of expertise. In a study of novice and expert surgeons, Hsu et al. [17] found that experts were able to attend equally to the main surgical task as well as other 'cognitive tasks', whereas the novices could attend to the surgical task at the expense of other 'cognitive tasks'.

Experts can transfer knowledge from one domain to another at an abstract level [18]. Intelligence is the ability to solve problems. Gardner listed seven intelligences: linguistic, logical-mathematical, spatial, musical, bodily-kinesthetic, interpersonal and intrapersonal [19]. Persons with innate ability or giftedness have high talent in one or more domains; with little tutoring, they can understand the abstract concepts, ask deep questions, reflect on various interpretations of the problems and can transfer their knowledge from similar domains [3].

Spatial intelligence allows a person to see depth and be able to manipulate and rotate three-dimensional (3D) objects. Presmeg [20] found visual–spatial scheme (pattern imagery) an important aspect of problem solving and abstracting knowledge. Sutton and Williams [21] observed that spatial abilities refer to, in general, a collection of cognitive, perceptual, and visualisation skills such as the ability to visualize mental rotation of objects, the ability to understand how objects appear in different positions, and the skill to conceptualise how objects relate to each other in space. Many studies have reported that spatial visualisation can be a predictor of problem solving success [22].

According to Sweller [23] cognitive load is considered to be of three types: intrinsic, extraneous and germane. Intrinsic cognitive load is due to the nature of the task and the expertise of the learner to think in abstract; the extraneous cognitive load is due to the task surrounding and presentation of the task and instructions; the germane cognitive load is due to processes that are used to create 'chunks' or schemas to hold information in long-term memory [23]. Extraneous cognitive load can be reduced and germane cognitive load can be optimised; the three cognitive loads are additive; the total load should remain below the working memory limit [23, 24].

Cognitive load can be measured by a rating scale technique, physiological technique, task and performance-based techniques [24]. According to Paas et al. [24] task and performance-based techniques provide a reliable measure of cognitive load. In this technique the performance in primary and secondary tasks, performed concurrently, are measured as performance, reaction time and accuracy.

In sum, the human memory and cognitive load literature shows that experts in their domain of expertise have the ability to perform abstract reasoning; have an accumulated store of knowledge; and have the ability to transfer their skills from one domain to other similar domains.

III. Research Questions

Based on studies of Anderson and Pearson [12], Kavakli [15], Cross [16], Merriënboer and Sweller [14], Winner [3] and Hsu et al. [17] we can assume that when experts conduct tasks in the domain of expertise, they have low cognitive load and are able to finish the given task with ease; experts can attend to both primary and secondary tasks equally as they have low response latency rate while responding to external stimuli.

In this paper we address two research questions:

- Can we use spatial ability test and cognitive load measures to identify a talented student in 3D computer graphics programming?
- Do students who do well in spatial ability test and the 3D programming task exhibit similar patterns of behaviour as experts?

IV. Methodology

In this study, empirical measures and a set of questionnaires were used to measure cognitive load of students solving a two-dimensional and a 3D computer graphics problem.

The study was conducted in four parts: All students undertook a spatial ability test, task and performance-based tests and a post study perception survey. Physiological measurements from four students were collected while they were doing the task and performance-based test.

A. Spatial Test

The spatial ability test that was used for this study was a 20 item version created by George Bodner [25]. The Purdue visualisation of rotations test (ROT) consists of 20 items that require students to study how the object in the top of the line of the question is rotated; picture in their mind what the object shown in the middle of the line of the question looks like when rotated in exactly the same manner and select from among the five drawings (A, B, C, D and E) given in the bottom line of the question the one that looks like the object rotated in the correct position [25].

B. Task and Performance-Based Tests

Task and performance-based techniques were used to measure cognitive load. The secondary task selected required similar cognitive load to the primary task. In the task and performance-based tests, the students concurrently conducted two sets of primary and secondary tasks. The primary task consisted of two parts: part one was drawing a two-dimensional shape (Fig. 1) and part two was drawing a 3D shape (Fig. 2). A percentage score was given to each of the primary tasks depending on degree of completion of the drawing.

The secondary task was required to respond to an applet. The applet consisted of a coloured rectangular, a text field displaying numbers with arithmetic operations, a text box to enter answer and a submit button. When the applet was displayed in green colour, Fig. 3, no attention was required; when applet was displayed in red colour, Fig. 4, attention was required.

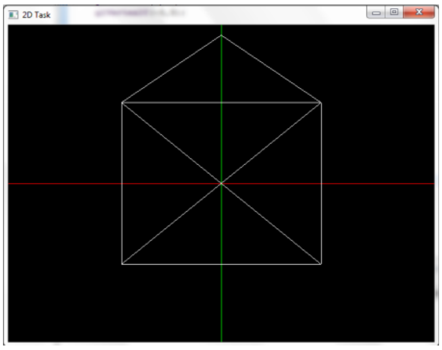


Fig. 1. Primary task: two-dimensional shape

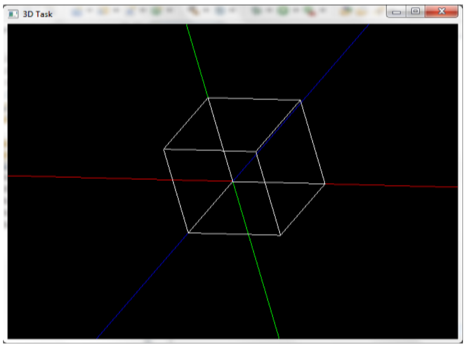


Fig. 2. Primary task: 3D shape

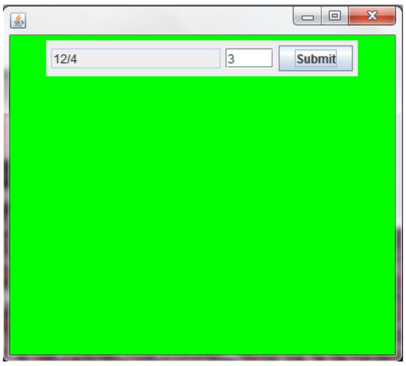
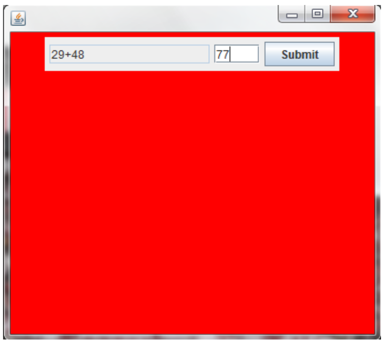


Fig. 3. Secondary task – no attention required



Fig, 4. Secondary task – attention required

In Fig. 4, the student would mentally carry out the arithmetic operation; enter the result in the text field and press the submit button. The display rectangle would change to green (Fig. 3). Log files recorded the following data: the contents of the text field; the time the applet changed its colour to red; the students' answer and the time they pressed the submit button.

C. Physiological Measurements

Four students from the eleven recruits undertook physiological measurements. The measurements consisted skin conductivity and heart rate variation. The device, WildDivine product Model No WDS01-40101, measured skin conductivity and heart rate variation using three finger clips and logged the readings to a file. The application ran on windows operating system.

D. Perception Surveys

The students provided answers to a perception survey questionnaire at the completion of the tasks. The answers to questions in perception surveys were scaled from 1 to 5. The following data were collected as part of the survey: interest, entertainment, eagerness, motivation, understanding, perceived difficulty and effort in carrying out the tests.

V. Experimentation

Eleven students volunteered to participate in the tests and surveys. The average age of the students was 25. Ten students came from an IT background, but none of the students had previous experience in computer graphics programming. They performed the tasks given in a tutorial session which was not part of their curriculum. Human Ethics approval was obtained prior to the experiments.

A. Experimental Procedure

The purpose of the study was explained to the students. They all agreed to participate.

Students were given 15 minutes to complete a spatial ability test using paper and pencil. One point was awarded for each correct response. The total score, which was a sum of correct responses, was scaled to 100 which represents the spatial ability performance in percentage for each student. (Table I)

All students completed the task and performance-based tests. The primary task for part one was drawing a two-dimensional shape. The time limit for this task was 15 minutes. For part two, the primary task was drawing a 3D shape. The time limit for this task was 20 minutes. A percentage score was given for each of the primary tasks depending on the degree of completion of the drawing. At the end of the tests all participating students answered the perception surveys.

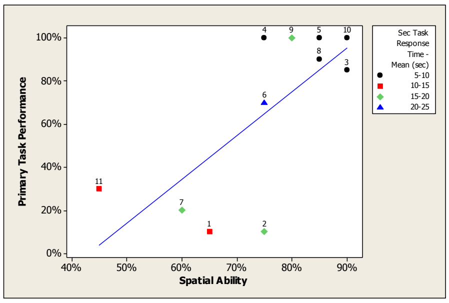


Fig. 5. Performance in drawing 3D shape vs. performance in spatial ability test. The scatter points labeled by student Id, are categorised by mean response time (seconds) for the secondary task

The result of physiological measurements and the two-dimensional task and performance-based test will be presented in a later paper.

B. Analysis of Results

All the results were analysed using Minitab version 16.2.1 running on Windows 7 for similarity in patterns to uncover performance differences. Table I and Fig. 5 show the students who performed well in the primary task of drawing 3D shape have scored 75% or above in the spatial ability tests

TABLE I: SPATIAL ABILITY SCORES AND STUDY RESULTS FOR THE PRIMARY TASK OF DRAWING A 3D SHAPE.

Stu-d ent Id	Spatial Ability Score %	Primary task 3D Perform-ance %	Secondary task Response Time in millisecond (msec)		Secondary task Response Correctness %
			Mean	SD	
1	65	10	13204	8377	100
2	75	10	17031	14448	94
3	90	85	8038	2930	94
4	75	100	6751	1628	97
5	85	100	8115	6534	97
6	75	70	21782	22746	89
7	60	20	16113	7352	91
8	85	90	8776	3467	85
9	80	100	18948	12722	92
10	90	100	8481	4056	92
11	45	30	13284	8085	100

C. Identification of 3DCGP Talented Students

A visual inspection of Fig. 6 and 7 reveals that students who scored below 70% in the spatial ability test had lower variability in response time compared to students who scored in the range of 70-80% in the spatial ability test; it seems the former students had low cognitive load. The students scored above 80% in the spatial ability test, had least variability in response time. The regression line shows a negative correlation between response time and spatial ability score.

These observations are indicative; further studies are required with larger samples to ascertain their significance. However the results indicate that students who scored high in the spatial ability test can organise their cognitive activities efficiently while performing a 3D computer programming task. They can attend equally to main task and other cognitive tasks. These results are supportive of previous research in expertise [5], [17], [26].

Fig. 8 shows that students 3, 4, 5, 8 and 10, who performed well in their primary tasks, had consistently low response time to the secondary tasks which demonstrates these students had low cognitive loads. Student 9 exhibited different characteristics; s/he had high and varied response time to the secondary task, however s/he performed well in the primary task; s/he was eager to complete the primary task (see Table II).

Fig. 9 shows that there are two main clusters of students: 1- those who scored high in the spatial ability test and consistently responded quickly to the secondary task and, 2- those who scored low in the spatial ability test or had trouble responding to the secondary task. The latter group, with the exception of student 9, did not perform well in the primary task.

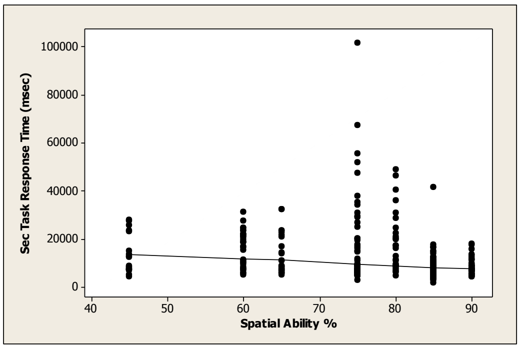


Fig. 6. Scatter plot of response time for the secondary task while drawing a 3D shape vs. spatial ability with linear regression line fitted

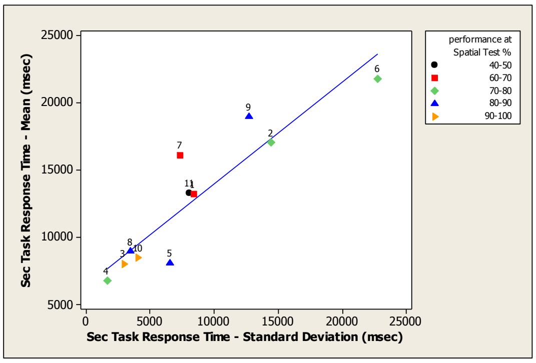


Fig. 7. Mean of the response time for the secondary task while drawing a 3D shape vs. standard deviation of the response time to the secondary task. The scatter points, labeled by student Id, are categorised by spatial ability test scores.

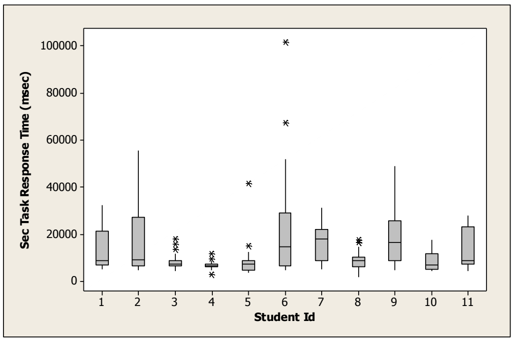


Fig. 8. Box plot of response time for the secondary task while drawing a 3D shape for each student.

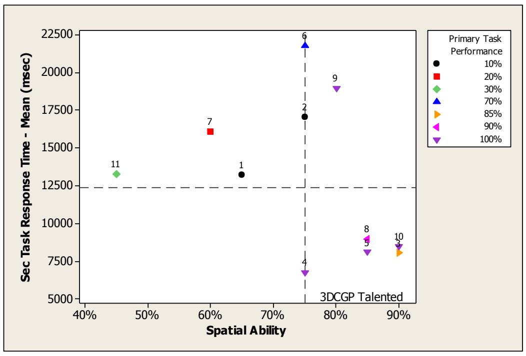


Fig. 9. Mean response time for the secondary task while drawing a 3D shape vs. spatial ability. The scatter points labeled by student Id, are categorised by their performance in the primary task

In Fig. 9, the lower right quadrant, labelled 3DCGP Talented, bounded by the sample mean response time and the mean spatial ability score includes students 3, 4, 5, 8 and 10. These students are identified as talented students in 3D computer graphics programming.

D. Individual Student'S Performance and Pattern of Behaviour

Fig. 9 shows that students 2, 4 and 6 achieved average scores in the spatial ability test. However, only student 4 is within the 3DCGP Talented quadrants. Although student 4 has an average score in the spatial ability test, s/he finished the 3D drawing. Fig. 7, 8 and 9 show that s/he had consistently very low mean response time. These results indicate that s/he was under very low cognitive load. From the perception survey, her/his motivation and efforts were above average and well above students 2 and 6 (see table II below). This is consistent with previous studies: the performance of students in carrying out novel tasks depends on their motivations [1], [27]-[28].

TABLE II: PERCEPTION SURVEY RESULTS IN PERCENTAGE.

Stud-ent Id	Intere sting	Enter-tain-in g	Eager -ness	Moti-vation	Tuto-rial Under stand-ing	Dual Task Diff-i culty	Prim-ary Task Diff-i culty	Secon dary Task Diff-i culty	Eff-or t
1	100	40	60	80	80	60	100	20	80
2	80	80	60	60	40	60	60	40	60
3	100	80	100	100	100	40	60	40	100
4	100	100	80	80	100	80	100	20	100
5	100	100	80	100	80	40	80	20	60
6	80	60	60	80	80	80	80	40	60
7	60	20	40	20	60	80	100	40	100
8	100	100	60	80	100	100	100	40	100
9	80	80	100	80	80	100	100	40	100
10	100	80	80	80	100	60	60	40	80
11	80	80	80	80	60	80	100	40	80
m	89	75	73	76	80	71	85	35	84

Fig. 9 shows that student 9 is not within the 3DCGP Talented quadrants. Although student 9 scored high in the spatial ability test and performed well in the primary task, s/he was under high cognitive load. From the perception survey, s/he found the dual task more difficult; s/he rated the task difficulty 100% (the mean was 71%). This indicates that in addition to spatial ability other cognitive qualities are needed to be a 3DCGP talented student.

Student 3 scored very well in the spatial ability test, yet did not finish her/his primary task. From the perception survey, s/he found the dual and primary tasks easy. We can deduct that her/his germane cognitive load was not optimised [4].

Our study suggests that talented students exhibit similar characteristics as experts; they perform well in their primary tasks and quickly and consistently respond to the secondary tasks [17].

E. Differences in Student Population

We used the results from section V - C and divided the students into two categories: 3DCGP talented students and others. Table III shows 3DCGP talented students have consistently lower response time to the secondary task; the statistical analysis show the two categories are from different populations (independent 2-sample t test, t(170)=7.55, p-value=0.000; F-Test, test statistics=11.0, p-value=0.000). The results of our study indicate that there are differences in population of students.

TABLE III: STATISTICAL ANALYSIS RESPONSE TIME TO SECONDARY TASK WHILE DRAWING A 3D SHAPE CATEGORISED BY 3DCGP TALENTED AND OTHERS

Student Category	Student Id	Mean	Standard deviation	Mean Standard Error
3DCGP Talented	3, 4, 5, 8, 10	8087	4087	327
Others	1, 2, 6, 7, 9, 11	16882	13554	1118

VI. CONCLUSIONS AND FURTHER RESEARCH

Our study has demonstrated that students, who are talented in 3D computer graphics programming, can be identified by conducting a spatial ability test, a performance and a cognitive load test using task and performance-based techniques and, perception surveys. The implication of our study is that talented students in computer graphics programming can be identified early in their studies; they can benefit by receiving advanced training. Likewise the less talented students in computer graphics programming can be given extra tutoring.

Our study shows that talented students exhibit similar pattern of behaviour as experts; they are able to attend equally to main task and other cognitive tasks [17].

While we have used the traditional methods to measure cognitive load, further research with sophisticated equipment is needed to accurately measure students' abstract thinking capabilities and performance. A study with a larger number of participants using biometric devices such as electroencephalography (EEG), electrocardiography (ECG) and galvanic skin resistance (GSR) is required to verify our findings.

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Dr Kavakli received a Research Professorship at the Virtual Immersion Research Group, Image Institute - Laboratory Le2i, Ecole Nationale Supérieure d'Artset Métiers ParisTech, Chalon Sur Saone, France to establish research collaboration in Virtual Reality in 2012. She has published over 122 research papers so far. Her research has been frequently profiled in media.