TetRotation: Utilising Multimodal Analytics and Gestural Interaction to Nurture Mental Rotation Skills

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ABSTRACT
Embodied Interaction (EI) offers unique opportunities to uncover novel ways to achieve experiential learning whilst keeping students stimulated and engaged. Spatial abilities have been repeatedly demonstrated as a success predictor for educations and professions in Science, Technology, Engineering and Mathematics. However, many researchers argue that training and assessment of this pertinent reasoning skill is vastly under-represented in the school curriculum. This paper presents TetRotation, a PhD centred on how affordances coming from Multimodal Analytics can be coupled with EI to nurture Mental Rotation (MR) skills. The overarching objectives of the project are two fold. First, the TetRotation Interaction Design study will highlight best practices identified through the assessment of efficiency, level of engagement and learning gains achieved when using gesture based EI to solve MR tasks. Next, in the TetRotation Game study, these design practices will guide the implementation of an interactive serious game purposed to support the development of MR skills. This research relies on mixed method techniques, including data collections from users' actions, like motion sensing, EEG, gaze tracking, video-recordings, click streams, interviews and surveys.

Author Keywords
Embodied interaction; gesture; multimodal analytics; rotation; spatial cognition; spatial skills; serious game.

CCS Concepts
•Human-centered computing → Gestural input; •Applied computing → Interactive learning environments;

INTRODUCTION & MOTIVATION
Research in learning technology and interaction design is in constant pursuit of innovative ways to enhance students' learning experience [6, 11]. Advancements in sensing technologies (eg. Kinect, Leap Motion) enable smooth collection of large scale data sets from multimodal inputs [1, 2]. The richness offered by these Multimodal Analytics (MMA) affords researchers opportunities to deepen their understanding of the complex nature of multidimensional learning environments.

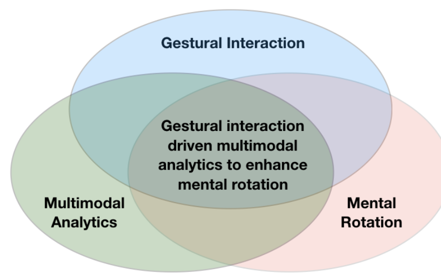

Figure 1. PhD research domain.

The intersect of EI and MMA boasts significant impact on helping researchers understand the effectiveness of embodied learning environments [1, 2, 19]. Notable studies have harnessed the power of MMA, such as fine-grained logs of hand movement and gaze data, to identify the significance of temporality in data modelling [2], as well as understand the correlation between student movement and learning gains [1]. These findings endorse embodied MMA as a persuasive instrument for advancing user-experience during learning (i.e., learner experience).

Clifton et al. [7] claim that Tangible, Embedded and Embodied Interaction Interfaces (TEI) systems are especially well suited to exploit the natural relationship between the body and spatial cognition in pursuit of developing spatial skills. Additionally, spatial abilities have been repeatedly demonstrated as a success predictor for educations and professions in Science, Technology, Engineering and Mathematics (STEM) [7, 12, 17]. However, many researchers argue that training and assessment of this pertinent reasoning skill is vastly under-represented in the school curriculum [7, 17]. From this, emanates a powerful motivator for pursuing the intersect of embodied interaction, MMA and spatial skills.

Mental Rotation (MR) is the spatial sub-domain that deals with visualizing the rotation of an object around an axis in 2 or 3 dimensional space [9]. Studies show that from a young age, males significantly outperform females in MR [4, 9, 15]. The contribution of this PhD centres on developing a collective

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understanding of users' MR skills through the lens of MMA and EI, see Figure 1. Specifically, the proposed research attempts to answer the following questions.

- RQ1: How can MMA be used to properly assess MR skills?
- RQ2: What are the most efficient and engaging gesture based EI to employ in order to understand/solve MR tasks?
- RQ3: How can the integration of MMA influence the creation of more efficient and engaging design practices for using gesture based EI to develop MR skills?

RELATED WORK

Here we highlight some noteworthy contributions that demonstrate the importance of EI and MMA into providing new ways to understand and actively participate in scientific learning, particularly concerning spatial reasoning. We also discuss limitations of each study to acknowledge areas where future research may take shape.

Zander et al. [18] demonstrated that touch gesture interactions, in conjunction with dynamic on-screen virtual objects, elevated learning gains for participants with prior acquired MR skills. Findings from Chiu et al. [5, 6] suggest that gesture based EI applied to MR and projection problems, promote deeper engagement in the cognitive process resulting in slower but more deliberate manipulations. It should be mentioned that each of these papers cited a small number of participants, which can cause "lack of explanatory power" [18]. As well, Zander et al. did not administer pre/post test of spatial skills, while Chiu et al. stated that their assessment was not robust enough due to an observed ceiling effect. Regardless, these studies support the claim that spatial abilities are malleable [7, 16], while also demonstrating that EI serves as an appropriate method for supporting and enhancing spatial skills.

Andrade et al. [2] used log data to illustrate the importance of temporality during gesture analysis of elicited bimanual hand movements. Their findings revealed that temporal analytics played a vital role in determining an appropriate data model for sequential gestures. In a similar study [1], fine-grained logs of hand movement and gaze data informed the correlation of student performed actions to learning gains. However, the lack of control group in these studies removed the possibility of determining if the student learning experience decreased in response to the induced cognitive load imposed by performing gestures and also by requiring that participants pay attention to dynamic on-screen population graphs. Furthermore, the elicited gestures were restricted to simple up/down hand movements, leaving much room for future analysis involving a more complex gesture set. Notwithstanding, in these inspiring works EI driven MMA amplified researchers understanding of the interplay between EI and learning, by enabling researchers to accurately infer students' theoretical proficiency.

There is limited empirical research combining EI with both MMA and spatial cognition. However, it is worth highlighting the works of Zhang et al. [19], which employed MMA to develop Bayesian Attentional Networks (BANs); a new structure to model the relationship between level of attention, EI input modality and feedback mechanism, while reasoning time sensitive visual-spatial navigation problems. Although an interesting method for determining user attention, BANs are not without limitation. They are computationally expensive and not yet capable of determining levels of attention in real time. Furthermore, researchers utilised a minimal number of input datastreams during observations; though they plan to extend their approach to include Electroencephalography (EEG) and other wearable technologies in future experiments.

Collectively, these contributions demonstrate that EI supported by MMA demonstrate potential for nurturing spatial skills more effectively than traditional methods, while also increasing learner enjoyment. As well, they comprise a starting space for further development in EI based interventions by suggesting an initial set of design principles.

To account for the limitation discussed in the aforementioned studies, the TetRotation Project (TetRotation) will employ a between group study with relatively high number of participants to ensure reliability and in various contexts/settings to ensure validity of data. In addition, we will use a diversified influx of MMA derived from: motion sensing technology, EEG, video-recordings, real time eye tracking, click streams, interviews and surveys. This will foster opportunities for a more holistic analysis of the students' multidimensional learning experience. Lastly, the assessed gesture set will represent greater range motion than simple up/down hand movement.

RESEARCH APPROACH & METHODS

TetRotation aims to address the aforementioned research questions. Design and development of TetRotation will be achieved by two case studies; TetRotation Interaction Design (TetRoID) and TetRotation Game (TetRoG), which investigate gesture based EI principles and their interplay with game design, respectively.

Literature Review & Pilot Study

In order to develop a comprehensive understanding of previous empirical and theoretical knowledge, we have conducted a Systematic Literature Review (SLR) in the domain of EI and spatial abilities. We identified a collection of successes, failures, and pertinent design guidelines from relevant works centred on gesture based systems and MR tasks [5, 6, 14]. In addition, we aim to conduct an exploratory pilot study to examine users' natural gestural tendencies when manipulating virtual objects around the x, y and z axes, as defined by the right hand rule. Findings from the pilot study and SLR will guide the initial design decisions for TetRoID. Specifically, we are motivated by the success of the rotation and translation gestures described by Radkowski et al. [14], and look to this gesture set, with possible adaptation from pilot study results as our starting point.

TetRotation: Interaction Design

TetRoID will use MMA to assess the learning gains, efficiency and engagement of the gestures proposed for reasoning about MR. Additionally, it serves as research into the interaction space that drives the input modalities utilised in TetRoG. High levels of engagement are associated with a wider breadth of knowledge, a deeper understanding of learned material, and

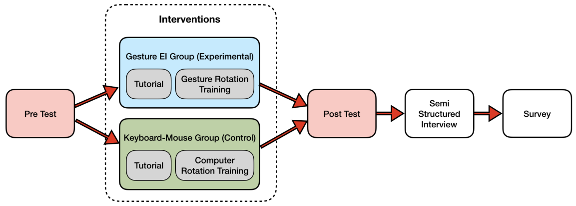

Figure 2. The 5 phases of the TetRotation Interaction Design Study.

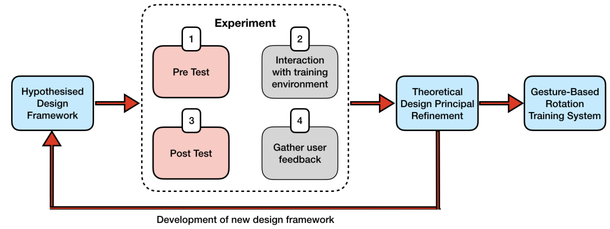

Figure 3. Life cycle of the TetRotation Game Study.

increased achievement [10]. Moreover, our desire to realise a MR training system with potential to integrate into a formal learning scenario motivates the need for efficiency.

TetRoID will adhere to a mixed methods between groups embedded design. Embedded design is implemented when a traditionally quantitative (or qualitative) research design integrates the collection and analysis of both qualitative and quantitative data types [8]. TetRoID is predominantly quantitative and will consist of five distinct phases; illustrated in Figure 2. The experimental group will be familiarised with a set of motion tracked hand gestures. Participants will be asked to solve a collection of exercises concerned with rotating virtual 2D and 3D objects that appear on screen. A control group will solve the same exercises using traditional keyboard and mouse interactions.

An influx of different multimodal data streams will be collected during the intervention phase of TetRoID. EEG and eye tracking technology will be utilised to capture brain wave patterns and gaze data, respectively. Motivated by the frequency of its use in pre-exsting studies [3, 6], Leap Motion has been selected for gesture tracking and collection of related data. Click stream data from the control group will be captured using custom written event tracking software. In addition, participants' MR skills will undergo pre and post assessment. A video/audio-recorded semi-structured interview will be administered, whereby participants will be asked to solve an object rotation task without the use of pen or paper. Participants will also complete an attitudinal survey.

The quantitative data will be used to evaluate the MR learning gains achieved by a participant, inform on the efficiency of the proposed gesture set, as well as provide insights into participant engagement. Collection of the qualitative data will supplement and refine the quantitative results through explanation of participants interaction preferences and levels of engagement. In addition, qualitative data will offer opportunities to observe participants while working through MR tasks, and solicit additional feedback to be used during extraction of hypothesised design principles informing best practices for gesture based EI and MR. Collectively, this data will address the concerns of RQ1 and RQ2, as well as provide insights into RQ3.

TetRotation: Game Design

TetRoG aims to develop an interactive serious video game purposed to support and enhance MR skills through the support of MMA and gesture based EI. Conceptually, it extends the classic video game Tetris, with an embodied twist. That is, a player controls virtual game pieces through motion tracked body movement. Unlike the original Tetris, TetRoG will offer interactive play in both 2 and 3 dimensions. Design principles resulting from the aforementioned TetRoID will provide a framework for the initial incarnation of TetRoG. Implementation will follow the design based research methodology, and will involve iterations whereby participants interact with the game based training environment, are assessed for learning gains and provide feedback to be considered during theoretical design principle refinement. We will investigate if the harmony between efficiency and engagement to optimise learning, persists through the game play experience. As well, we will solicit suggested changes to foster an improved user experience. Figure 3 illustrates this life cycle. Findings from this study will further address RQ3 by exploring the integration of MMA verified gestures into a serious game.

Data Analysis

This section discusses the data to be measured and analysed to address metrics raised in the proposed research questions.

Learning Gains: are defined as the improvements of a target ability in response to a stimulus over a given period of time [2]. In TetRotation, learning gains are the change in MR skills attained by a participant's engagement with TetRoG, as measured by the difference in performance between the pre and post assessment conducted in each study.

Efficiency: describes the ratio of useful work to actual work performed [13] and will be determined through comparison between a participant's input and the optimal input utilised when solving a problem. The number of gestures and number of clicks performed in relation to each other and the minimum number required to solve the given problem [6], as well as the speed of transitions between gestures and clicks [2], will be considered when analyzing mental and temporal efficiency. Data offered by EEG will determine if use of gestures reduces efficiency by imposing excess cognitive load.

Engagement: refers to the level of involvement demonstrated by a participant throughout their interactions. To determine this metric, eye tracking data, EEG, and survey response will be collectively analysed.

CONCLUSION

Further research efforts possess the potential to unlock valuable information capable of transcending how researchers and students interact with learning materials while developing and amplifying spatial abilities. In this paper, we present relevant literature that motivates our research questions. We also discuss the successes and limitations of notable related studies.

We present TetRotation; a project that builds upon elements of the aforementioned research by examining the capacity of MMA to nurture pedagogical opportunities involving spatial abilities by exploring new ways to incorporate gesture based EI into the training and evaluation of MR. The findings we gather during TetRotation will address the overarching research objectives to (1) incorporate MMA across heterogeneous data sets to identify efficient and engaging design principles that achieve optimal learning gains, and (2) deliver an interactive serious video game purposed to amplify MR skills through EI. This research broadens the domain for development of gesture driven technologies that require a solid understanding and execution of mental rotation. Some examples include interactive geometry applications (i.e., rotating a 2D shape in a 3D environment to explore the relationship between it's area and volume), as well as gesture controlled robotics as tools to perform in hazardous or unpredictable conditions (i.e., spacecraft mechanics).

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