Educational Values of Virtual Reality: The Case of Spatial Ability

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Abstract—The use of Virtual Reality (VR) in schools and higher education is proliferating. Due to its interactive and animated features, it is regarded as a promising technology to increase students' spatial ability. Spatial ability is assumed to have a prominent role in science and engineering domains. However, research concerning individual differences such as spatial ability in the context of VR is still at its infancy. Moreover, empirical studies that focus on the features of VR to improve spatial ability are to date rare. Thus, this paper explores the possible educational values of VR in relation to spatial ability to call for more research concerning spatial ability in the context of VR based on studies in computer-based learning. It is believed that the incorporation of state-of-the-art VR technology for educational purposes should be justified by the enhanced benefits for the target learners.

Keywords—Ability-as-compensator, ability-as-enhancer, spatial ability, virtual reality.

I. INTRODUCTION

VIRTUAL Reality (VR) has been extensively used in applied fields such as medical and aviation, and it has also begun to edge it ways to schools and higher education institutions in the recent years [1] . Though immersive VR is of high cost, but a rapid fall in prices, a huge leap in the processing power of personal computer and the proliferation of World Wide Web have unleashed new opportunities for educators to use non or partial immersive VR that runs on desktop computer as an alternative or a supplement to the traditional way of teaching

One of the reasons that VR is being used in educational settings and for training purposes is because it provides interactive and complex three-dimensional (3-D) structures in a highly realism manner [2], [3]. It is assumed that with such a learning environment, learners could develop their spatial ability to create internal representations of complex 3-D structures that are pertinent particularly in the field of scientific and engineering study [4], [5]. However, though VR is a promising medium for teaching spatial characteristics of places, structures and situations due to its inherent spatial

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nature [5], [6], yet research concerning individual differences such as spatial ability in the context of VR is still at its infancy [6]. Interactive 3-D visualization and immersion are significant and unique features of VR. Yet, empirical studies that focus on the impact of such features on learning in the context of VR are to date rare. Inoue [2] has stated that "there have been few empirical studies on the use of VR for learning and it is necessary to investigate VR both in different scenario and for different applications for learning." Thus, this paper aims to explore the possible educational values of VR in relation to spatial ability to call for more research concerning spatial ability in the context of VR based on studies in computer-based learning. As mentioned by Mayer [7], the incorporation of state-of-the-art technology for educational purposes has to be justified and to understand how best the technological features can be incorporated to optimize learning outcomes.

II. WHAT IS VIRTUAL REALITY?

VR has been defined as a highly interactive, 3-D computer generated program in a multimedia environment that provides an immersion effect to the users [8]. With other computer-based learning, learners are often distanced from the environment and objects. In the contrary, VR allows learners to immerse in the learning environment to have a feeling of "being there" [3]. Thus, learners could expand their perceptions of the real world in a way that were previously impossible. Nevertheless, VR can be classified into two major types based on the level of interaction and immersive environment. In non-immersive VR, computer simulation is represented on a conventional personal computer and interaction with the virtual environment is done using keyboard, mouse, joystick, or touch screen [1], [9]. Conversely, immersive VR environments are presented on multiple, room-size screen or through a stereoscopic, head-mounted display unit [1], [9], [10]. Special hardware such as gloves, suit and high-end computer systems might be needed in immersive VR environment.

Furthermore, depending on the level of immersion, Allen *et al.* [11] have classified VR into three levels: partially or semi-immersive VR, which gives users a feeling of being at lease slightly immersive by a virtual environment [12], where users remain aware of their real world [11]; fully immersive, where users are completely isolated from the physical world outside, to fully immerse in the virtual environment [12] with special

peripheral devices. Head-mounted device, sensor gloves and sensors are attached to the user's body to detect, translate real movement into virtual activity; augmented reality or mixed reality, where users can have access to a combination of VR and real-world attributes by incorporating computer graphics objects into real world scene [8], [11]. In view of this, it can be concluded that state-of-the-art technology is being used in VR technology.

III. WHAT IS SPATIAL ABILITY?

Spatial ability refers to a group of cognitive functions and aptitudes that is crucial in solving problems that involve manipulating and processing visuo-spatial information [13], [14], [15], [16], because it is the mental process used to perceive, store, recall, create, edit and communicate spatial images [17]. Gardner [18] states that spatial ability is one of the seven major components in multiple intelligences. He defines spatial intelligence as the ability to think in pictures and images, to perceive, transform, and recreate different aspects of the visual-spatial world. Whilst some of the overt spatial behaviors, identified by Durlach et al. [19], include the behavior exhibited in exploring a space, searching for some items in a space, planning or following a route in a space, selecting and recognizing a landmarks in a space, constructing or interpreting maps of a space, imaging how a space and objects in it would appear from different viewpoints.

Though a number of spatial abilities has been identified, a consensus concerning various factors of spatial ability has not been reached [16], [20]. According to Micheal et al. [21], there are two major spatial factors: spatial orientation and spatial visualization. Ekstrom et al. [22] defines spatial orientation as a measure of the ability to remain unconfused by changes in the orientation of visual stimuli, and therefore it involves only a mental rotation of configuration. McGee [23] defines spatial visualization as a measure of the ability to mentally restructure or manipulate the components of the visual stimulus and involves recognizing, retaining, and recalling configurations when the figure or parts are moved. Depending on the relationships of specific types of spatial ability to specific types of concepts learned, spatial ability can be assessed by using the Mental Rotation Test (MRT) [24], the Perdue of Visualization of Rotations Test [13], Differential Aptitude Test: Space Relations [25], and Group Embedded Figures Test [26].

IV. SPATIAL ABILITY AND LEARNING OUTCOMES

Spatial ability is one of the cognitive factors that may influence student performance, and is assumed to have a prominent role in science and engineering domains. Studies have found high correlation between spatial ability and learners' achievement in various domains, such as chemistry [13], [27], engineering drawing [28], [29], medical surgery [30], biology [31], science and mathematics [32], [33]. Additionally, learners with different degree of spatial ability are likely to hold different attitude toward multimedia instruction with animated 3-D visualization [34]. Thus, it seems that spatial ability not only influences students' performance in scientific and engineering skills, but also affects students' perception of learning activities and affective level.

V. VIRTUAL REALITY AND SPATIAL ABILITY

Research findings show that appropriate computer technologies can be used to improve spatial ability. Due to its interactive and animated features, VR serves as a promising technology to increase students' spatial ability [5]. McMellan [35] states "VR is a superb vehicle for enhancing and possibly improving spatial ability, because its interactivity nature is aimed at extending and enhancing human cognitive abilities." However, the effects of spatial ability may be moderated by the features or characteristics of the VR simulation. VR features that might potentially enhance or diminish student performance include learner control [4], [36], [37], the complexity of image, the depth cue available and the type of interface used to manipulate and interact with the learning environment [37]. Moreover, there is a concern if learner characteristics might influence the use of such features. Norman [38] mentions that the positive impact of computer-based technology in education is depending on the individual ability of users. While some computer-based technologies may serve to benefit some learners, at the same time they may also serve to handicap others [38].

It is believed that spatial visualization ability is the primary cognitive factor that causes the differences in performance and has an impact on comprehension of 3D computer visualization [31], [38], [39]. Students with different spatial ability will benefit differently when learning with interactive 3-D animations or simulations [27], [31], [40], [41], which depends on their ability to extract relevant information and then reconstruct or incorporate the information into their existing mental model. Thus, it is inappropriate to think that the mere application of VR technology in education will benefit everyone equally in relation to spatial ability. Owing to this, more research is needed to qualify and quantify the impact of the use of VR for learning. Moreover, the development of VR program is demanding in terms of technical expertise, financial resources and time. Such an effort, that is, the incorporation of state-of-the-art interactive and visualization techniques for educational purposes should be justified by the enhanced benefits for the target learners [34], particularly in the context of VR which involves different level of immersion.

VI. RESEARCH ON ENHANCING SPATIAL ABILITY WITH 3-D VISUALIZATION

As mentioned earlier, spatial ability will influence learners' performance differently when learning with 3-D computer animations and simulations. Recent research has shown that lower spatial ability learners have difficulty in developing internal representations of 3-D structure [4], [42]. According

to the cognitive theory of multimedia learning, students with higher spatial ability construct dynamic mental models better while watching an animation compared to students with lower spatial ability [43]. Various models have been proposed to predict on the overall outcome when technology is combined with human performance [38]. In general, it is expected there is a multiplicative effect when user proficiency and system power are combined as shown in Fig. 1 [38]. The top line indicates the effect of an increase in the power of technology for individuals with high proficiency while the bottom line shows the effect of an increase in the power of technology for individuals with low proficiency. It is noted that the performance for individuals with high proficiency is amplified as indicated by the steep line. However, there is no significant improvement for individuals with low proficiency which is indicated by the nearly flat line.
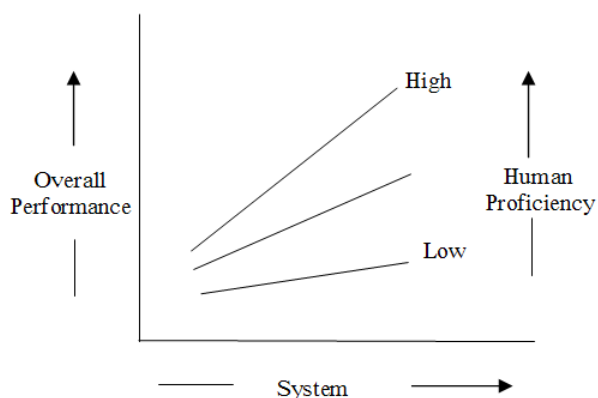

Fig. 1 Multiplicative effect of user proficiency and system power on overall human/computer performance [38]

Based on this model, individual differences such as spatial ability may widen the gap of achievement between high and low spatial ability learners, though there is positive impact for both groups of learners. To date, research that measures the degree of achievement with regard to VR-based learning is limited.

According to the ability-as-enhancer hypothesis, high spatial ability should benefit particularly as they have enough cognitive capability left for mental model construction [31], [41]. This hypothesis is supported by Huk's [31] research where only students with high spatial ability benefited from learning with interactive 3-D multimedia environment on understanding cell biology. Students with high spatial ability benefited from the 3D models because their total cognitive load remains comfortably within the limits of working memory [31], [41]. On the other hand, low spatial ability learners did not benefit with such a 3-D learning environment because of cognitive overload. However, generally, it is believed the graphical presentation format may in principle supports the ability-as-compensator hypothesis which proposes that low spatial ability learners should gain particular benefit as they have difficulty to mentally construct their own

visualization [31], [40], [41]. As mentioned by Durlach *et al.* [19], one of the strategies being used to solve information overload problems is to present the information spatially and to use virtual environment interfaces to help users to perceive, understand, and manipulate visuo-spatial information.

The findings of Chen [6] are in agreement with these two hypotheses. Chen conducts a study to investigate the effects of VR-based learning on learners with different spatial visualization abilities. The findings show that learners from both high and low spatial ability benefit from the VR-based learning environment where additional navigational aids are provided, that is, in the form of a tracer that provides real-time indicator of the virtual vehicle position on a map and directional arrow [6].

In the affective aspects, students with high spatial ability are found to have a more positive attitudes toward the inclusion of high quality and expensive 3D graphics and animations in the learning software, whereas students with low spatial ability prefer simple graphical representation [34]. This indicates that low spatial ability students might suffer from cognitive overload while learning with sophisticated 3D objects and animations [34], [44].

Most research investigates the correlations between spatial ability and achievements on domains relevant to spatial information and manipulations. However, there is very limited research that investigates the statistical effect of aptitude-by-treatment interaction (ATI) between instructions and spatial ability [45]. ATI research investigates the effect of individual differences on learning outcomes from different forms of treatment or instruction [46]. Two types of interaction are possible: Disordinal Interaction and Ordinal Interaction [47]. Fig. 2 shows Disordinal Interaction. Learners with low scores on the aptitude measure perform poorly on the instructional outcome measure under treatment A. However, learners with similar scores on the aptitude measure do better on the outcome measure under treatment B. Conversely, learners with high scores on the aptitude measure perform poorly in treatment B but better in treatment A. The regression slopes are different, and they are intersected [47]. Knowing such interaction will allow instructors to appropriately assign learners to different instructional methods.
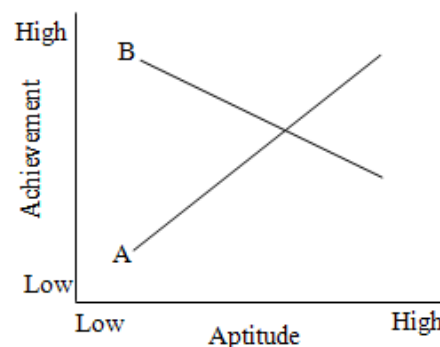

Fig. 2 Disordinal Interaction

On the other hand, in ordinal interaction, one treatment produces better results for all learners within the range of aptitude studied as shown in Fig. 3. The two slopes are the different and do not intersect [47], [48]. This means that all learners within the range of aptitude studied perform better under treatment B. The learners with high score on the aptitude measure perform better than the learners with low scores on the aptitude measure for both treatments.
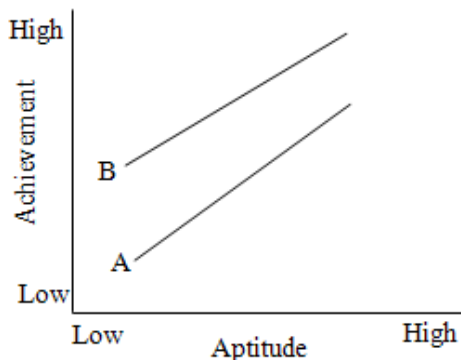

Fig. 3 Ordinal Interaction

In the context of VR, there are limited findings on the use of VR compared to other learning methods, and between different types of VR in educational settings with respect to spatial ability. Studies on the relation of spatial ability and instruction are not mature enough to direct real application. Two main questions include: (1) how to design a VR-based instruction for science/engineering learning that would benefit low spatial ability students, and at the same time does not pose disadvantages to high spatial ability students because expert learners may confront with extraneous load, i.e., cognitive load that is not relevant for learning, (2) how different types of VR influence students' performance, for instance, does non-immersive VR as good as immersive VR?

Empirical studies that focus on the learner control of the 3-D visualization on learning in relation to spatial ability are inconsistence. And studies that focus on other features such as the complexity of the images and the depth cue available of 3-D visualization are rare. Preliminary study of Jang *et al.* [4] shows that active learner control in rotating the 3-D structures enhances learner's internal representation of a complex structure compared to just viewing the structure in virtual space. Similarly, the study on the effect of multiple viewpoints of carpal bones by Garg, Norman & Speratoble [36] shows that learner control improves mental representations. This implies that the incorporation of direct interactivity in virtual learning can improve students' mental representations of 3-D structures, though some research has found that certain viewpoints of an object are more important than others [36], [42]. For instance, learners are found to extract more spatial information from standard view points such as front, back, top and side. This is consistent with the theories of mental representation of spatial objects, which advocate that objects are remembered in a canonical orientation and that unfamiliar orientation is recognized by rotating it back to key views [42].

One the other hand, research by Keehner & Khooshabeh [37] depicts that there is no difference in the performance between active and passive groups. In their research, active group is allowed to rotate the 3-D visualization freely during the drawing task while passive group has no control over the movements. Similar result is obtained with simple key-press system as the control interface as well as more intuitive and naturalistic interface where hand-held device is used [37]. Moreover, in the case of 2-D versus 3-D features in multimedia learning design, Wang, Chang & Li [45] find that there is no significant difference in spatial visualization skills between the two groups of students. Thus, more research is needed to support the incorporation of state-of-the-art features in VR program for improving spatial ability skills. Consequently, if evidence shows that objects are best visualized and the spatial information is assimilated and remembered most through slightly change or wiggle canonical or key viewpoints of 3-D objects, then a VR system with such feature may be all that is necessary [42]. This is because spatial ability is strongly related to the ability to perform mental rotations, thus information presented in oblique orientations may handicap poorer spatial ability learners as a heavy load is placed on them to rotate the figures [42].

VII. CONCLUSION

Researchers have suggested that spatial ability can be enhanced and improved through interactive 3-D visualization programs such as VR. This paper points out the use VR could widen the gap between high and low spatial learners and also calls for more ATI test to support the use of VR to improve the spatial ability of the learners. There have been few empirical studies that investigate the impact of the unique features of VR such as the depth cue and immersive characteristics on internal representations of a complex structure. The use of high quality VR program should be justified by the enhanced benefits of the target learners. This is crucial because the development of a VR program requires technical expertise, financial resources and time. If simple 3-D visualization program and learning control are sufficient to yield the targeted benefits or results, then a less sophisticated VR program may be all that is necessary.

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