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Exploring And Training Spatial Reasoning Via Eye Movements: Implications On Performance

Victoria A. Roach
The University of Western Ontario

Supervisor
Dr. Timothy D. Wilson
The University of Western Ontario

Graduate Program in Anatomy and Cell Biology
A thesis submitted in partial fulfillment of the requirements for the degree in Doctor of Philosophy

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Integrated Article

by

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The School of Graduate and Postdoctoral Studies
The University of Western Ontario
London, Ontario, Canada

Abstract

This dissertation sought to determine if eye movements could serve as an indicator of success in spatial reasoning, and if eye movements associated with successful completion could be applied to strategically improve spatial reasoning.

Using the line images of Shepard and Metzler, an electronic test of mental rotations ability (EMRT) was designed. Two versions of the test were created, allowing for both a timed (6 seconds per question) and untimed testing environment. Four experiments were designed and completed to relate mental rotation ability (MRA) scores from the EMRT, to patterns in chrononumeric and visual salience data. In each experiment, participants completed the EMRT under a different protocol. These protocols included an untimed EMRT, a timed EMRT, a within-participant crossover study where participants completed both the timed, and untimed EMRT in series, and a training crossover study where low MRA participants completed the timed EMRT in both a guided and unguided environment.

In the untimed experiment, individuals of high and low MRA were asked to complete the EMRT while their eye movements were observed. As no time limit was imposed, the results allowed for observations based on MRA alone, and served to demonstrate and how individuals of different skill level differ in terms of eye movement.

In the following experiment, the addition of a time limit to the EMRT revealed how individuals of high and low MRA perform when under a time restriction. The results of the Timed experiment confirmed differences between the high and low MRA group in terms of eye movements, and attention to salient regions of test images.

In the third experiment, the addition of a time limit was further explored through a crossover design. By adding a time limit to an MRT, the ability of individuals to solve spatial problems is impaired, and is manifest in eye movements. Data derived from the Crossover Experiment suggested that salience-based metrics might serve to distinguish between groups of MRA, and that time restrictions may influence both participant accuracy, and identification of visually salient elements.

The results from the first three experiments were then applied in the Guidance Experiment to confirm the role that visual salience plays in the context of spatial problem solving. By mapping the apprehension patterns of successful high MRA individuals onto the EMRT, low MRA individuals could be guided to salient areas on the timed EMRT. The results revealed that the application of visual guidance is an effective mechanism for MRA training.

This research attends to a previously unaddressed niche in eye-movement and spatial ability training literature. As a result, it may serve as a foundation to cultivate methods of honing and improving spatial skills in the general population.

Keywords

Spatial Ability, Mental Rotations Ability, Eye Tracking, Eye Movement Modeled Examples, Spatial Training, Visual Guidance, Working Memory and STEM.

Co-Authorship Statement

The written material in this thesis is the original work of the author. Victoria Roach participated in all aspects of the work contained herein: conception of the hypotheses, conduction of the experiments, and authorship of the manuscripts. The role of the co-authors are detailed below by chapter.

Chapter 3: Eye movements during untimed tests of mental rotation ability.

The manuscript is published in the journal *Anatomical Sciences Education*. All authors on the manuscript shared in the conception of this research study. V. Roach and J. Kryklywy, using digital images created by Michael Peters, with permission, developed the Electronic Mental Rotations Test (EMRT). The data for this study was collected, analyzed and interpreted by V. Roach and G. Fraser. V. Roach carried out the composition of the manuscript with inputs from Drs. Wilson and Mitchell.

Chapter 4: Eye movements during timed tests of mental rotation ability.

Conception of this research study was shared by V. Roach, T. Wilson, and D. Mitchell. V. Roach and J. Kryklywy carried out the modifications to the Electronic Mental Rotations Test. The data for this study was collected, analyzed and interpreted by V. Roach and G. Fraser. V. Roach carried out preparation of the manuscript with inputs from Drs. Wilson and Mitchell. The manuscript is under review at the journal Cognitive Science.

Chapter 5: Comparison of eye movements during tests of mental rotation in timed and untimed conditions.

Conception of this research study was shared by V. Roach, T. Wilson, and D. Mitchell. V. Roach and J. Kryklywy completed the modifications to the Electronic Mental Rotations Test. The data for this study was collected, analyzed and interpreted by V. Roach and G. Fraser. V. Roach carried out preparation of the manuscript with inputs from Drs. Wilson and Mitchell. The manuscript is under review at the journal Anatomical Sciences Education.

Chapter 6: The effects of visual guidance on success in tests of mental rotation.

Conception of this research study was shared by V. Roach, T. Wilson, and D. Mitchell. V. Roach, J. Kryklywy and G. Fraser completed the modifications to the Electronic Mental Rotations Test. The data for this study was collected, analyzed and interpreted by V. Roach and G. Fraser. V. Roach carried out preparation of the manuscript with inputs from Drs. Wilson and Mitchell. The manuscript will be submitted to the journal Cognitive Science.

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Finally, and most importantly, I wish to thank my parents, John and Dora Roach, for their years of support, encouragement and love. Even through the challenging moments in this degree, their faith in me has never faltered. You raised me with the mentality to “reach for the stars”, and when it seemed that I wasn’t quite tall enough to reach, you gave me the tools to build a ladder long enough, and the strength and perseverance to climb all the way there.

To you I dedicate this thesis.

Table of Contents

List of Acronyms And Abbreviations

1. Mental Rotation Ability (MRA)
2. Mental Rotation Test (MRT)
3. Vandenberg and Kuse Mental Rotation Test (VKMRT)
4. Electronic Mental Rotation Test (EMRT)
5. High Mental Rotation Ability (HMRA)
6. Low Mental Rotation Ability (LMRA)
7. Eye Movement Modeled Examples (EMME)
8. Region of Interest (ROI)
9. Analysis of Variance (ANOVA)
10. Standard Deviation (SD)
11. Male (M) /Female (F)
12. Confidence Interval (CI)
13. Science, Technology, Engineering and Mathematics (STEM)
14. Science, Technology, Engineering, Mathematics and Medicine (STEMM).
15. Electro-oculography (EOG)
16. Photo-oculography (POG)
17. Video-oculography (VOG)
18. Congenital adrenal hypoplasia (CAH)
19. Milliseconds (ms)
20. Hertz (Hz)
21. Three-dimensional (3D)
22. Posterior Parietal Cortex (PPC)
23. Dorsolateral Prefrontal Cortex (DLPFC)
24. Lateral Geniculate Nucleus (LGN)

List Of Tables

List of Figures

Chapter 1

General Introduction

1.1 Spatial Ability

Loosely defined as a cluster of cognitive skills that allow an individual to navigate their surroundings, spatial ability has been closely studied by cognitive psychologists for decades[1–5]. Unfortunately, despite the years of dedicated research, a unified, firm definition of spatial ability has yet to be reached[6]. The lack of a firm definition is likely the result of the multi-faceted nature of spatial ability. It is accepted that spatial ability is not a singular unitary construct, but more accurately, an assortment of sub-skills which each lend to an individual's ability to interact with their 3D environment in different ways[2].

Research in spatial cognition and spatial ability has served to elaborate on each of the sub-skills of spatial ability. At present, several schemas exist to categorize the sub-skills of spatial ability, including those of Carroll (1993), Lohman (1988), and Linn and Petersen (1985). In the sub-division by Linn and Peterson, three sub-skills of spatial ability were identified as discrete constructs: spatial perception, spatial visualization, and mental rotation[2].

1.2 Mental Rotation Ability

Of particular interest to this research is mental rotation ability. Mental rotation ability incorporates qualities of both spatial perception and visualization into a well-defined concept. Mental rotation can be generally described as an individual's intrinsic ability to maintain a mental image of a two-dimensional or three-dimensional object turning in space[7].

Mental rotations ability has dominated educational psychology literature due to numerous correlations with success in technical skill acquisition[8–10], knowledge acquisition in anatomy[11–13], and performance in the STEM (Science, Technology, Engineering and

Mathematics) disciplines[14–18] . The correlates to academic success have resulted in mental rotations ability catching the attention of the American National Science Board, and led to the publication of "Preparing the next generation of STEM innovators: Identifying and developing our nation's human capital" in which spatial ability features heavily[19]. In the publication, the authors argue that individuals possessing high spatial ability are an "untapped, pool of talent that are critical to our highly technological society" (p20). This report alludes to individuals possessing high spatial ability, and raises the question of training this cognitive skill[19].

1.3 Training Spatial (and Mental Rotation) Ability

In a recent meta-analysis by Uttal *et al*. the concept of training spatial ability is explored through a review of current published and unpublished studies attempting to train or elevate individual spatial ability scores[18]. Uttal *et al*. was able to discern three different categories of training efforts: those employing video games as a method of training [20], those employing an instructional course[21] and those employing practice, or repeated exposure to spatial tasks as a method of training[22,23]. The findings of this meta-analysis concluded that spatial training, regardless of technique, yielded an average improvement in spatial scores by almost one-half of a standard deviation on related, untrained spatial tasks[18]. This suggests that spatial skills are in fact, moderately malleable, and further research is required to discern the most advantageous method of spatial ability training.

In effort to decipher the most advantageous mechanisms to train spatial ability, research has sought to decipher the cognitive underpinnings that govern mental rotations ability. One theory, proposed by Just and Carpenter, suggests that mental rotations ability may manifest in the finite and measureable movements of the eyes. The theory suggests that as an individual attends to spatial task stimuli, their attention is manifest in each fixation of the eye; defined as the act of maintaining visual gaze on a single location for a duration exceeding 200 milliseconds[24]. Just and Carpenter further suggest that each fixation of the eye is intimately involved with the ability to visually encode spatially distributed information[25,26]. With this in mind, patterns in eye movements may represent the initial cognitive stages (i.e., search, transformation and comparison, and confirmation) that occur as visual information is being processed mentally[26] at the information gathering stage of learning[27].

In a foundational study by Just and Carpenter (1985) employing eye-tracking technology and two computer simulation models, significant differences were observed in the visual approaches taken by individuals of high and low MRA during the performance of the Cube Comparison Test[28]. The significant result obtained by Just and Carpenter gives credence to the theory of a link between cognitive processing and eye movement. The relationship thus provides a sound rationale for the exploration of an eye movement-based, or "gaze- directed", protocol to formulate and guide the training of mental rotations ability.

1.4 Gaze-Directed Training

Gaze-directed training has been employed with varied success in variety of domains; the majority of which pertain to the psychomotor relationship of hand-eye coordination during the completion of physical tasks. Studies within the field of kinesiology have long employed successful gaze-directed training approaches to inform athletes where and when to look for the best results on a variety of athletic maneuvers[29–33]. The studies of gaze and attention in sport subsequently informed a series of studies in surgical education that applied the gaze-directed approach to training novice laparoscopists. In the studies of several research groups, eye patterns of novice and expert laparoscopists were collected during the performance of standardized technical laparoscopic tasks[34–36]. These studies exploited differences in the patterns of eye movements between the novices and experts, and elucidated the successful approach employed by the experts[34,35]. The findings of these two studies yielded a gaze-directed approach employing the eye movements of expert laparoscopists to train novices on specific laparoscopic techniques. When evaluated, the gaze-directed approach based proved to be an effective protocol to guide the attention of novices, and improve their performance on a specific laparoscopic task[37].

The success of these expert-guided, eye-movement based training protocols provided insight into the potential application of such a strategy for the training of mental rotations ability. If the eye movements of expert spatial problem solvers can be elucidated, then they too may prove useful as a mechanism to train mental rotations ability. As such, this thesis aims to identify patterns existing in the eye movements of high and low mental rotation ability individuals, as they complete the Electronic Mental Rotation Test (EMRT). The EMRT is based on the line drawings of Shepard and Metzler[38,39]. These patterns will provide a foundation for the development of a gaze-directed mental rotation training tool to enhance the performance of low spatial individuals on subsequent spatial tests.

1.5 Overview of Dissertation

The purpose of this dissertation is to explore the relationship between eye movements and spatial reasoning in groups of individuals with varying spatial ability, and the implications of this relationship for training mental rotation. Spatial ability, the ability to comprehend three-dimensional structures, is key in how individuals perceive and interact with their surroundings. One subset of spatial ability, mental rotations ability, is linked to success in skill acquisition, and academic success in the STEM disciplines, particularly anatomy, and may serve as a consideration when designing methods for instruction. By using eye tracking, we investigated how eye movements can be recorded and related to underlying cognitive processes associated with spatial test completion. The value of this approach is that it allows us to characterize visual apprehension strategies used by adept individuals during spatial reasoning with and without a time limit, and employ successful visual apprehension strategies to improve mental rotation performance in individuals who typically struggle. In addition to enabling us to improve the performance of low ability individuals, this approach also allows us to begin to assess more effectively how visual cueing strategies can be used to guide instruction in spatially complex disciplines, including anatomy, aeronautics, surgery and STEM.

The remainder this dissertation is divided into 6 chapters:

Chapter 2 is the literature review. I begin with an introduction to the eye and the visual system, including the relevant anatomy and an introduction to eye tracking technologies and applications. I follow with a historical account of research in spatial ability, and describe the relationship between spatial ability and its sub-factors, including mental rotation ability. Next, I discuss the neural underpinnings of both the visual system, and spatial ability, and briefly refer to working memory as it relates to spatial problem solving. Finally, I discuss the effect of time limitations on accuracy in spatial problem solving, and refer to literature that summarizes the efforts made to train spatial problem solving, including those employing eye movement modeled examples to direct the visual attention of trainees.

Chapters 3 – 6 are the four experiments in this dissertation. "Chapter 3: The Untimed Experiment" examines whether there are observable differences in eye movement patterns between High and Low MRA individuals on an untimed version of the Electronic Mental Rotations Test. "Chapter 4: The Timed Experiment" examines if there are observable differences in eye movement patterns between High and Low MRA individuals on a timed version of the Electronic Mental Rotations Test. "Chapter 5: The Crossover Experiment" examines the within-group ramifcations of the application of time limits in terms of eye movement patterns, and accuracy on the Electronic Mental Rotations Test. Finally, Chapter 6: The Guidance Experiment" examines the effect of using expert-based eye-movement-modeled-exemplars (EMME) as cues to guide the visual attention of Low MRA individuals during the Electronic Mental Rotations Test.

Chapter 7 is the general discussion and conclusion. Here, I propose explanations for the patterns of performance seen in the four experiments and their implications for anatomy education. I end with recommendations for future experimentation.

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Chapter 2

Literature Review

2.1 The Eyes, Sight, and Tracking their Movements

2.1.1 The Anatomy of the Visual System

The human visual system consists of a series of visual pathways that serve to connect the photosensitive cells of the retina to the visual processing areas of the brain. The pathways that connect multiple brain areas associated with common visual functions are termed "streams". These structures, and their roles in the processing of visual stimuli are discussed herein.

2.1.2 The Eye and Extra-Ocular Muscles

When considering the anatomy and physiology of sight, it is often useful to consider the mechanics of a digital camera. In the human eye, light entering the eye is focused first by the cornea; which acts much like the lens of a camera. The light passing through the cornea then passes through the iris of the eye; which serves much like the aperture blades of the camera. Both structures serve to control the amount of light that reaches the photosensitive posterior; in the case of the camera, the aperture blades move to increase or decrease the aperture, while in the case of the eye, the pupil will dilate or contract accordingly. Posterior to the iris, the eye's crystalline lens is found, and serves to further focus the beam of light entering the eye through a process called accommodation. The light that leaves the lens then travels posteriorly through vitreous humour to reach the photosensitive posterior of the eye, the retina. The retina acts much in the same way that an electronic light sensor does, as it serves to convert light energy into electronic signals, which are transmitted to the visual cortex via the optic nerve (Figure 1)[1].

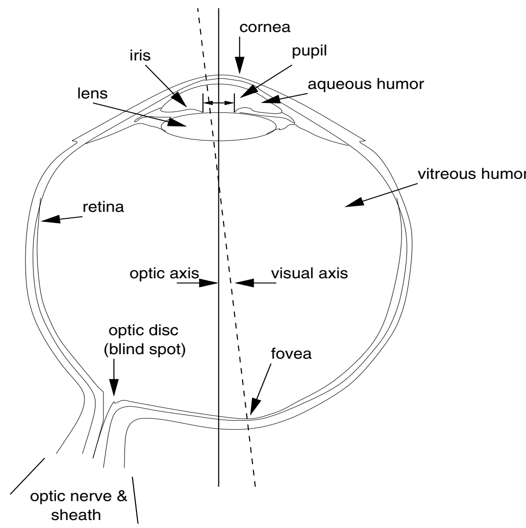

Figure 1: The basic anatomy of the structures of the human eye, adapted from Duchowski (2007) with permission © 2007 Springer Science & Business Media

Six extra-ocular muscles serve to move the eyes about the orbit, and bring objects of interest into view through coordinated contractions and relaxations. Side to side (lateral) movement is achieved through actions of the medial and lateral recti, while up-and-down movements are largely achieved through the action of the superior and inferior recti. Finally diagonal movements of the eyes are achieved through the efforts of the superior and inferior obliques[2]. Three cranial motor nuclei provide efferent control of the extra-ocular muscles: the abducens nucleus, the trochlear nucleus and the oculomotor complex. The abducens nucleus transmits its axons along the abducens nerve to provide innervation to the lateral rectus. The trochlear nucleus sends its axons along the trochlear nerve, which decussates to control the superior oblique of the contralateral eye. Finally, the oculomotor complex houses nuclei that send their axons along the oculomotor nerve, to control of the medial rectus, inferior oblique, inferior rectus and superior rectus (Figure 2)[1].

Left (view from above): 1, superior rectus; 2, levator palbebrae superioris; 3, lateral rectus; 4, medial rectus; 5, superior oblique; 6, reflected tendon of the superior oblique; 7, annulus of Zinn. *Right (lateral view):* 8, inferior rectus; 9, inferior oblique.

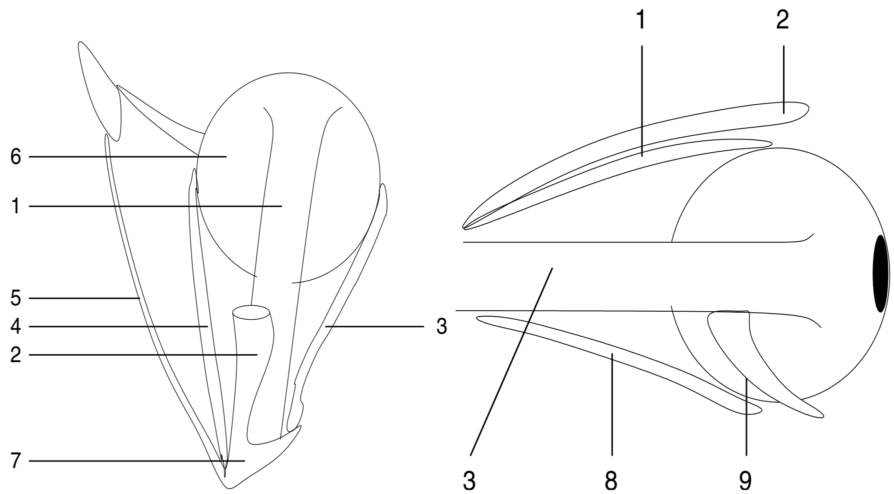

Figure 2: Extrinsic (Extra-ocular) muscles of the eye, adapted from Davson (1980) with permission © 1980 Academic Press.

2.1.3 The Retina

As mentioned previously, at the rear of the eye there is a multi-layered structure known as the retina. The retina houses many light-sensitive cells (photoreceptors) that serve to transform light energy into electrical impulses. These electrical impulses are conveyed as neural signals to the deeper centers of the brain responsible for visual information processing. There are two varieties of photoreceptors: rods that are responsible for detecting achromatic light and provide scotopic vision, and cones that are sensitive to brighter chromatic light and provide photopic vision. Each retina holds approximately 120 million rods, and 7 million cones

The photoreceptors are arranged in parallel to comprise one layer of the retina. One may be surprised to observe that the photoreceptive layer actually resides in the deepest, innermost layer of the retina, farthest away from the incoming light. The three cellular layers of the retina are separated by plexiform or synaptic layers, which provide connections between the cellular layers. These synaptic layers are responsible for transmitting the signals created in the photoreceptors across the cellular layers and into the ganglion cells in the outermost layer of the retina. The ganglion cells in the outermost layer of the retina receive signals from the photoreceptors, and transmit those signals along their unmyelinated axons. The unmyelinated axons then converge at the structure called the optic disk, and unite to form the myelinated optic nerve. The optic nerve is myelinated to provide insulation that accelerates impulse conduction and facilitate signal transmission. However, as myelin would block the light passing to the photoreceptors, the axons of the ganglia preceding the optic disk are not myelinated (Figure 3)[1].

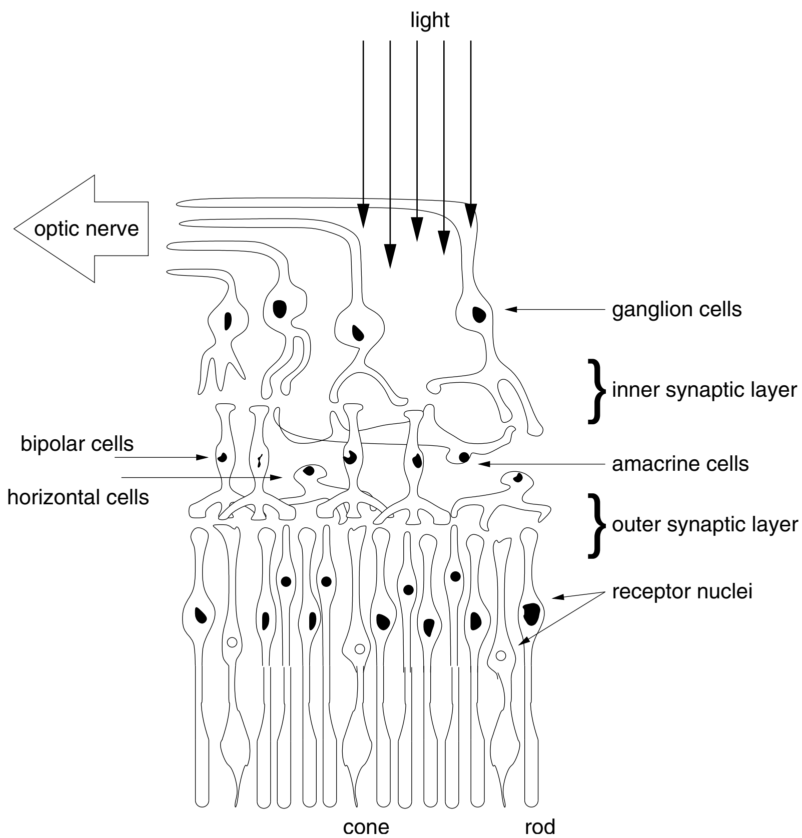

Figure 3: The basic composition of the layers of the human retina, adapted from Duchowski (2007) with permission © 2007 Springer Science & Business Media.

2.1.4 Movements of the Eyes

In an effort to position the fovea in line with a stimulus of interest, the extra-ocular muscles work in coordination to execute movements. The most common of these movements is called a saccade. Saccades are the rapid, ballistic movements of the eyes that are used to position the fovea in line with a stimulus of interest. Saccades can range in amplitude; being very short while an individual is reading, to long and sweeping while gazing around a vast space. When the eyes are open, saccades occur reflexively, but can be commanded voluntarily. Saccadic eye movement begins within 200 milliseconds of stimuli detection in the periphery of the visual field. In the 200 milliseconds prior to saccade, the distance between the current foveal position and the position of the peripheral target stimuli is calculated. This distance is termed the "motor error". The motor error is then translated to a motor command that signals the extra-ocular muscles to move the eyes to the calculated position. It should be noted that saccades are considered ballistic due to the fact that once a saccade generation signal is fired, any changes to the target position will cause a misalignment in the position of the fovea with respect to the target.That is, if the target moves during the 200 millisecond latency prior to saccade, the saccade will miss the target, and a second saccade will be required to reach the revised target position[3].

The period between two saccades, when the fovea is held relatively still and in line with a target of interest, is termed a fixation. Fixations are the maintenance of gaze on a single position in the visual field. This is the time period in which all visual input occurs[1]. In order to achieve fixation on a stationary stimuli, the eye conducts three types of micro-movements: microsaccades, ocular drift, and microtremor. Consequently, the human eyes are never completely stationary.

Microsaccades, first discovered by Robert Darwin, are small, "jerk-like" involuntary movements of the eye, which are much like voluntary saccades[4]. Microsaccades occur during prolonged visual fixations (lasting several seconds, and typically, range from in amplitude from 0.03 to 2 degrees of visual angle.

Ocular drifts are slow movements away from a point being fixated, and occur simultaneously with tremor between the epochs of microsaccades[5]. During drift, the image of the object of interest is moved across multiple photoreceptors[6], essentially maintaining accurate visual fixation in the absence of microsaccades.

Tremor, often referred to as "physiological nystagmus", is a wave-like motion of the eyes[7]. The smallest movement of the eyes, tremor amplitudes are approximately the same size as the diameter of a retinal cone[6,8,9]. While difficult to record with accuracy, it is unclear as to tremor's role in the maintenance of vision. Research suggests that the high frequency of tremor maintains the activity of the visual system, and thus facilitates visual perception[5].

2.1.5 Eye Tracking Technology

The primary requirement of analyzing eye movements is the identification of fixations and saccades. It is assumed that these movements provide evidence of voluntary, overt visual attention. Naturally, fixations relate to the desire to maintain one's gaze on a region of interest, while saccades are considered manifestations of the desire to change the focus of attention.

There exist two types of eye tracking systems: the sort that track the position of the eye in the head, and the sort that tracks the position of the eye in space[10]. With this considered, there are four types of eye movement measurement methods:

- Electro-OculoGraphy (EOG)
- Scleral Contact Lens/Search Coil
- Photo-OculoGraphy (POG) / Video-OculoGraphy (VOG)
- Video-Based Combined Pupil and Corneal Reflection

Electro-OculoGraphy

Electro-OculoGraphy is characterised as DC signal recordings of the potential difference across the skin around the ocular cavity. The DC signal is monitored using electrodes attached to the skin, and measures the position of an individual's eye relative to their head.

Scleral Lens/Search Coil

The scleral lens method of tracking eye movement is one of the most precise methods available, but is also the most intrusive. It requires that a mechanical or optical reference object be mounted to a lens that is worn on the eye. Typically, a wire coil is attached to the lens, which is then measured moving through an electromagnetic field. Despite the accuracy associated with this technique, it is no longer commonly used, due to participant discomfort, and because it does not permit "point of regard" measurements that reflect the position of the eye in space relative to a given stimulus.

Photo-OculoGraphy (POG) / Video-OculoGraphy (VOG)

Much less invasive than the scleral lens method, both POG and VOG record eye movements by optically recording the participants' eyes, either photographically, or through video capture. These methods, while non-invasive, are time consuming for scientists, who must manually step through each frame of film to inspect and measure each eye movement that is recorded, and do not provide point of regard measures.

Video-Based Combined Pupil and Corneal Reflection

In order to calculate the position of the eye in space there are two approaches that may be employed: the head must be fixed to ensure that both the head and the stimulus of interest are aligned, or multiple ocular features must be measured in order to dissociate the movement of the head from the movement associated with rotation of the eye. The latter of which is achieved through video-based combined pupil and corneal reflection methodologies, wherein the corneal reflection of infrared light is measured relative to the location of the center of the pupil. At present, the majority of eye tracking devices are video-based, and employ both corneal and pupil reflection. Typically, these tools are low-cost, non-invasive, and able to compute the point of fixation in real-time[1]. One drawback, however, is the requirement for calibration. Prior to use, video-based systems must be calibrated to align the relative motions of the eye to the absolute coordinates of the screen or monitor presenting the target stimuli.

2.1.6 Applications of Eye Tracking

It is accepted that eye movements provide a unique, and rich perspective into an individual's thoughts, and intentions while interpreting visual stimuli, and as a result, eye tracking has played a prominent role in many applications across many disciplines. The use of eye tracking has featured prominently in the analysis of clinical conditions such as schizophrenia[11,12], aphasia[13], Alzheimer-type dementia[14] and Parkinson's disease[15]. Further, eye tracking has shown usefulness in the detection of drowsiness[16], in applications of cognitive and behavioral therapy[17], in analysis of visual search[18], as a mechanism to facilitate "eye typing" in the physically disabled[19] and to guide marketing and advertising[20]. Moreover, eye-tracking applications have served as a mechanism to illustrate different cognitive processes in individuals[21]; including processing associated with reading[22], and processing associated with Human-Computer-Interactions[23].

Further, eye tracking has served a significant role clinically in fear-recognition studies. Research has revealed that individuals with amygdala damage display a marked lack of spontaneous fixation on the eye regions of individuals when free-viewing images of faces[24]. The neglect for the eye regions likely contributes to their inability to perceive fear in other individuals, as the eyes are the most important feature for identifying this emotion[24]. Moreover, eye tracking has served to provide a notable mechanism to alleviate this impairment through cueing. When individuals were instructed to attend specifically to the eyes, normal fear-recognition was restored[24]. These findings motivated further work by Dadds et al., who applied the same method of directed attention in children with impaired fear-recognition resulting from psychopathic traits; and concluded similar success in employing a gaze-directed approach to augmenting cognitive processes[25].

2.1.7 Summary

Through its role as the primary visual sensory organ, the eye allows visual information to enter the visual pathway for interpretation in cortical areas. In so doing, the eye and its movements serve as an indication of visual attention, and acts as a window to the underlying cognitive processes associated with stimuli interpretation. Literature has shown that by tracking the movements of the eyes, dichotomies in the way that different groups process information can be revealed based on their patterns of apprehension. These dichotomies, when recorded and displayed, may serve as diagnostic measures in disease states, and as visual guidance mechanisms to direct attention in clinical settings and learning paradigms.

2.2 Spatial Ability

2.2.1 A Brief History

While credit for the initiation of research in spatial ability is given to Galton for his pioneering work on mental imagery[26], the first published identification of spatial ability did not occur until 1921, in a paper by Thorndike. Thorndike's paper serves as the true beginning of spatial ability research, as his work revealed a three-fold model of intelligence, which broke away from the singular model of intelligence posited by Spearman[27]. In the paper by Thorndike, he suggested that intelligence was composed of three varieties of intellect; namely "abstract", "social" and "mechanical"; where abstract intelligence referred to the ability to understand and manage ideas, social intelligence referred to the ability to understand and manage people, and mechanical referred to the ability to understand and manage concrete objects[28]. He further defined mechanical intelligence as the ability to visualize relationships among objects, and understand how the physical world worked. Thorndike also expressed that further research was merited to explore appropriate methods of evaluation of mechanical intelligence, as the majority of intelligence tests evaluated only to abstract intelligence[28]. This call to action would pave the way for the many years of spatial ability research to follow.

In response to this call, research was conducted by Kelley[29] and El Koussy[30], who like Thorndike, each conducted psychometric studies to refute the idea of a singular, verbal-based concept of intelligence[31]. The work by El Koussy explored spatial intelligence and yielded evidence of "K"; a factor which he defined as "the ability to obtain and utilize visual spatial imagery"[30]. Likewise, Kelley's work sought to further explore the notion that intelligence was plural; and further hypothesized that spatial ability itself was, like intelligence, a modular construct encompassing its own distinct factors[29]. These findings and hypotheses led the way for a period of time between 1940 to 1960, wherein research in the area was dedicated primarily to ascertaining what factors comprised spatial ability.

2.2.2 Factors Comprising Spatial Ability

Like Kelley and El Koussy, Thurstone sought to explore spatial ability as a construct distinct from general intelligence. Thurstone was of the opinion that intelligence was composed of multiple primary mental abilities[32]. Through his Multiple Factors Theory, he was the first to propose and demonstrate seven discrete mental abilities that contributed to intelligence; associative memory, number facility, perceptual speed, reasoning, verbal comprehension, word fluency and most notably, spatial visualization[32], which he described as the "ability to operate mentally on spatial or visual images". Thurstone's research continued along the trajectory set by Kelley, and sought to explore the plurality of spatial ability itself; identifying three primary spatial ability factors, S1, S2 and S3[33]. These three abstract factor names were later replaced by Smith with the more descriptive titles of "Mental Rotation", "Spatial Visualization", and "Spatial Perception"[34]. Smith further elaborated on each of these factors, designating Mental Rotations as the ability to recognize an object if it were moved to different orientations or angles; Spatial Visualization as the ability to recognize the parts of an object if they are moving or displaced from their original position, and Spatial Perception as the ability to use one's body orientation to relate to questions regarding spatial orientation[34].

Research continued in effort to further describe, or re-describe the factors comprising spatial ability, and due to the application of different factor analysis methods, and evaluation through different types of spatial ability tests, many contradictory names and definitions of factors were suggested[35], along with variable schemas in which many factors were proposed[36]. At present, several schemas exist to categorize the sub-skills of spatial ability, including those of Carroll, Lohman, and Linn and Petersen. The sub-division by Linn and Peterson, which most closely resembles that of Thurstone, is composed of three sub-skills of spatial ability, spatial perception, spatial visualization, and mental rotation[37].

Spatial perception, as described by Linn and Petersen, is the ability or aptitude for determining the spatial relationships that pertain to the orientation of one's own body, despite distracting information[37]. Simply stated, this skill relates to the coding of spatial position of one object, in relation to another object with respect to gravity[38].

Spatial visualization, perhaps the least specific of the three sub-skills, is roughly defined as the ability to complete complicated, multi-step manipulations of spatially presented information[37]. Essentially, this sub-skill requires that an individual retain an image in their working memory, and spatially transform it mentally without assistance.

The third sub-skill of spatial ability, mental rotation, incorporates qualities of both spatial perception and visualization into a well-defined concept. Mental rotation is a dynamic process characterized by the mental rotation of a visible stimulus to align it with another comparison stimulus; followed by a visual assessment to discern if the pair of stimuli are identical[38]. The mental rotation ability is measured via standardized tests such as the Vandenberg and Kuse Mental Rotations Test[39] and the Card Rotation Test[40].

An additional re-classification of the sub-skills of spatial ability came through the research of Carroll; providing what is likely the most comprehensive assessment of spatial ability sub-skills to date[38]. Carroll's research yielded five major sub-skills of spatial ability: Visualization, Spatial Relations, Closure Speed, Flexibility of Closure, and Perceptual Speed[41]. The first two, Visualization and Spatial Relations mirror the definitions of Linn and Petersen's Visualization and Speeded Rotation respectively; while the remaining sub-skill (Spatial Perception) is broken down and remodeled into three distinct sub-skills which were previously unaddressed. The three new sub-skills, Closure Speed, Flexibility of Closure and Perceptual Speed, each employ the use of distracting or hidden material to obscure the target image[42] but have been further classified as "minor" sub-skills of spatial ability in literature[43].

2.2.3 Developmental Research in Spatial Ability

There is a well-documented dichotomy in spatial ability along the sex line; wherein males typically out-perform females on evaluations[44]. The biological factor theory suggests that gonadal hormone levels may be related to the development of spatial skills[45]. In an experiment by Hampson (1998) investigations into the relationship between congenital adrenal hypoplasia and mental rotation ability were completed to explore the role that prenatal androgen exposure plays on an individual's spatial ability[46]. It was observed that girls with CAH typically and significantly outscores girls without CAH, and the inverse was observed for boys with CAH compared to boys without CAH. These findings suggest that early exposure to androgens may facilitate organization of the brain regions associated with spatial processing[46].

Moreover, in work by Moffat investigating circulating salivary testosterone levels in adults observed that elevated testosterone levels were negatively correlated with spatial performance in males, but positively correlated with performance in females[47]. As a result, it is thought that pre-natal exposure, and circulating exposure to androgens may be an important factor in the development and adult expression of spatial ability[42]. Further, more recent work by Van Anders suggest an association between spatial abilities and heteroflexible (non-heterosexual) sexual orientations, which may be mediated by high prenatal androgens[48]. Van Anders observed that non-heterosexual females exhibit elevated spatial performance compared to their heterosexual counterparts despite having equivalent circulating testosterone levels[48], and hypothesize that the difference is associated with dichotomies in prenatal androgen exposure that are maintained into adulthood[48].

Conversely, and more recently, it has been reported that exposure to estrogen may negatively affect spatial ability[49,47]. In a study by Hampson involving premenopausal females, it was observed that the low levels of estradiol that occur during menstruation are associated with significantly improved accuracy in tests of mental rotation ability[50]. This finding gives further support to the role that gonadal hormones play on the development and maintenance of spatial ability.

2.2.4 Links to Academics, STEM, and other disciplines

While spatial ability literature is largely dominated by explorations of the number and nature of sub-skills of spatial ability, and the dichotomy of performance between males and females[44], the theme of its real world application is also well-explored. Spatial ability as a whole has occupied educational psychology literature due to numerous linkages between spatial ability and success in technical skill acquisition[51–53], knowledge acquisition[54,55], and performance in the STEM (Science, Technology, Engineering and Mathematics) disciplines[34,56,57]. These studies all report that spatial ability serves as a robust predictor for an individual's interest and success in the STEM fields [58].

2.2.5 Efforts to Train Spatial Ability

In a recent meta-analysis by Uttal *et al*. the concept of training spatial ability is explored through a review of current published and unpublished documentation of studies attempting to train or elevate individual spatial ability scores[38]. After accounting for a heterogeneity of effect size and experimental design measures, Uttal *et al.* described three different categories of training: those employing video games as a method of training[59], those employing an instructional course[60] and those using spatial tasks as practice[61,62]. Uttal concluded that spatial training, regardless of technique, yielded an average improvement in spatial scores by almost one-half of a standard deviation[38]. This suggests that spatial skills are in fact, moderately malleable, and further research is required to discern the most advantageous method of spatial ability training.

Some investigators have argued that efforts to train spatial ability have yielded only transient improvements, with little durability, and where success is restricted to the instances in which the training task and the evaluation task are very similar[63–65]. In line with this, the American National Research Council has called for additional exploration into spatial ability training, as the transfer of spatial training to untrained skills has yet to be convincingly shown. The National Research Council (NRC) also called for research that is aimed at determining how best to improve spatial performance in a generalizable way[66]. In response to the call from the NRC, educational researchers have begun exploring alternative avenues to determine the underpinnings of spatial ability, in effort to decipher the most advantageous mechanisms to train spatial ability.

2.2.6 Summary

Despite a long history of discord in academic literature regarding the various facets of spatial ability, there is little doubt that spatial ability and its sub-factors are linked to success in a wide variety of fields. Studies have shown that spatial ability can be reliably trained through various mechanisms, and the literature invites the creation of new and durable methods to educate populations who lack the ability to interpret spatially distributed information.

2.3 The Effect of Time Limits in Scholastic Assessment

2.3.1 General Introduction

In secondary and tertiary education systems, the vast majority of assessment takes place under regimented time restrictions[67]. But how does limiting the amount of time available for task completion influence an individual's ability to accurately complete the task? Research in the area of assessment design has debated the role of time limitations and test speededness, relative to success on outcome measures, and conclude that individual differences, such as working memory capacity and mental processing speed may influence the effect of time limits on test success.

2.3.2 Time Limits and Speededness

When designing a test with a time limit, often a test creator will devise a limit that will allow enough time for all participants to complete the test, while still maintaining an economical administration duration[68]. However, there are instances in which test creators will restrict the time available for test completion intentionally; these instances result in "speeded" tests. Tests may be considered as speeded when less than 90% of the individuals writing the test are able to complete all of the test questions during the time allotted[69]. More implicitly described, a test is speeded when "not (nearly) all items are answered by (nearly) all participants; or if the participants perceive pressure when working on the test"[67]. If speeded tests intentionally restrict the proportion of individuals that are able to access all of the questions on a test, what would result if the time limit were relaxed? It follows that one of the most debated topics in the field of testing resides in the role that extended time and time limits play on standardized test scores[68].

2.3.3 The Validity of Speeded Tests

By applying time limits, tests may be considered tests of "rate"; representative of how many questions the individual could complete during the time allotment. Conversely, untimed tests may be considered tests of "power", and representative of the level of difficulty mastered by the individual on the presented task[67]. In applied settings, the selection of speeded or unspeeded tests should depend on the purpose of testing. If the test seeks to establish how accurately an individual can complete a task, an unspeeded condition would be the best choice. However, if the criteria is contingent on the rate of performance, then a speeded environment would be best suited[67].

Several studies have sought to investigate how time limits influence test performance in various paradigms, including reasoning ability[67,70], divergent thinking[70], intelligence[71], and problem-based learning[72]. In all paradigms, all mean difference scores were significantly different between the speeded and unspeeded measures; demonstrating higher scores in the unspeeded conditions[67,70–72], and validating the claim that the imposition of time limits alter the skill being tested. Moreover, in a meta-analysis conducted by Voyer et al., it was observed that gender differences in mental rotation are significantly greater in timed than untimed conditions, and that the magnitude of sex difference is proportional to the amount of time allotted for test completion[73,74]. Further it was also observed by Voyer et al, that when time limits are relieved, the difference in score between the sexes was significantly reduced on the Vandenberg and Kuse Mental Rotation Test[39,74]. These findings suggest that different individuals respond differently to application of time limits, and these differences in response accuracy may be further extended to individuals of different levels of spatial ability, as females typically demonstrate lower mental rotation test scores than males.

Further, research on speeded tests suggest that when time limits are imposed, the test results cease to be a pure measure of the intended task, and are transformed into a representation of a complicated interplay between several factors; inclusive of mental processing speed, working memory capacity and strategic approach to the task at hand. Moreover, the issue with speeded tests is not that participants must stop early, but that variations in working speed (including mental processing speed, working memory capacity and strategic approach) will dictate success[75]. Despite this issue, few studies have sought to investigate quantitatively the difference in working memory capacity, mental processing speed and strategy in instances of timed, and untimed testing conditions[67].

2.3.4 Individual Differences in Working Memory

Literature states that the process of problem solving, whether verbal, spatial, or numeric, is complex, and is characterized by an understanding of the relationships between multiple elements. As such, in order to solve problems effectively, one must have access to mental representations of the elements undergoing comparison, which are held in an individual's working memory. The main function of working memory is to prepare and maintain temporary representations of the relationships between elements, in an effort to understand and manipulate the elemental relationships[76–78].

However, it is assumed that those representations held in an individual's working memory are not held indefinitely, residing there for only a brief period of time. As a result, fast processing of the information associated with the elemental relationships is vital to task completion prior to the decay of the mental representation in working memory[79,80]. Research into the impact of time limits on spatial reasoning tests suggest that when tests are administered with a time limit, a substantial variance will be observed in the outcomes. It is assumed that this variance is largely attributed to differences in individual working memory capacity[67]. Indeed, research suggests a very strong correlation between an individual's ability to solve spatial problems, and their working memory capacity[78,81–83]. That is, individuals who are proficient at reasoning will typically have high working memory capacities, and vice versa. With this in mind, when tasks are considered speeded, and the burden on working memory is high, the rate of mental processing becomes critical to performance.

2.3.5 Individual Differences in Mental Processing Speed

Wilhelm and Schulze suggest that the more quickly information in working memory can be interpreted; the less likely the maximum capacity of working memory will be reached. Thus, performance on a task that requires high working memory capacity would be improved by elevated mental speed[67]. In theory, the addition of a time limit applies pressure on performance, and favours individuals with high cognitive processing rates, as higher rates of processing yield more time to inspect more questions[75,84,85]. This theory is supported empirically, as in speeded tests, the participants who rapidly go through the test have an essential advantage over slower participants[67].

Further, in evaluations of the relationship between mental processing speed and time limits, it was observed that the relationship is a function of complexity of the test[75,86], the more complex the reasoning task is, the higher the correlation between mental processing and success in reasoning will be [87,88]. However, few investigations have sought to compare speeded and unspeeded conditions and their respective correlations to mental processing [67].

If one's ability to solve reasoning problems is contingent on both their working memory capacity, and their rate of mental processing, it can be suggested that harder questions present greater burdens on working memory. As such, the greater the burden on working memory, the more valuable mental processing speed becomes. With this considered, if more time is allotted to task completion, or if time limits are relaxed, then an increase in reasoning ability may be expected via increases mental processing[67].

2.3.6 Individual Differences in Strategy

In addition to individual differences in working memory and processing speed, success on timed and untimed tests may be also reflected in the strategic approach taken by the individual during completion. A recent experiment by Gluck and Fabrizii suggests that the sex differences observed on the time-restricted Vandenberg and Kuse Mental

Rotations Test are at least partially explained by the response format of the test itself, requiring the expedient selection of two correct answers from four possible options[89]. Literature explains that typically, males tend to outperform females on timed mental rotation tests because they progress through tests more quickly than females, and are less likely to cross-check alternatives than females[90,91]. Lunneborg further postulates that males do not cross-check their answers on VKMRT questions because they are more confident in their mental rotation ability than their female counterparts[90,91]. Gluck and Fabrizii further attribute the observed sex differences on the timed VKMRT to the actual structure of the test questions, in that participants must select the two correct options from two incorrect distracters under high time pressures. They suggest that males adopt a "quick and dirty" method to answering, which can be characterized as follows[89].

Males tend to inspect the target, and inspect the answer options quickly. If the male identifies that the first two answer options are likely the correct answers, they will answer and proceed to the next question. This is unlike the approach adopted by females, who will inspect the target, and each answer option. When females identify two answer options which may be correct, instead of answering and moving on, they will often cross-check the other two answer options to ensure that they are not rotations of the target[89]. This takes a longer period of time, and often leads to confirmatory re-checking of the target with the two initial answers believed to be correct. Lunneborg suggests that females lack confidence in their initial answers and double-check their answers with greater frequency than males; adding to longer question durations, and fewer possible questions per test[90,91].

Further work on strategies applied to mental rotation has been conducted recently by Geiser et al., which mirrors the theories of Gluck and Fabrizii referring to the strategic female approach to mental rotation[92]. Geiser suggests that there are five classes of strategy used to complete mental rotation tests[92]. Of these five classes, four complete the process of mental rotation at various rates, while the remaining class is considered "non-rotators". Individuals populating this group are the lowest scoring of all participants, and adopt an analytical strategy of feature matching, rather than a spatial strategy of holistic rotation, to complete questions[92]. While approximately one-third of VKMRT style questions are answerable using this method, it is temporally expensive, and inapplicable to the remaining two-thirds of questions wherein obvious distractors are not present [92]. Individuals populating the non-rotation group are typically female, while individuals occupying the upper two classes of the rotation group are typically male[92].

Given the proportion of females that typically populate the low MRA population, it is possible that this dichotomy of strategies, and their implications could be extended to the low MRA/ high MRA dichotomy, and account for some of the effects of timing on accuracy in low and high MRA groups.

2.3.6 Summary

In essence, the application of a time limit not only modifies what the outcome of a test represents, but also creates a bias for success based on the relationship between working memory capacity,mental processing speed, and strategy. Those individuals with lower working memory capacity, those demonstrating reduced rates of mental processing, and those adopting inefficacious strategies will likely be disadvantaged by the application of time limits, as they cannot process the information efficiently enough to reach the answers during the allotted time parameter.

2.4 Neural Underpinnings

The Visual Processing System

2.4.1 Brief Summary of the Cortical Areas in the Visual Pathway

According to Palmer, there are three main neural regions associated with eye movement programming: the posterior parietal complex which is responsible for disengaging attention, the Pulvinar which is responsible for engaging attention, and the Superior Colliculus which is responsible for relocating attention. However, this description only refers brain regions governing attention-based eye movements, and fails to consider the interpretation of the visual stimuli. As such, a brief elaboration of the neuroanatomical regions associated with the visual system is merited (Figure 4).

The Primary Visual Cortex (V1)

The primary visual cortex serves to detect stimuli, such as information pertaining to orientation, colour and variations in colour, that are presented through pathways coming from the Lateral Geniculate Nucleus (LGN) of the thalamus, and then create a spatially precise representation of the visual field, called retinotopic mapping. The primary visual cortex then serves to project these incoming signals to other brain regions; namely the superior colliculus, the pre-striate cortex (V2) and Visual Area V4[93].

The Pre-Striate Cortex (V2)

The prestriate cortex receives stimuli from V1 both directly, and via the pulvinar, and relays that stimuli information onward to V3, V4 and V5, and replies to V1 with feedback. The spatial mapping that was established in V1 is maintained in V2 as a complete map of the visual field. The cells present in the mapped area are tuned to orientation, spatial frequency and colour[94].

The Third Visual Complex (V3)

While the precise arrangement of V3 is not yet defined; it is accepted that there are two V3 domains, Dorsal and Ventral V3[95]. Dorsal and Ventral V3 have distinct connections with other parts of the brain, and contain neurons that respond to different combinations of visual stimulus. Dorsal V3 is normally considered to be part of the “dorsal stream”, receiving inputs from V2 and V1 and projecting to the posterior parietal cortex (PPC). Whereas Ventral V3 has much weaker connections from V1, and stronger connections with the inferior temporal cortex (ITC)[93].

Visual Area 4 (V4)

Visual Area 4 is the third cortical area in the human ventral stream of visual information processing. It receives input from V2 and V1, and sends input to the posterior inferotemporal area. Much like V1, the cells of V4 are tuned for orientation, spatial frequency and colour, but unlike V1, is also tuned to recognize more complex features, including geometric shapes[93].

Visual Area V5/MT

Visual Area V5, referred to commonly as visual area MT (Middle Temporal) is considered to be essential in motion perception, and the guidance of some eye movements[96]. Visual Area MT is connected to many brain regions, including inputs from V1, V2, and Dorsal V3[97], the K pathway of LGN[98], and the inferior pulvinar[99]. It is hypothesized in the literature that the projections to the MT are variable, depending on the representations of the foveal and parafoveal visual fields, however it is accepted that V1 sends information of greatest value to MT, and that MT relays its major outputs to the areas which surround it; the fundus of the superior temporal lobe (FST), MST, and V4, as well as FEF and LIP to aid in eye movements.

Frontal Eye Fields (FEF)

The Frontal Eye Field is a brain region responsible for controlling visual attention and eye movements[100]. The FEF is works with the superior colliculus to initiate eye movements including voluntary saccades[101]. When combined with the supplementary eye field (SEF), the intraparietal sulcus (IPS) and the SC, the FEF is part of a brain region that is critical to generating and controlling eye movements.

Lateral Intraparietal Area (LIP)

Found in the intraparietal sulcus, the LIP is involved memory-based saccade generation [102]. The neurons in the LIP temporarily store information pertaining to the location of the target stimuli, and use that information to guide the saccade to that target stimuli.

Posterior Parietal Cortex (PPC)

The posterior parietal cortex is crucial for the execution of planned movements; including those of the eyes. The PPC receives input from the visual system via MT, MST and LGN, and relays information to the FEF to execute eye movements including saccades, fixations and smooth pursuit movements[93].

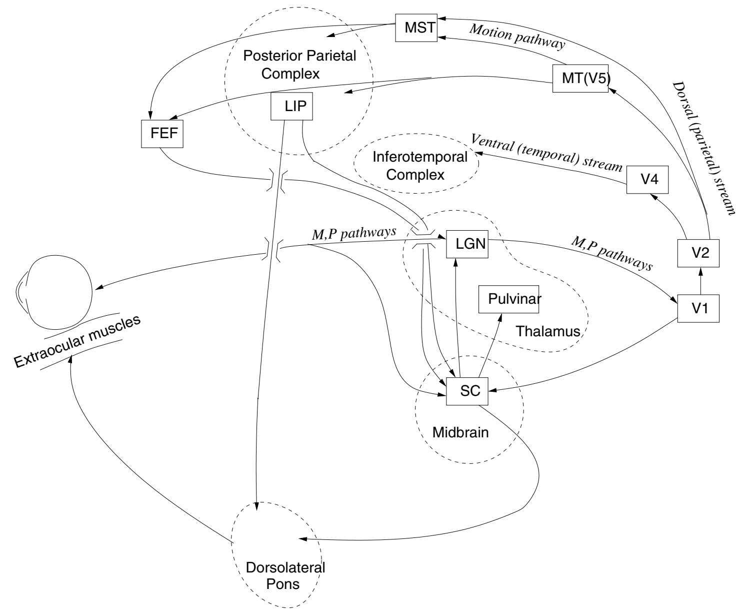

Figure 4: Schematic representation of the brain and the visual pathways that are relevant to eye movements and attention, adapted from Duchowski (2007) with permission © 2007 Springer Science & Business Media

2.4.2 Visual Pathways

2.4.2a The Parvocellular Pathway (Ventral):

The Parvocellular Pathway ("P Pathway") receives stimuli from retinal ganglion cells with small bodies, and slow rates of transmission ("P Cells" or Midget Cells). Because the receptive fields of the retinal cell ganglia in the P Pathway are small, the P Pathway is sensitive to detail, and contrast. Further, the P Pathway is insensitive to changes in light levels, and motion, but is receptive to colour. The cells in the parvocellular layers of the LGN project into the striate cortex (V1), which in turn project to V2. These cells then project to discrete sub-regions of V4, and onto the inferior temporal cortex and comprise the "ventral" pathway of human visual processing[93,103,104].

2.4.2b The Magnocellular Pathway (Dorsal):

The Magnocellular Pathway ("M Pathway"), receives signals from retinal ganglia that are large, fast and possess large receptive fields. The cells of the M pathway are insensitive to small objects, colour, and contrast, but highly sensitive to light changes, and motion. The M pathway projects from the magnocellular layers of the LGN to V1. The cells in V1 project directly to the middle temporal area (MT) and also to V2, from which cells also project to MT, and onwards to the posterior parietal cortex, comprising the "dorsal stream" of human visual processing (Figure 5)[93,103,104].

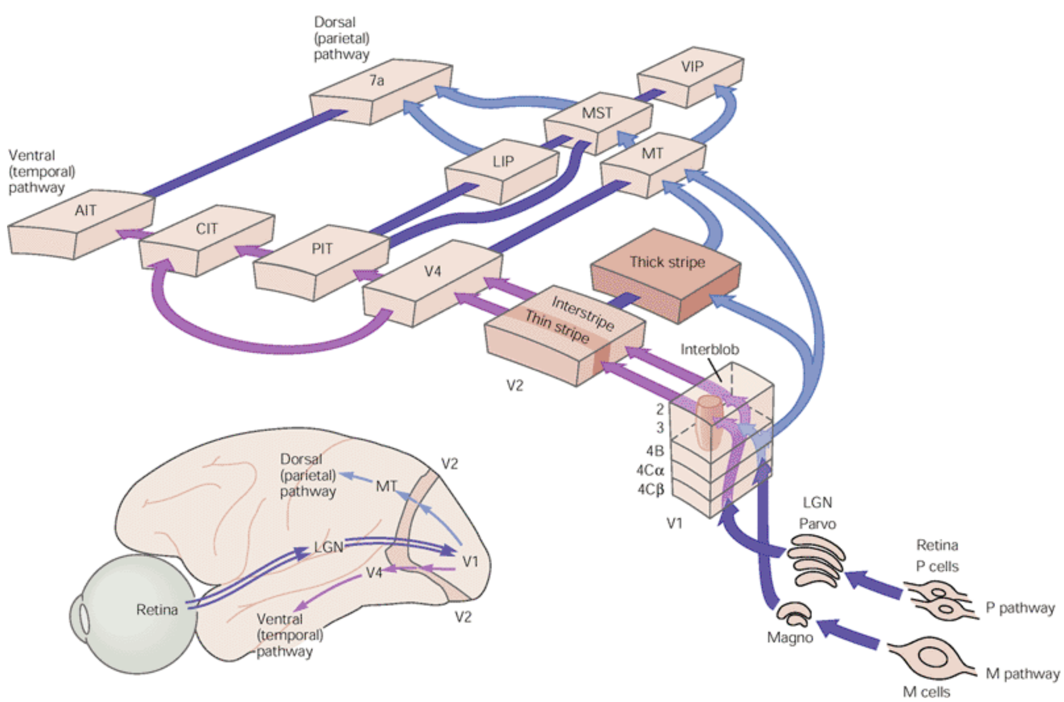

Figure 5: The basic anatomy of the visual pathways of the human brain. Kandel (2000) with permission © 2000 McGraw-Hill.

2.4.3 Neural Underpinnings of Mental Rotations Ability

It is accepted across the literature that mental rotation, like many other complex cognitive processes in humans, requires multiple brain areas for success[105,106]. Early explorations into the distribution of activation across the two cerebral hemispheres have yielded conflicting results in response to mental rotation.

In a study testing mental rotation of geometric icons based on the line drawings of Shepard and Metzler[107] by Cohen, bilateral activation of the cerebral hemispheres in the superior parietal lobes, the dorsolateral prefrontal cortex, and the premotor areas were observed[106]. However, in a study by Alivisatos & Petrides involving the mental rotation of alpha-numeric characters, only the left parietal lobe showed activation[108]. Further, and paradoxically, in a study by Harris using the same task as Alivisatos & Petrides, Harris found that there was marked activation in the posterior parietal lobe on the right side[109].

In a recent meta-analysis of cortical activation following mental rotation by Zacks (2008) it was concluded that the brain regions that were consistently activated during mental rotation included the superior parietal, frontal, and inferotemporal cortices[110]. The activity was observed bilaterally in most areas; however, in the parietal cortex activity was more consistently observed in the right hemisphere, while activity in the frontal cortex was more consistently observed in the left hemisphere[110].

Zacks (2008) suggests that the foci of activation found in the superior parietal, frontal and inferotemporal cortices contribute to a large focal activation area surrounding the intraparietal sulcus, and roughly equates to Brodmann's Areas 7 (Superior Parietal Lobule), 19 (Secondary Visual Cortex), 39 (Angular Gyrus) and 40 (Inferior Parietal Lobule)[110]. These findings are well supported by neuropsychological data obtained by Ratcliff, who found consistent activation of the superior parietal cortex during mental rotation tasks[111]. Further, the superior parietal cortex is known to create maps of space that encode the spatial position of targets of intended actions. This can be seen most clearly in electro-physiological studies of eye movements and reaching in the monkey [112,113].

Moreover, the posterior parietal cortex (and the brain regions extending into the superior posterior occipital cortex) is consistently activated during mental rotation across a range of tasks, imaging modalities, and statistical analysis strategies[110]. As a result, it is reasonable to suggest that this region may implement the transformation-specific computations required to complete mental rotation. This finding aligns with the work of Farah, who conducted neuropsychological studies on mental rotation[114] and the work in transcranial magnetic stimulation conducted by Harris[115].

2.4.4 The Neural Underpinnings of Working Memory

Decades of research have demonstrated that the ventral occipitotemporal stream carries out the sensory processing of object information, while the dorsal occipitoparietal stream carries out sensory processing related to spatial relations[103,116]. This dichotomy of streams is supported by the work of Kleist involving patients with focal brain lesions in the posterior parietal cortex resulting from missile injuries incurred during the First World War[117]. In Kleists' study, the patients demonstrated one of two deficits; "blindness" of object form, or deficits in spatial relations[117]. Later, Newcombe *et al.*, observed a patient whose right temporal lobe was removed following a traumatic car accident, and suffered significant deficits in object recognition, but displayed intact spatial capabilities[118]. Interestingly, this individual excelled when subject to an experiment where judgments of relative shape were required, yet performed no better than chance when asked to complete a spatial task[119]. Subsequently, Owen et al., reported that lesions to the anterior temporal lobe impair working memory associated with object form (Visual Working Memory), while leaving spatial relation processing (Spatial Working Memory) intact[120,121]. Further, supporting lesion studies have demonstrated this claim, as patients with hemorrhagic parieto-occipital lesions did exhibit severe deficits in spatial relations[122,123].

Working Memory and the Frontal Lobe

In both humans and nonhuman primates, the activation of the prefrontal cortex (PFC) has been linked to the performance on tasks, which require working memory[124–126]. For example, in a study using monkeys, it was observed that the dorsolateral PFC is key to performance on the delayed response task; a task that is widely reputed to be an index of spatial working memory[124].

Further, the critical role that the PFC plays in working memory has now been established in a variety of experiments, including lesion and electrophysiological studies in primates [127,128], experiments of neurological patients with localized cortical excisions[120,129], and functional neuroimaging studies in healthy volunteers[121,130–133]. While it has been argued that there are separate regions involved in non-spatial and spatial working memory, current evidence suggests that the PFC may facilitate cognitive processes that are common to working memory tasks, regardless of the type of information being held in working memory[121,134–136].

Moreover, recent studies have reported a domain specific dissociation across the regions of the PFC, wherein the dorsolateral PFC maintains spatial information, while the ventrolateral PFC maintains object information[127,137–140]. These findings thus suggest that the ventral and dorsal processing streams present in the posterior cortex may extend into the prefrontal cortex[116]. This view is supported neuroanatomically, as studies have demonstrated evidence of fiber connections between the temporal lobe and ventral prefrontal cortex, as well as between the parietal lobe and dorsal PFC[116].

In a study by Muller and Knight, patients with ventromedial and or dorsolateral PFC lesions completed four tasks in which object or spatial information had to be maintained or manipulated in working memory[141]. It was observed that patients with lesions performed identically to matched controls across all tasks; suggesting that none of these single regions alone are critical to working memory. Further, it seems that a critical component of working memory is not found in the prefrontal cortex[116]. This theory is supported by an imaging study by Postle, wherein working memory tasks were shown to cause activation in the posterior brain regions solely[142].

In the model described by Postle, the model of working memory storage is mediated by discrete, networks in the posterior cortices[142]. It is suggested that the working memory storage of verbal material is supported by the posterior perisylvian regions that are associated with language comprehension[143–146], while visual working memory storage of spatial and object features is supported by the posterior regions of the dorsal and ventral processing streams[147,136].

In a further study by Postle, evidence was observed that object working memory calculations are preferentially supported by the posterior cortical regions of the ventral stream; specifically the fusiform, lingual and inferior temporal gyri[145]. Further, additional studies have observed that spatial working memory is localized to the occipital lobe [140,148–150]. In the work of Smith *et al*., served to dissociate the neural correlates of verbal from spatial working memory using positron emission tomography, and observed that several regions were activated in spatial working memory tasks, that were not implicated in verbal working memory[151]. It was observed that area 40 of the right parietal cortex and right premotor cortex were activated specifically in spatial tasks. Further, two additional right-hemisphere regions were also implicated in spatial working memory; area 46 of the dorsolateral prefrontal cortex, and area 7 of the posterior parietal cortex[151]. The activation of area 46 is further supported by other research in the neuroimaging studies of human spatial working memory[133,152].

As a result, it can be considered that the maintenance of spatial working memory requires a complex network of cortical regions, inclusive of the dorsolateral prefrontal cortex, dorsal parietal cortex, and the occipital cortex, working in concert to process and interpret spatial information.

2.4.5 Summary

While from the outset, it may appear that the cortical regions associated with vision, mental rotation and working memory are discrete, there is mounting evidence to suggest that these three systems are well integrated across the brain, from the dorsolateral prefrontal cortex along both the dorsal and ventral processing streams. This intertwined relationship between the three structures gives further support to the role that cognitive load plays on sensory information processing, and one's aptitude for interpreting spatial relationships.

2.5 Training using Expert Eye Modeled Examples

2.5.1 Gaze-Based Training

Recent research has confirmed the relationship that exists between one's visual environment, their attention, and the underlying cognitive processes associated with interpreting their environment[153–157]. Salience, operationally defined as the perceptual quality of an item to stand out relative to its surroundings, is known to play a large role in drawing visual attention. Structures with high degrees of visual salience are looked at faster, for longer, and are recalled more vividly than less salient structures[158]. However, many perceptual tasks require that an individual distinguish task-relevant salient features (or thematic features), from task-irrelevant features[158]. Unfortunately, when novices are presented with a perceptual task, they are unable to identify thematically relevant information due to inexperience, and rely predominantly on visually salient areas[159].

Recent research inspecting the value of salient structures in tests of mental rotation have found that by experimentally increasing the salience of perceptual depth cues on mental rotation tests, test performance is improved and more pronounced in females than males[160]. Through the use of LCD glasses and 3D demonstration of the test images to better identify the depth-specific salient domains of the figures, participants were better able to construct accurate representations of the objects, and reach conclusions more accurately[160]. By assisting in the visual identification of salient regions, better, more effective visual search strategies can be impressed upon low-performing individuals[160].

The development of visual search strategies has hinged on two basic principles: The Worked Examples Principle, and The Signalling Principle. The former hinges on the concept that exemplars can be applied to guide novices to improved task performance[161,162], while the latter uses cueing techniques to highlight important information[163]. By highlighting the task specific information attended to by experts, novices can be directed where to attend during perceptual tasks.

2.5.2 Expert-Data-Driven Approaches to Visual Guidance

Research suggests that people frequently refer to the gaze of others to drive reasoning and decision making[164]. As a result, research has sought to investigate how novices react to the presentation someone else's eye movement patterns in an effort to explore how this type of guidance can improve problem solving[164].

Indeed, literature suggests that because experts attend to task-relevant regions more often than novices[165–169], and because they focus faster, and proportionally longer on relevant information, while ignoring task-irrelevant salient information[170–173] , it is possible that the eye movement patterns of experts may be useful in training novices[174–176]. By exposing novices to expert eye movement patterns, the expert's allocation of attention can be made visible. As a result, the attention of the novice should be synchronized with that of the expert. Such a synchronization should thus aid the novices' selection of task-relevant information, and potentially encourage improvements in future problem solving tasks[177].

Such an approach is supported in educational literature, as it follows the format of "Example-Based Instruction"; an effective method for training novices[161]. Example-based instruction is characterised as the provision of written, worked-out solutions prior to task completion; or as the observation of a model demonstrating the correct performance of the task live[162]. In the case of instruction using eye movement modeled examples (EMME)[178], the novice may view the visual search process of an expert, and potentially acquire improved visual search techniques that could manifest in accelerated learning on the task at hand[164].

2.5.3 Types of Eye Movement Modeled Example (EMME) Cueing

While multiple varieties of EMME training mechanisms exist, they can be divided into two broad categories: subtractive and additive cueing. Subtractive cueing, often referred to as a spotlight display[177], or “anti-cueing”[179] serves to keep the elements fixated by the model clearly visible, while reducing the visual salience of the surrounding structures; much like a spotlight on a stage[180]. Because the key regions attended to by the model are in clear focus, the observer’s attention is drawn to the image elements that are key to problem solving, while ignoring the irrelevant, but potentially salient, “background” information. In the spotlight display design described by Jarodzka, the focus of the models attention (with a radius of 32 pixels) was visible in an unaltered way; while the non-fixated background surrounding it was "blurred" by reducing contrast and colour saturation[177]. As a result, by employing a spotlight approach, the amount of information that has to be interpreted by the observer is lowered, and working memory load is reduced, potentially improving learning[177]. This is particularly important in instances where the background information is full of salient, perceptual stimuli that could distract from the task-relevant elements.

Conversely, additive cueing, often referred to as “Dot Cueing” showcases the fixations of experts as solid dots, overlaid over the target image. These dots serve to increase the contrast of the “to-be-cued” element, through the use of a salient colour[177]. One caveat of the dot display technique is that it occludes the precise location of the model’s gaze, while requiring the observer to attend to information surrounding that attended to by the model. As a result, observers are guided around the relevant areas during task, rather than being guided directly to the information the model attended to[177]. This method is particularly useful for instances where a holistic view of the target image is useful, as the dot display allows the observers to get a “big picture” understanding of how the fixated elements relate to their surroundings, while these relationships are obscured in the spotlight display[177]. However, in instances where the background stimuli is full of perceptual information, the dot-display can obscure relevant information and draw attention to the surrounding irrelevant information[177].

Despite the differences associated with both types of cueing, research has found that the benefit of EMME is independent of display style[180]. However, when choosing a cueing style, one should consider the requirements of the task in question. In tasks requiring complex background information, and identification of key elemental features, the subtractive method of cueing is recommended. Conversely, in instances requiring comprehension of the relationships between key elements, an additive approach is merited[177].

2.5.4 EMME Training in Psychomotor Tasks

Many groups within the field of sport and psychomotor learning have endeavoured to explore how visual apprehension strategies differ between individuals of different skill levels during task performance[181]. Indeed, research in sport has explored differences in the eye movements of experts and novices in activities including badminton[182], squash[183], basketball[184], gymnastics[185–187], soccer[188–198], tennis[199–203], baseball[204], cricket[205], handball[206], boxing[207,208] and volleyball[209]. In general, it was observed in a meta-analysis by Gegenfurter that experts conducted more fixations of longer duration on task-relevant areas, and fewer fixations of shorter duration on task-irrelevant areas than novices[181]

As a result, research efforts have capitalized upon the well-established dichotomy to develop training approaches based on the eye movement patterns of experts to inform novice athletes where and when to look for the best results on a variety of athletic maneuvers, including the performance of the ideal golf putt[210], basketball free-throw[211,212], and soccer penalty kick[213]. Indeed, these studies each demonstrated that where an individual looks during a task plays a direct role in dictating success. In soccer, when kickers directed their gaze at the goal keeper, their scoring accuracy was significantly decreased[213]. In basketball, when basketball players directed their gaze to a specific point on the hoop, their scoring accuracy was elevated significantly compared to the control group[211]. Finally, in golf, when golfers attended to a region on the ball with a circumference of one degree prior to the initiation of their backswing (for a minimum of 120 ms), their putting accuracy was improved by 1.9 putts per round[210].

2.5.5 EMME Applications in Surgery

The studies of gaze and attention in the domain of sport have informed work in surgical education; wherein EMME approaches to training novices are being explored. Recently, in the studies of several research groups, eye patterns of novice and expert laparoscopists were collected during the performance of standardized technical laparoscopic tasks[214–216].

These studies yielded significant differences in the patterns of eye movements between the novices and experts, and elucidated the successful approach held by the experts[214,215]. The findings of these two studies yielded an EMME subtractive approach employing the eye movements of expert laparoscopists to train novices on specific laparoscopic techniques. When evaluated, the EMME approach based on expert eye movements proved to be an effective protocol to guide the attention of novices, and improve their performance on a specific laparoscopic task[217].

2.5.6 EMME Applications in Perceptual Tasks

In addition to the successes found in the domain of psychomotor learning, EMME has found an additional niche for successful application in field of psychology as a mechanism for training visual problem solving. Successful applications of EMME have been observed in such tasks as diagram-based radiation problem solving[218], pulmonary nodule detection[219,220], aircraft inspection[176], circuitry board inspection[175], and identification of fish locomotion patterns[177].

More specifically, in the work of Grant and Spivey, it was hypothesized that an empirically informed attentional guidance strategy could serve to improve reasoning on the diagram-based task in question[218]. They reasoned that if the perceptual salience of the critical diagram features (those attended by successful problem solvers) were highlighted, that they would command a “bottom-up” influence, and would increase the likelihood of generating a correct inference[218]. Indeed, when the critical areas were highlighted, 67% of participants were successful in problem solving; compared to only 37% successful in the control group[218].

Likewise, in the area of radiology, similar results were obtained in a study of performance in pulmonary nodule identification. When radiologists were shown task-specific eye movement behaviours of expert radiologists, performance on a nodule identification task was improved in novices, but no improvement was observed when generalized eye movements were presented that did not reflect the task-at-hand, and no improvement was observed by experts in either paradigm[219,220], suggesting that perceptual feedback may be the most beneficial to radiographers at the early stages of their career[221].

Similarly, in the work by Jarodzka et al EMME was applied to train skill in classifying fish locomotion patterns[177]. It was observed that EMME improved the process of visual search and enhanced the interpretation of relevant information for novel stimuli compared to the control group[177]. Moreover, by applying the eye movement behaviours of experts, additional studies have shown that novices can improve performance in aircraft inspection[176], circuitry board inspection[175], and effectively translate the search behaviours to novel, untrained tasks when using feed-forward guidance protocols[175].

2.5.7 Summary

Expert eye movement modeled examples can be applied either additively, or subtractively to direct an individuals gaze during a task. Studies in the domains of psychomotor skills acquisition, surgical training and perceptual skill acquisition have all shown robust benefits of EMME guidance on task performance. Further, research by Terlecki et al., and others suggest that trained skills, such as spatial ability may be translated reliably to untrained, novel skills[38,59,62,222]. With this in mind, EMME appears to be a reliable method of training spatial ability through the reduction of cognitive load burden that is imposed in tasks requiring visual search, by cueing task-relevant, salient information.

2.6 Overview of empirical chapters

The current research aims to elucidate if the movements of the eyes reflect aptitudes for spatial reasoning, and to ascertain if visual guidance derived from expert eye movements may be applied to improve spatial reasoning skills.

More specifically, in "Chapter 3: The Untimed Experiment" of this dissertation, we pose the question "How does mental rotations ability influence the movement of the eye during the performance of a spatially complex task?" and through experimentation, address our objective of discerning how eye movements are reflective of success in mental rotation ability in an untimed environment.

Further in “Chapter 4: The Timed Experiment” and “Chapter 5: The Crossover Experiment” of this dissertation, we ask “What role does a time limit play on one’s ability to reason spatially, and how does limit influence eye movements?” By imposing a time restriction, we aim to explore how the addition of stress influences how individuals view, and perform on a mental rotations test, in an effort to determine if aptitude is robust to time limits, and how visual search is effected.

Finally, in “Chapter 6: The Guided Experiment”, the question of “Can we guide visual attention to improve an individual’s ability to reason spatially?” is raised, and answered. Through experimentation using expert eye movement modeled examples, we investigate how performance on mental rotations tests changes when individuals are shown where to look.

2.7 Overall Objectives

This research aims to relate levels of mental rotation ability, as evaluated by scores on the Electronic Mental Rotation Test and the Vandenberg and Kuse Mental Rotation Test, to patterns in average fixation duration, average response time, average number of fixations per question, and attention to salient regions on test images. Further, this research aims to investigate how the role of timing (both timed, and untimed testing environments) impact performance, eye movement, and attention to regions of salience in individuals of high and low MRA. Moreover, this research aims to investigate how low MRA performance on the timed EMRT is affected by visual guidance using expert eye-movement modeling.

It is hypothesized that there is a quantifiable distinction between High and Low MRA individuals, and that difference is manifest in the movements of the eyes. Through eye tracking, such differences may be detected and applied more broadly as training protocols to direct attention in spatial disciplines, such as anatomy and the STEM disciplines.

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Chapter 3

3 Eye Movements During Untimed Tests of Mental Rotation Ability

3.1 Introduction

Spatial ability, the capacity to understand and remember spatial relationships between objects, is thought to be a key factor that dictates how individuals perceive and interact with their surroundings[1–3]. Furthermore, the role of spatial ability influences not only how learners succeed in STEMM disciplines (science, technology, engineering, medicine and math)[4] but also specifically the anatomical sciences[5–7]. Gross anatomy is a visually complex topic, wherein students must learn to recognize anatomical features in different orientations, planes of section, and through different visualization modalities, through the application of visual cues, their spatial relationship to other structures[8]. Despite the variety of methods available to teach anatomy, the role that an individual's spatial ability plays cannot be understated; particularly when utilizing resources that display anatomical features from varying viewpoints[9]. With this in mind, one must consider the possible spatial-ability-based pedagogical techniques that could be designed to bolster this trait, and yield enhancements in the training of gross anatomy[6].

Commonly used as an umbrella term, spatial ability is not monolithic, but rather composed of several discrete, but interrelated sub-abilities[1]. One of these sub-abilities is mental rotations ability (MRA); the capacity to rotate two or three-dimensional figures rapidly and accurately[10]. For decades, MRA has occupied a niche in cognitive psychology, and has been linked to a number of other domains, including skill acquisition, knowledge transfer, and academic performance in spatially complex disciplines, such as surgical training and anatomical science[5,11–14].Typically, MRA is measured by performance on standardized tests of mental rotations, such as tests employing the line-images of Shepard and Metzler[15] and the Vandenberg and Kuse Mental Rotations Test[16,17]. These tests can serve to identify individuals as high, intermediate, or low MRA based on individual score[18]. It is accepted that in timed conditions, individuals with higher mental rotation ability complete these tests in less time and with greater accuracy than those with lower spatial ability[19].

Researchers have attempted to investigate the cognitive processes that underlie MRA, and its relationship with skill acquisition and anatomical knowledge acquisition, but conclusive answers have yet to be determined[20]. One hypothesis suggests that mental rotation may manifest in the movements of the eye, as fixations, (maintaining gaze on a single location[21]), are intimately involved in our ability to visually encode spatially distributed information[22,23]. Foundational experimentation has demonstrated that individuals' gaze patterns are under cognitive control, and tailored to the task at hand[24,25]. Subsequently, investigations have shown that the order and duration of fixations are tightly linked to the specific target task[26–30].

In a pioneering study, Just and Carpenter (1985) explored how eye movements may relate to strategies undertaken by individuals during spatial reasoning. Under their paradigm, significant differences in average response time of individuals of high and low MRA were identified, and mapped according to question difficulty while participants answered questions composed of Shepard and Metzler line-images of blocks and the cube comparison test[31]. These results have thus encouraged further inquiry into the fundamental differences that exist between high and low spatial individuals, and how these intrinsic human factors can pre-define success in mental rotations in terms of comprehension and apprehension of spatially salient structures. Regions of spatial salience are areas that possess perceptual qualities that make them stand out relative to their surroundings[32]. In the case of the line-drawn blocks of Shepard and Metzler, spatially salient structures are hypothesized to be the regions of the figures that convey depth and positional information pertaining to the orientation of the structure in space.

The current study aims to explore eye movements and mental rotation ability (MRA), during the completion of an adapted, electronic test of mental rotations (EMRT) where no time limits are imposed. The goal is to elucidate both temporal and salience patterns associated with MRA. It is hypothesized that MRA score will be negatively correlated with average fixation duration, average response time, and number of fixations occurring during the performance of the EMRT. Furthermore, individuals with different levels of MRA will attend to different features of the block-figures presented in the EMRT as they solve spatial questions. Finally, it is predicted that individuals of high MRA will demonstrate more variation in question response time across the performance of the EMRT indicative of cognitive flexibility in solving spatially challenging visual problems. It is thought that through this line of investigation, differences between low and high MRA individuals will be revealed, and serve as a foundation for future eye-movement directed spatial ability training protocols. Such protocols would serve to enhance spatial reasoning in low MRA individuals on MRA tasks, and potentially lead to enhanced performance in the both anatomical science, and the STEMM disciplines.

3.2 Material & Methods

Participants

Participants were volunteer graduate students in the allied health sciences and anatomy and cell biology at The University of Western Ontario with normal, or corrected to normal vision by way of contact lenses, were invited to participate in this exploratory study (n=23; 7 males and 16 females), under approval from the institution's Research Ethics Board. Individuals with EMRT scores exceeding one standard deviation above the mean were considered to be high MRA, and those with EMRT scores less than one standard deviation below the mean were considered to be low MRA. All other individuals who demonstrated scores within one standard deviation of the mean in either direction were considered to have intermediate MRA. This approach was adopted, rather than a median split, to exacerbate the distinction between high and low MRA individuals[33]. That is, individuals of high and low MRA are separated by a degree of two standard deviations of MRA score.

Experimental Design

Participants completed the EMRT while monocular gaze was monitored using corneal reflection eye tracking. Measurements of gaze were obtained from movements of the right eye, collected at a rate of 1000 Hertz using EyeLink 1000 eye-tracking equipment (SR Research Ltd., Mississauga, Ontario, Canada). On a question-by-question basis, eye movement metrics consisted of average fixation duration, number of fixations, and the region of highest salience (Table 1), wherein a "fixation" may be considered the maintenance of gaze on a single point for a period of time exceeding 200 milliseconds. Additionally, the eye-tracking equipment also collected the average question response time per participant to supplement analysis. Target images were viewed from a distance of forty centimeters, so that each figure subtended approximately ten degrees of visual angle, and the center-to-center distance between the two figures subtended approximately fifteen degrees. Ambient light conditions were kept constant in the testing room at all times.

Table 1: Selected eye movement measurements, defined.

Measurement	Definition
Average Fixation Duration	The mean length, in milliseconds, of a fixation performed by an individual. This value is calculated for each question presented, for each individual participant.
Question Response Time	The time required in milliseconds (from the onset of image presentation, to button-press) for the participant to respond to the question.
Number of Fixations	The number of fixations completed by a participant during the course of a single question.
Region of Highest Salience	The region on the presented image that was attended to with the greatest frequency and duration. This is represented by Gaussian distributions that are scaled by duration, where multiple fixations are summed (frequency)

Target Images

The target images presented to the participants constituted an electronic Mental Rotations Test (EMRT). This visual test requires participants to view two three-dimensional (3D) block figures (a "block pair"), and indicate if the pair was the same, or different (Figure 6) by responding using two keys on the keyboard as quickly, and accurately as possible. A button-press of "1" indicated a "same" pair, while a "2" indicated a "different" pair.

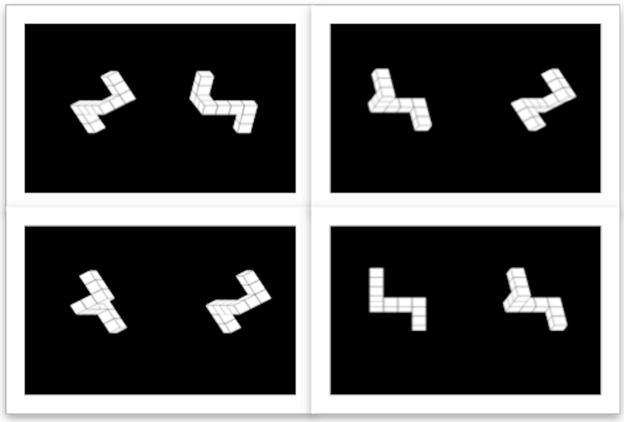


Figure 6: Four sample questions based on the Shepard and Metzler block pairs used in the EMRT[15]. Each pair represents one question. Participants used a keyboard to indicate if shapes were the same or different. Answer key: clockwise from the top-left: images are different from each other, different, identical and identical.

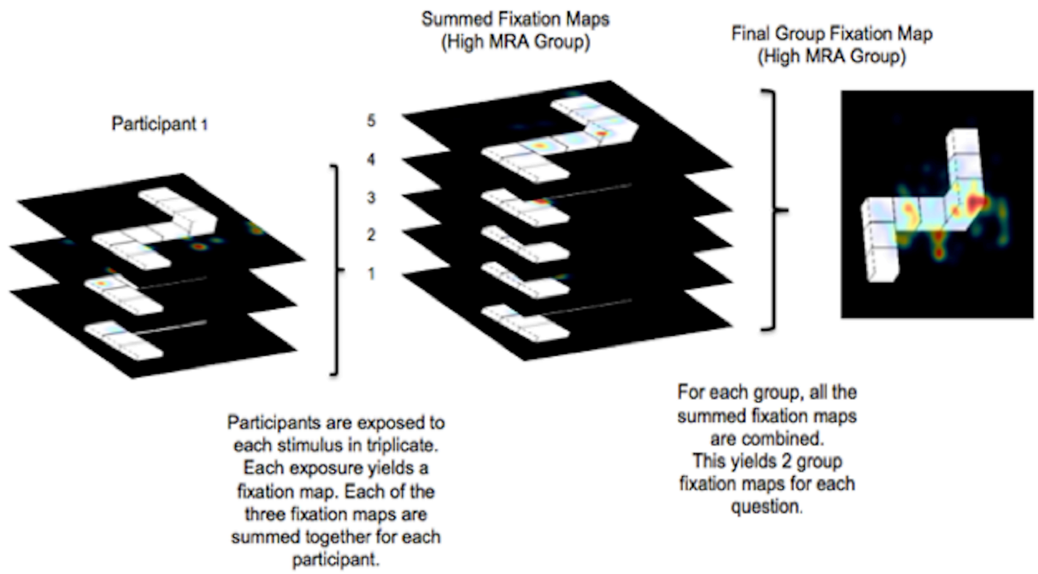
The design and execution of the EMRT is based on the original line drawings of Shepard and Metzler, used to test Mental Rotations Ability. Unlike the original question battery used by Shepard and Metzler, which was composed of a large number of block pairs, and presented as a paper and pencil test, the adapted EMRT consists of sixteen unique block pairs that were each presented three times throughout the course of the test with the presentation order randomized for each participant. This adaptation yielded a total of forty-eight image presentations per participant. Both the original Shepard and Metzler question battery, and the EMRT held the same proportion of "same" and "different" questions, where fifty percent of questions were of the "same" condition and fifty percent were of the "different" condition.

The EMRT was selected for this study, over other tests of mental rotations for its clarity and ease of use in the context of eye tracking. The observational task requires a comparison of only two images making analysis according to region of salience more feasible, unlike the case of the Vandenberg and Kuse MRT, which requires the comparison of a target image and four possible answers. Within the original 16 unique images, the angular disparity between each block pair was varied across these two unique

3D objects. Angular disparity was increased in twenty-degree clockwise increments, from twenty to eighty degrees. Participants' time performing the test battery was recorded, but no time limit was applied to ensure that each participant was exposed to the full battery of EMRT questions.

The use of eye tracking enabled the quantification of individuals' gaze locations during the presentation of each of the 16 block pairs. Salience maps for the right and left block for each image were created for each participant using a Gaussian distribution to represent visual acuity[34]. The magnitude of each resulting Gaussian was scaled by the fixation duration resulting in a salience map for each trial that represented both the spatial distribution of fixations and the relative durations. Each trial salience map was then normalized to the magnitude of the Region of Highest Salience (the peak representing the combination of both spatial attention and duration) for that trial. Normalized maps for each image were combined to produce overall visual salience maps for high and low spatial groups (Figure 7).

A



B

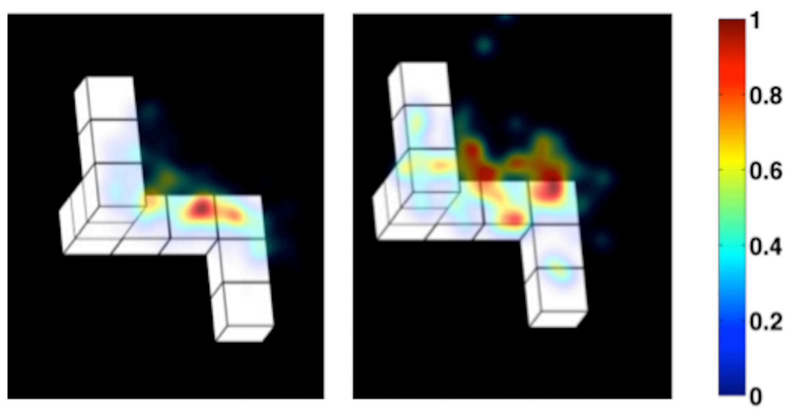


Figure 7: A schematic representing the creation of salience maps. A, A representation of the protocol employed to interpret spatial data employing the summation of individual fixation maps to the development of a group level heat map; B, The dichotomy between high and low MRA group heat maps indicative of the position of highest salience. High MRA, on the left, fixate predominantly on one

location and on little else; while Low MRA on the right attend to several points of interest. The color bar indicates the salience of the region, where red (1) represents areas of highest salience, and blue (0) represents areas of lowest salience in arbitrary units

The region of highest saliency occurring on each heat map was then compared between groups according to location. Six location-based categories for the region of highest saliency were created ad hoc based on the features of the blocks (Figure 8). This identification system served to enable the classification of which regions of the blocks drew the most attention, or spatial salience, from the participants during the problem-solving process. The areas colored red represent the most attended region of the image, and are indicative of the highest salience across the group.

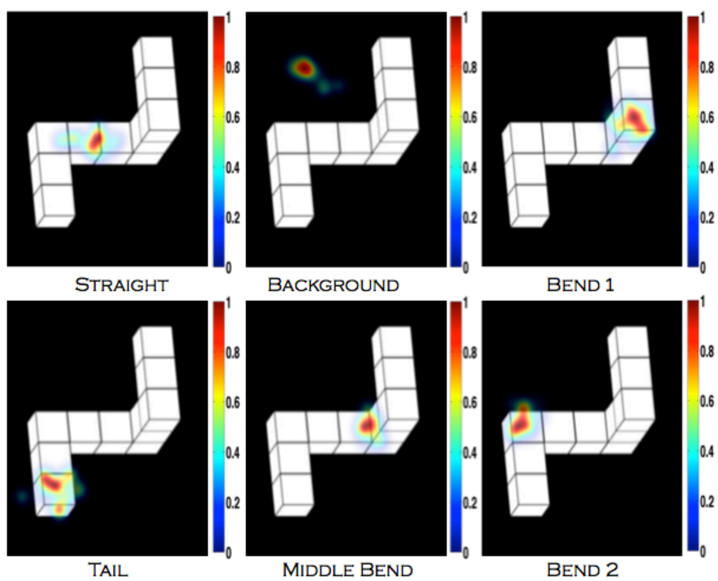


Figure 8: A representation of the six categorizations for the location of highest spatial salience, scales to right of diagrams are arbitrary units.

Data Analysis

As eye tracking yields eye movement metrics in the form of both gaze time and location, the data analysis is separated accordingly.

Temporal Analysis. The collection of eye movement metrics facilitated a correlational analysis of MRA score with average fixation duration, question response time, and number of fixations per question. Additional comparisons in terms of response times for correct and incorrect answers for all participants were also conducted by way of the paired Student t-test.

Analysis of Salience: The location-based classification of highest saliency facilitated a between group comparison across each category by frequency using the non-parametric Fisher Exact test. This test was employed as the Fisher Exact Test is robust to smaller sample sizes, and is specific to categorical data [35–37], such as the locations employed for our salience metrics. An additional comparison of question-by-question agreement was then conducted using Cohen's kappa to determine how often the two groups attended to the same location on a given question[38].

For all analysis, a significance value of less than $p = 0.05$ was considered to be statistically significant.

3.3 Results

Mental rotation ability as defined by the electronic mental rotations test

Twenty-three individuals participated in the study. The mean age of participants was 25±5 years (M/F: 26±6 / 25±5). Participants with EMRT scores exceeding one standard deviation above the mean (scores in excess of 44/48) were classified as high MRA (M: F; 1:4), and those with EMRT scores less than one standard deviation below the mean (Scores of 34/48 or less) were classified as low MRA (M: F; 2:3). All other individuals who demonstrated scores within one standard deviation of the mean in either direction were classified as intermediate MRA (M:F; 4:9)[33].

The electronic mental rotations test and the Inclusion of the low mental rotation ability group

In studies of performance, often only the individuals of the highest performance ability are studied, and used as exemplars for the behavior[31]. However, as the goal of this experiment, and of many other studies of mental rotation ability[5,13,18,31,33,39,40], was to discern how high and low MRA individuals differ behaviorally and how it may affect performance, it was prudent to include this low ability group of individuals.

This methodology has received scrutiny, as the EMRT is considered a “2-Alternate Forced Choice” or 2-AFC test, in which the participant must make a selection of “same” or “different” when presented with a question[41]. On 2-AFC tests, a score of less than fifty percent is indicative of a failure to complete the test, as the score is no better than that incurred by guessing, or by chance[42]. As some of the participants populating the low MRA group demonstrated scores approaching fifty percent, further investigation was conducted to ensure that the group performance was indeed different from that expected by chance. That is, evidence was required to ensure that the low MRA group was relying on their limited ability to reason spatially, rather than “guessing” on each question. A Binomial Test[43] was performed to reach this end, and it was found that the individuals of the Low MRA group were performing higher than that expected by chance; low group (0.65) was higher than that expected by chance (0.5), $p = 0.03$ (1-sided). This finding confirmed that the group was not guessing as they completed the test, and re-affirmed our inclusion of the data derived from the Low MRA group. This finding was critical to the current study, as these individuals show significant shortcomings during the completion of these spatial tasks; shortcomings which could be further exemplified through additional experimentation. If additional differences can be observed between high and how individuals, these differences may be capitalized upon to develop a guided approach to spatial problem solving for the low MRA individuals.

Temporal Measurements

To better understand the relationship between temporal eye movements during the completion of the EMRT, this study first conducted an investigation to discern if differences existed for these variables (average fixation duration, question response time and number of fixations) based on whether the question was answered correctly or incorrectly. This was achieved through a paired Student's t-test, in which each participant's correct and incorrect mean values were contrasted. No significant differences were observed for the incorrect and correct answers for the measures of average fixation duration and number of fixations; but there were differences observed for response time, which aligns with the findings of MRA and response time (Figure 9).

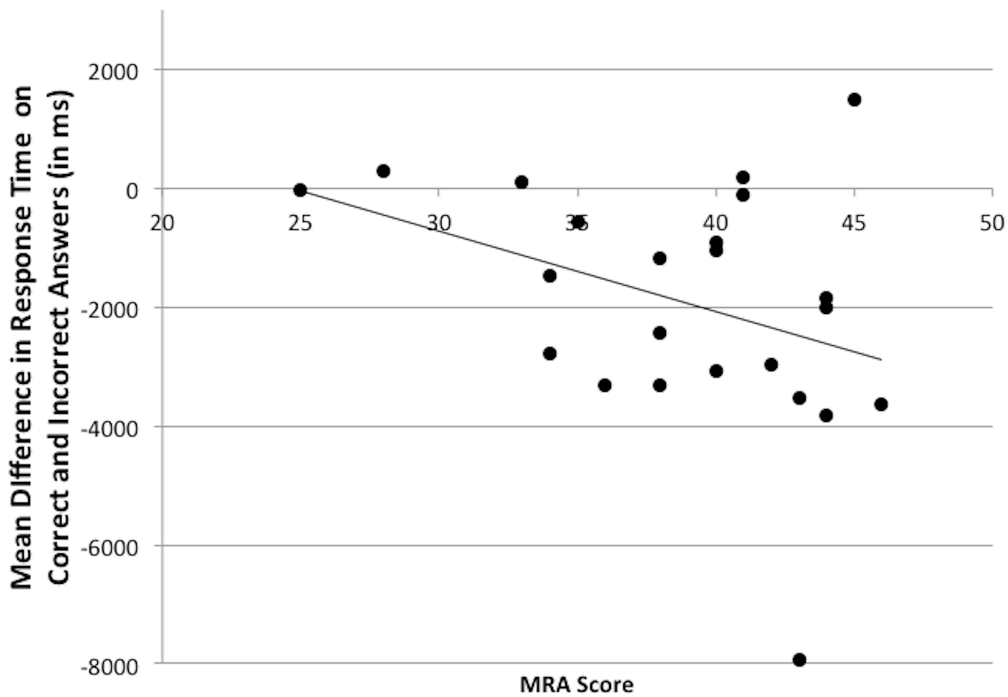


Figure 9: The relationship between MRA score and the mean difference of response time for questions answered correctly and incorrectly. High MRA individuals dedicate more time to incorrect answers, and less time to correct answers than low MRA individuals do, thus creating a larger mean difference.

Additional analysis with regard to MRA score and the duration of time dedicated to question solving were conducted. A Pearson correlation was employed to elucidate this relationship, (r = - 0.35, n = 23, p = 0.044). Individuals of high MRA showed a greater mean difference between response times dedicated to correct and incorrect answers (Figure 9). This finding suggests that during the process of solving a given question, individuals of high MRA will dedicate more time to solving a question they perceive to be challenging than a low MRA individual would.

Additionally, an investigation into the hypothesized relationship between the temporal variables and MRA score was conducted by way of a correlational analysis. A Pearson correlation showed no significant relationship between average fixation duration (r = 0.16, n = 23, p = 0.457), number of fixations (r = 0.17, n = 23, p = 0.445) and response time (r = 0.26, n = 23, p = 0.228) with MRA.

An additional Pearson correlation was employed using within-participants standard deviations to elucidate any intra-participant differences that exist between the temporal variables and MRA. This approach is commonly employed in physical task performance analyses to elucidate patterns of variability between groups, to demonstrate consistent performance on a given task, such as reaching or grasping[44–46]. In this case, the within-participant analysis of individual variance was completed in effort to observe how consistent individuals of high and low MRA were (in terms of response time) as they completed all 48 questions. This was achieved through analysis of the intra-participant standard deviations for each of the variables, for each participant. The within-participant standard deviations, when correlated with MRA, demonstrate a significant positive correlation between individual question response time variability and MRA (r = 0.49, n = 23, p = 0.018). No other correlations were observed between the within-participant variation of the other two variables of interest and MRA scores (average fixation duration: r = 0.09, n = 23, p = 0.699) and number of fixations (r = 0.32, n = 23, p = 0.128).

Salience Measurements

In order to address the second aim of this study, to determine where individuals of high and low MRA attend on the images during spatial reasoning, only the five highest, and five lowest scoring individuals' eye movement metrics were analyzed (n = 10). Each block pair question was sub-divided into right and left side blocks and fixation maps were generated for comparison. The regions of greatest saliency were calculated based on the combined group fixation maps, and contrasted per question (Figure 7A). The analysis indicated that the parts of the image with the highest salience occur in the same frequency for both groups, overall (Figure 10).

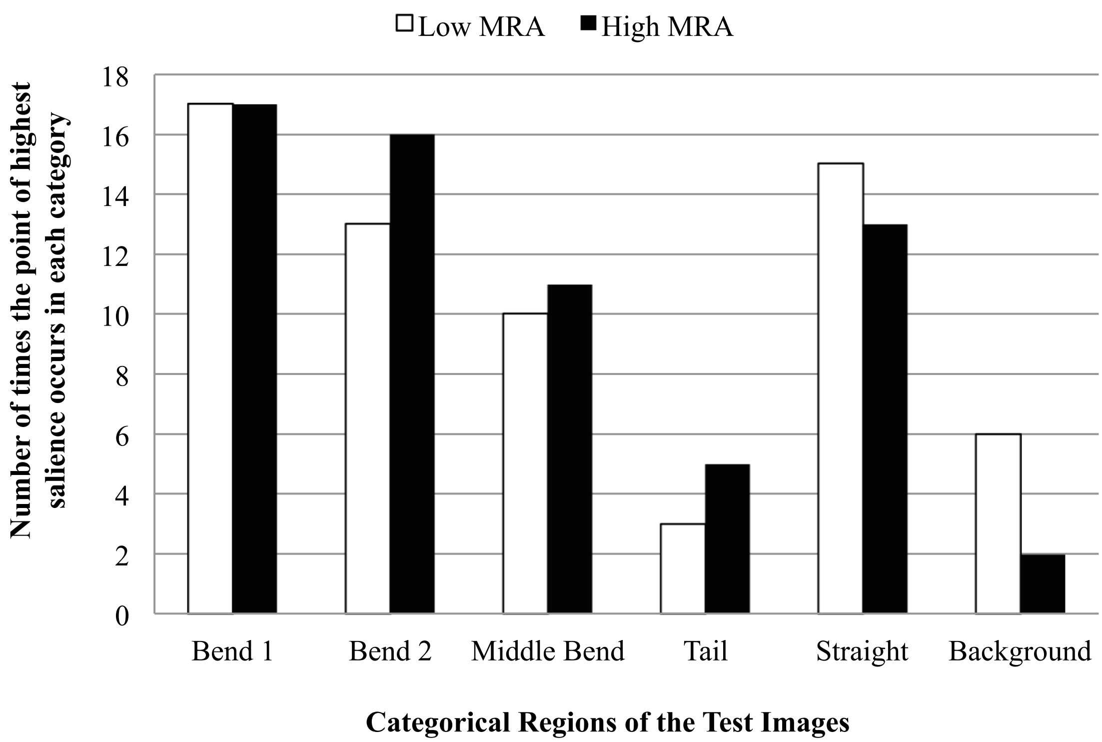


Figure 10: The frequency distribution of highest saliency by region, for both high and low groups. No significant difference between the two groups was observed, suggesting that the groups attend to the regions in the same proportion.

However, when a question-by-question analysis was completed to establish the agreement between the two groups, it was observed that in sixty-five percent of questions, the region of highest salience was different (K = 0.21). Indeed, the two groups attend to the same region on a given question only thirty-five percent of the time, representing a poor agreement between the two groups. That is, the timing of when and where high and low MRA subjects attended differed significantly on a question-by-question basis.

3.4 Discussion

This study correlated measurements of eye movements to mental rotations ability in an effort to distinguish if gaze patterns are associated with successful completion of a mental rotation test. In previous studies, individuals with higher mental rotation abilities (MRA) completed the original Shepard and Metzler test questions[15] faster, and with fewer errors than low MRA individuals[31] thus, it was hypothesized that MRA would be negatively correlated with average fixation duration, average response time and number of fixations. Additionally, it was predicted that MRA would be positively correlated with higher average fixation duration in spatially salient regions of the block image pairs of the electronic test of mental rotations (EMRT).

Through the observation and quantification of the eye movements of high and low MRA individuals, it was thought that a greater understanding of the processes that lend to success on spatial tasks could be revealed. The findings of this analysis are two-fold as the first half pertains to temporal measurements (average fixation duration, question response time and number of fixations), to distinguish how low and high MRA individuals differ temporally during the EMRT. The second half of analysis focuses on spatial information pertaining to both the duration of time and location individuals dedicate to salient regions of the presented images on the EMRT.

Temporal Measurements

From a temporal perspective with this untimed test, there appears to be a considerable lack of distinction between the high and low MRA individuals with regard to overall time to complete the EMRT. Closer examination of eye movements reveals the relationship between average fixation duration and EMRT score ($r = 0.16$) and trial response time and EMRT score ($r = 0.26$). These findings suggest that, when unencumbered by a time limit, individuals of high MRA tend to spend more time in fixation, and spend more time in answering overall, than individuals of low MRA. These findings are not mirrored in the findings of number of fixations per question, however, as there is no apparently relationship between the number of fixations per question and overall EMRT performance (r=0.17). Given that fixation is related to cognitive processing[22,23], results of the current study suggest that individuals of high MRA tend to spend more time assessing spatially salient features of the blocks on average, than their low MRA peers. It is hypothesized that the high MRA individuals implement these features to assist in correctly identifying if the block pairs are the same or different. However, the lack of significant correlational relationships between the time-related measures and MRA score encouraged a subsequent within participants comparison, to elucidate patterns in variability that are specific to high and low MRA individuals.

The within-participant analysis of variability for each of the time-related measures, coupled with the mean difference analysis of response time for correct and incorrect answers was more descriptive in establishing a dichotomy between high and low MRA individuals. Despite the observation of very little relationship between AFD variability and variability in the number of fixations, there was a significant relationship between response time variability and MRA score ($r = 0.49$, $n = 23$, $p = 0.018$), and between mean difference in response time for the ratio of correct/incorrect answers and MRA score ($r = -0.36$, $n = 23$, $p = 0.044$). This finding suggests that individuals of high MRA demonstrate much more variability in response time throughout the course of the EMRT while low MRA individuals are more rigid in their response times, answering each question after approximately 5 seconds regardless of the inherent visual properties of the question. This may be evidence of the phenomenon known as “learned helplessness”, that are typically associated with lower echelon performance. Learned helplessness is a phenomenon in which an individual establishes that the outcome associated with a response to a task is unpredictable, and becomes debilitated and unable to complete the task[47]. In this study, low MRA individuals may have been confronted with questions they perceived as very challenging, perhaps overwhelming their visual working memory, and rushed to an answer, rather than taking the required time required to solve it[48]

Although indirect, these observations may indicate an increased working memory capacity for individuals possessing higher MRA[49]. Much of the literature on performance and training suggests that with increased proficiency comes reduced variability, and improved consistency[50]. The current data suggest that the consistency of average response time in questions in reflective of flexibility in underlying cognitive functions, and that additional factors are at play when high MRA individuals completed this test. That is, greater variability observed in high MRA individuals may relate to increased flexibility in underlying cognitive processing linked to increased working memory. For example, the observation of high variability of response times in the high MRA group may be representative of enhanced conflict monitoring. The conflict hypothesis posits that monitoring of response conflict may serve as a signal that activates control mechanisms required to overcome conflict and perform effectively[51]. The conflict hypothesis suggests that behavioral adjustments and the engagement of cognitive control follow exposure to a response conflict. Thus, differences in response time are attributable to the high level of conflict associated with "incongruent" (or "different") questions, that yield a greater recruitment of cognitive control and attention for the following question[51].The act of conflict monitoring, and sub-consciously devoting more time to more challenging questions may be responsible for the dichotomy of performance between our two groups.

Salience Measurements

Secondary to the analysis of the time-related measurements associated with EMRT completion, this study also set forth to discern the relationship between MRA and regional apprehension patterns during test completion. The analysis of the regions of visual salience provided perspective into apprehension approaches typical to both high and low MRA individuals. The results demonstrated that across the entire EMRT, both groups attend to features of the blocks at approximately the same frequency. However, as this measure only refers to the overall distribution of the regions of highest salience, little information can be garnered as to how the two groups behave on a question-by-question basis. Individuals with higher spatial ability may demonstrate different visual search patterns compared to lower spatially able individuals[52]. This may also be the direct result of limitations of working memory in the low MRA group[49]; which could influence a more dispersed, less focal, searching of the images for comparison, due to their reduced ability to hold an exemplar image in one's working memory during the process of spatial reasoning[53] (Figure 7B).

The difference in approach between the two groups is further illustrated through the application of the Cohen's kappa coefficient to evaluate the agreement between them. Through this analysis, it was possible to observe the likelihood of the two groups attending to the same location on a given question[38] was quite low. High and low MRA individuals attended to the same location on a given question only thirty-five percent of the time. This dichotomy of visual apprehension between high and low groups is mirrored in the work of others who contrasted the visual search patterns of novice and expert laparoscopists[54] and experience with images in anatomy students[8]. In these paradigms expert laparoscopists directed their gaze to very specific regions of a visual familiar surgical scene, while novices directed their gaze non-specifically over a broad range of visual areas without apparent direction or focus[55]. In the student population, as familiarity grew students attended to "cognitively salient regions" with more fixations and longer observation times overall.

If individuals of high and low MRA approach or "view" identical images in different ways, and reach different conclusions, then eye movement data-driven approaches and gaze-directed instructional methods may present an opportunity for education[56,57]. In domains of high spatial complexity such as anatomy, informing low MRA populations where and when to "look" during task completion could serve to improve their spatial reasoning and potentially improve task performance overall [57,58]. The data derived from this study also lends indirect support to Vorstenbosch's suggestions that using images on anatomical examination changes the item difficulty and may jeopardize the validity of the assessment itself [59]. Implications of our current study suggest persons with widely differing spatial ability approach spatially challenging questions quite differently. Furthermore, high and low MRA participants shared common approaches only 35% of the time further indicating differing strategies linked to spatial ability that significantly affects performance on an anatomical task[19]. Whether a strategy is related purely to sensory input, that is gaze alone, or other factors potentially related to memory, is yet to be determined, but the current study suggests gaze to be a significant contributing factor.

Limitations

Unlike other research evaluating MRA, this study did not limit the duration of time that individuals were permitted to complete the EMRT. This approach was employed to ensure that all participants gained exposure to all of the image pair stimuli. This decision may have served to limit this study as the speed of problem solving may be a factor predicting success on tests of mental rotations[19,60,61]. Without the pressure of a temporal "cut-off", participants of all levels of MRA may have spent a greater duration of time deciphering the image pairs, and "double-checking" their choice prior to answering. In fact, this study observed that without a cut-off time, participants spent up to twenty times longer per question than that typically observed in timed tests of mental rotations.

The paradigm employed image replication in order to decrease variability in the temporal eye metrics. Each image pair was presented in triplicate, a decline in duration required to solve the question on each subsequent presentation may have occurred. Thus, individuals may have been reliant on recollections of previous answers, rather than on active spatial reasoning to solve the problems. Theoretically, this could thus yield shorter response times for each subsequent viewing, and hearken more to the participants working memory capacity than their abilities. However, this theory was not supported empirically in the data obtained from this study.

Further, this study may have been limited by the angular disparity of the block pairs. Literature suggests that question difficulty increases proportionally with increasing angular disparity[17]. As such, it is possible that the level of angular disparity did not adequately challenge participants of either spatial ability, and may account for the lack of clear distinction between the two groups.

Finally, the current study may have been limited by sample size. As the analysis of salience was conducted on data derived from a subset of the overall sample, there is a possibility that greater differences may have been observed if a larger sample size was examined.

Future studies should seek to examine if similar patterns exist in time-sensitive environments that are more reflective of traditional MRTs and typical assessment in anatomy and the STEMM disciplines. The application of a time-limitation may serve to exacerbate the dichotomy between the high and low MRA individuals, compelling participants to rely on their innate cognitive abilities relating to speeded rotation, rather than on potential strategy. Such a modification would likely yield lower average MRA scores, and a reduction of the positive kurtosis noted in the scores of this study [62].

Future Directions

The current approach explores a previously unaddressed participant-centered, eye movement-based, approach to analyzing spatial test completion. The implications of future research along this trajectory may inform eye movement guided strategies for the instruction of spatially relevant information [57], and possibly extend to spatially complex disciplines including, but not limited to anatomical sciences, surgical skill training, and other science, technology, engineering, medical and mathematical (STEMM) disciplines.

The findings of the current study suggest further analysis under the constraint of a time limitation and perhaps with a greater number of visual elements, to better understand the role that eye movements play during spatial reasoning. Additionally, as the current work delves into the underlying mechanisms that govern spatial reasoning, future work aims to better illustrate the complex cognitive processes, such as conflict monitoring, that underpin the innate aptitudes for success in mental rotations. If additional differences can be observed between high and how individuals, these differences may be capitalized upon to develop a guided approach to spatial problem solving for the low MRA individuals.

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Chapter 4

4 Eye Movements During Timed Tests of Mental Rotation Ability

4.1 Introduction

The term "spatial ability" is often used to describe an individual's aptitude for interpreting three-dimensional relationships in space[1]. A prevalent topic in cognitive psychology for decades, work has sought to explore not only spatial ability itself, but its related sub-skills, spatial visualization, orientation, and relations[2]. Spatial relations, often referred to more generally as mental rotation ability (MRA)[3,4], is the ability to translate an object about an axis, while recognizing that it is the same from any perspective[5]. Spatial ability has drawn particular attention due to its numerous linkages to success in technical skill acquisition[6–8], knowledge acquisition[9,10], and performance in the STEM (Science, Technology, Engineering and Mathematics) disciplines[11–13]. Recent literature on spatial ability has suggested that spatial ability may serve as a robust predictor for success in the STEM fields[14], and recommends that efforts be taken to possibly train spatial ability in those who lack aptitude for the cognitive skill. Research in cognitive psychology has sought to investigate the neural processes that underlie MRA, yet conclusive answers have yet to be determined[15]. One hypothesis suggests that mental rotation may be intrinsically linked to the movements of the eye, as fixations (maintaining visual gaze on a single location)[16] are intimately involved in our ability to visually encode spatially distributed information[17,18]. With this considered, the fixations of the eye may represent overt human behavior linked to cognitive stages (i.e., search, transformation and comparison, and confirmation) that occur as visual information is processed[17].

In a pioneering study, Just and Carpenter explored how average response time related to spatial reasoning. Under their paradigm, significant differences in average response time of individuals of high (H) and low (L) MRA were identified using simulations[19], derived from samples of participants completing a test of Cube Comparisons[20], originally a component of the Primary Mental Abilities Battery[21]. On average, LMRA individuals exhibited longer trial response times. However, the results obtained by Just and Carpenter were in contrast with the results observed in “Chapter 3: The Untimed Experiment”, where a similar test of mental rotation ability (the EMRT), was employed in an untimed condition. The results of the Untimed Experiment found little relationship between most chronological (average response time) and numeric (number of fixations per question) measures of eye movement and MRA; but upon conducting an analysis of salience, found wide differences between the H and LMRA groups.

Salience, in this context, can be defined as a quality held by a region of an image, that through perceptual characteristics, makes it conspicuous relative to its surroundings[22]. In the Untimed Experiment, spatially salient regions referred to structures of the stimuli that conveyed depth and positional information that may have been critical to completion of the untimed EMRT. However, despite studies evaluating the behavior of H and LMRA individuals in untimed environments, little is known about how individual eye movement behaviors differ in time-restricted, or speeded environments, like those typically used to quantify MRA.

Typically, mental rotation ability is measured by performance on timed, standardized tests of mental rotations, such as tests employing the line-images of Shepard and Metzler [5] and the Vandenberg and Kuse Mental Rotations Test (VKMRT)[23,24]. Both types of tests are commonly employed to stratify individuals as either high, intermediate or low MRA based on their individual score[25] and have served to facilitate comparisons between groups according to their underlying spatial ability[9,19]. Investigations into participant accuracy on timed tests of spatial reasoning have reported that individuals who score higher on tests of mental rotation ability do so in less time, and with greater accuracy than those with lower spatial ability[26]. With this considered, if accuracy and response time are implicated differently across levels of MRA in speeded testing environments, how might these findings manifest in the movements of the eyes during the completion of a speeded test of MRA?

The current study explores how specific eye movements relate to mental rotation ability (MRA) during the completion of a timed electronic test of mental rotations (Timed EMRT). More specifically, the study aims to investigate the chrononumeric and salience patterns associated with accurately completing mental rotation tasks. In this instance, the term “chrononumeric” refers to a group of eye-related, and performance-related measures collected during the completion of the Timed EMRT, (including the average number of fixations per question, average response time, and average fixation duration that were selected as indices of performance that represent individual behaviour during completion of the test), wherein the term “fixation” refers to the maintenance of gaze on a single point for a period of time exceeding 200 milliseconds. As this overarching aim is composed of two distinct, yet related components (chrononumeric and salience measures), they will be addressed separately in the interest of clarity.

1: Relating chrononumeric patterns to mental rotation ability

Through analysis of the chrononumeric data collected from participants during the completion of the Timed EMRT, the current study aims to identify how the chrononumeric metrics relate to MRA score. More specifically, the current study aims to ascertain how average fixation duration, average response time and average fixations per question each relate to MRA score. Additionally, the current study also seeks to identify how the accuracy of an individual’s answer impacts their average fixation duration, average response time, and average fixations per question. It is predicted that each chrononumeric metric relates to MRA in a different way and varies according to the accuracy of an individual’s answer. It is hypothesized that average fixation duration will be shorter for HMRA individuals than for LMRA individuals, and it is expected that average fixation duration will be equivalent across both correct and incorrect answers. Like average fixation duration, it is expected that average response time will also be shorter for HMRA individuals than for LMRA individuals, but average response time will differ according to accuracy; being shorter on correct answers, than on incorrect answers. Finally, it is predicted that the average fixations per question will be consistent across both MRA groups, and equivalent across both correct and incorrect answers.

2: Relating salience patterns to mental rotations ability

As video-based corneal reflection eye tracking also yields spatiotemporal data during the performance of the Timed EMRT, the current study aims to ascertain if the attention directed to particular regions of spatial salience is contingent on MRA. That is, do individuals of different MRA look at different areas of images while problem solving? It is predicted that the regions of spatial salience will differ between the two groups, as measured by the Fisher Exact Test, illustrating that the two groups attend to different structures during spatial problem solving.

4.2 Materials & Methods

Participants*:* Participants were who were volunteer graduate students in the allied health sciences and anatomy and cell biology at The University of Western Ontario with normal, or corrected to normal vision by way of contact lenses, were invited to participate under approval from the institution's Research Ethics Board. Individuals (n = 10; 5 M and 5 F) first completed an electronic standardized test of Mental Rotations Ability, the Vandenberg and Kuse Mental Rotations Test (VKMRT)[23,24]. Individuals with VKMRT scores exceeding one standard deviation above the sample mean were considered to be HMRA (n = 5; 1F and 4 M), and those with VKMRT scores less than one standard deviation below the sample mean were considered to be LMRA (n = 5; 4 F and 1 M). All other individuals who demonstrated scores within one standard deviation of the sample mean in either direction were considered to have intermediate MRA, and were not included in this study. The division into H and LMRA groups was adopted, rather than a median split, to exacerbate the distinction between HMRA and LMRA individuals[9,19,27].

Experimental Design: Participants completed the electronic Timed EMRT (defined as a maximum exposure time of six seconds per question) while monocular (right eye) gaze was monitored. Measurements of gaze were obtained according to the specifications detailed in the Untimed Experiment. All measurements were collected at a rate of 1000 Hz using eye-tracking equipment (EyeLink 1000-SR Research, Mississauga, Canada). Chrononumeric metrics consisting of average fixation duration, average number of fixations per question, and average response time were collected, along with the region of highest salience. Target images were viewed from a distance of 40 cm, such that each figure subtended approximately 10 degrees of visual angle, and the center-to-center distance between the two figures subtended approximately 15 degrees. Ambient light conditions were kept constant in the testing room at all times.

Target Images: The target images presented to the participants constituted a timed electronic Mental Rotations Test (Timed EMRT) based on the original line drawings of Shepherd and Metzler, and used previously in the Untimed Experiment. This visual test required participants to view two 3D block figures (a "block pair"), and indicate if the pair was the same, or different by responding using two keys on the keyboard as quickly, and accurately as possible. A button-press of "1" indicated a "same" pair, while a "2" indicated a "different" pair. In the timed iteration of the EMRT, each participant had six seconds to respond to a given stimulus. If the participant did not answer, they would be automatically advanced to the next question. This time pressure would serve to encourage quick mental rotation, in line with other standard mental rotation tests.

The use of eye tracking enabled the quantification of eye movements during the presentation of each question's block pair. Individual fixation maps for the right and left block image were created for each participant for all images in the EMRT. By tracking the position of a participant's eye during EMRT performance, information pertaining to the participant's locus of attention on the image could be recorded. This information was assorted visually, as a fixation map, where each point of fixation was overlaid onto the presented image. The fixation maps were then transformed into salience maps by overlaying Gaussian distributions over each discrete fixation to represent visual acuity[28]. The spread of the Gaussians were then scaled according to the duration of the fixations, effectively representing both the location, and time spent attending to the locations. The salience map was then normalized in magnitude based on the region of highest salience (the peak of duration and salience). Normalized maps for each image for each participant were then combined to yield mean group salience maps for comparison across H and LMRA.

Three observers served to classify the regions of highest salience into six location-based categories (ICC: 0.88) (Figure 11). This identification system served to classify which regions of the blocks had the greatest visual salience for participants during the problem-solving process. The areas colored red represent the most attended region of the image, and are indicative of the highest salience across the group.

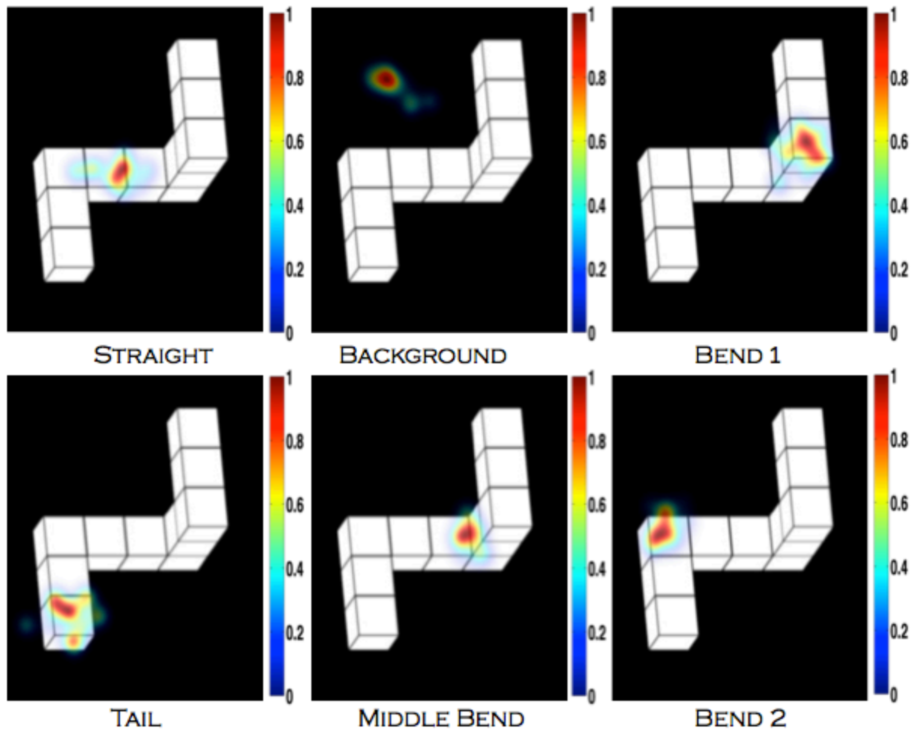

Figure 11: A diagrammatic representation of the 6 possible categorizations for the location of highest spatial salience. The areas colored red represent the most attended region of the image, and are indicative of the highest salience across the group.

Data Analysis

Chrononumeric Analysis: The analysis of the relationship between MRA score and accuracy (correct v. incorrect answers) with average fixation duration, question response time, and number of fixations per question was undertaken via 2x2 (MRA: HMRA or LMRA) x (Accuracy: Correct or Incorrect) Mixed ANOVA for each metric.

Analysis of Salience: The location-based categorization of salience facilitated a between-group comparison across each category by frequency using the Fisher Exact test[29]. This test was employed as the Fisher Exact Test is robust to small sample sizes, and is specific to categorical data, such as the locations employed for our salience metrics[29–31]. An additional comparison of question-by-question agreement was then conducted using Cohen's kappa to determine the how often the H and LMRA attended to the same location on a given question[32].

The EMRT and The Inclusion of the Low MRA Group

Often in studies of performance, individuals of the highest performance ability are studied and used as exemplars for the behavior[19]. However, as the goal of this study, and of many other studies of mental rotation ability[6,9,19,25,27,33,34], is to distinguish between the characteristics of HMRA and LMRA, it was necessary to include low functioning individuals in analysis.

The EMRT is classified as a 2-Alternate Forced Choice or 2-AFC test, where the participant must make a decision of "same" or "different" when presented with a question[35]. As some individuals in the LMRA group demonstrated EMRT scores approaching 50%, analysis to ensure that the individuals were actively engaged in the task, and not guessing (or scoring at the level of chance) was required. Analysis by way of the Binomial Test[36] was completed to investigate if the LMRA group was responding at the level of chance, and it was found that the individuals of the LMRA group were performing statistically higher than that expected by chance. The binomial test indicated that the proportion of correct answers obtained by the low group (0.58) was higher than that expected by chance (0.5), $p = 0.025^*$ (1-sided). The result of the binomial test confirmed that the LMRA group was not guessing as they completed the test, and re-affirmed our inclusion of the data derived from the LMRA group.

For all analysis, a significance value of less than $p=0.05$ was considered to be statistically significant.

4.3 Results

In effort to ensure that the Timed EMRT was a valid measure of MRA, the scores on the Timed EMRT were correlated with scores on the VKMRT. The relationship between Timed EMRT scores and VKMRT scores was significantly positive, as tested by a Pearson Correlation ($r = .77$, $n = 10$, $p = 0.009$) (Figure 12).

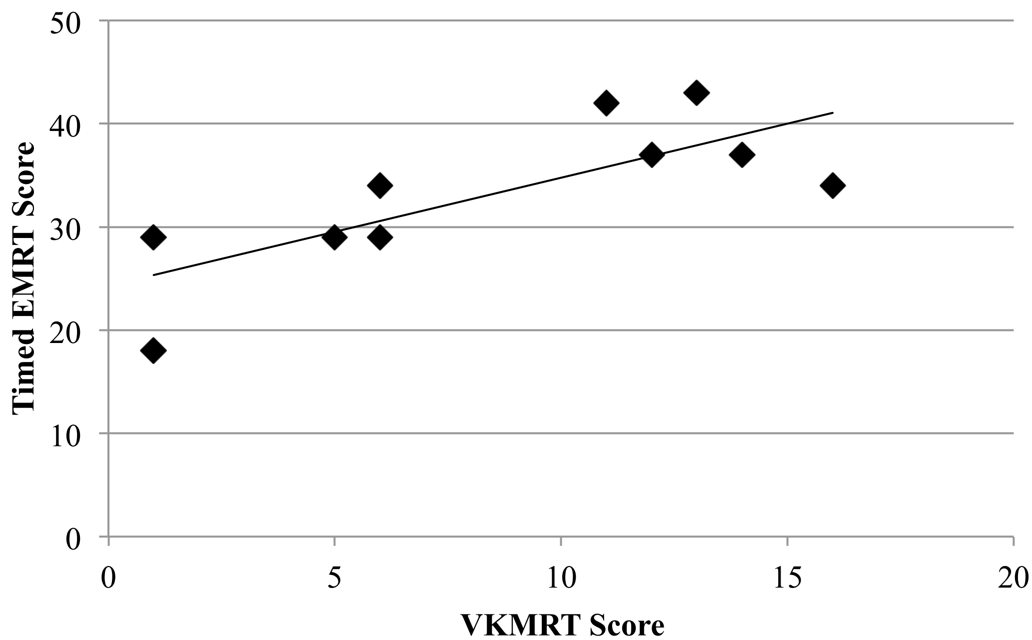

Figure 12: The relationship between Timed EMRT Scores, and VKMRT Scores, confirming the Timed EMRT as a valid measure of MRA. The maximum score is 24 on the VKMRT and 48 on the Timed EMRT.

1: Relating chrononumeric patterns to mental rotation ability

The average fixation duration (mean ± SD) of the HMRA group (223.24 ± 19.89 ms) was significantly shorter than the LMRA group (288.93 ± 46.18 ms) $F(1,8) = 7.99$ ($p = 0.022$) (Figure 13).

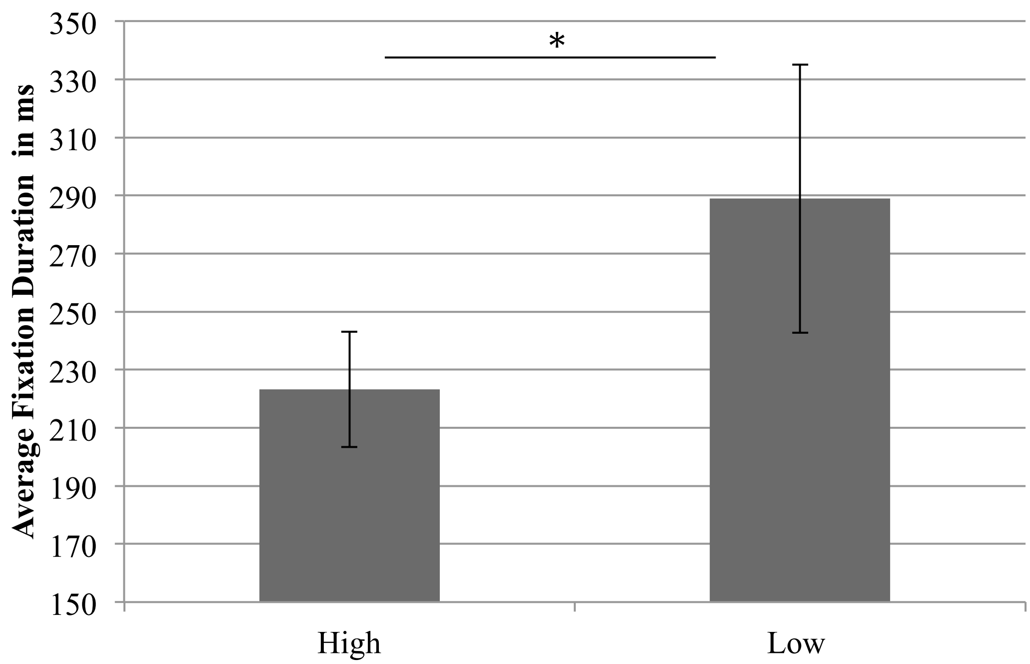

Figure 13: High MRA individuals conduct fixations that are quicker than those completed by LMRA individuals, on average, during spatial problem solving. Error bars indicate one standard deviation.

In addition to eye-related performance differences occurring between H and LMRA groups, the within-group differences occurring in average fixation duration when questions were answered correctly, or incorrectly were also of interest. In this case, average fixation duration did not differ significantly according to question accuracy, for either group $F(1,8) = 0.011$ ($p = 0.918$) (Partial η^2 : 0.001), (Figure 14)**.** The average fixation duration (mean ± 95% confidence interval) for HMRA on correctly answered questions (226.56 ± 4.91 ms), and incorrect questions (219.92 ± 4.91 ms), compared with the LMRA group's correct (285.10 ± 7.99 ms) and incorrect answers (292.75 ± 7.99 ms).

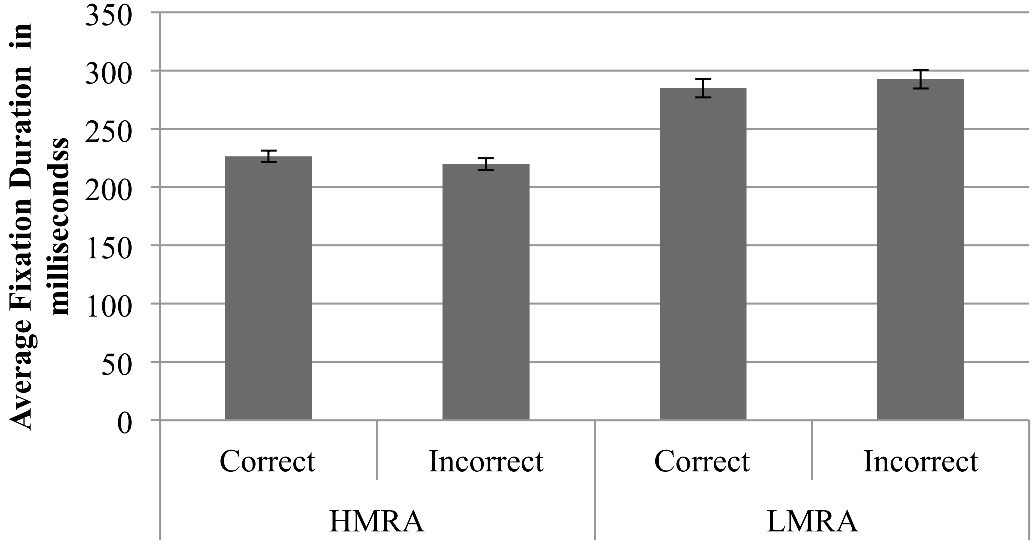

Figure 14: Average Fixation Duration is constant across different levels of accuracy for both MRA groups. Error bars indicate 95% confidence interval for within-group comparison.

Average response time was also analyzed in the same manner as average fixation duration, via 2x2 (MRA x Accuracy) Mixed ANOVA to discern both group and participant level differences. Both groups responded with approximately equivalent response times (mean ± SD), HMRA: 3706.46 ± 752.26 ms and LMRA: 4669.57 ± 872.82 ms, $F(1,8) = 4.82$ ($p = 0.059$) (Partial η^2: 0.376) (Figure 15).

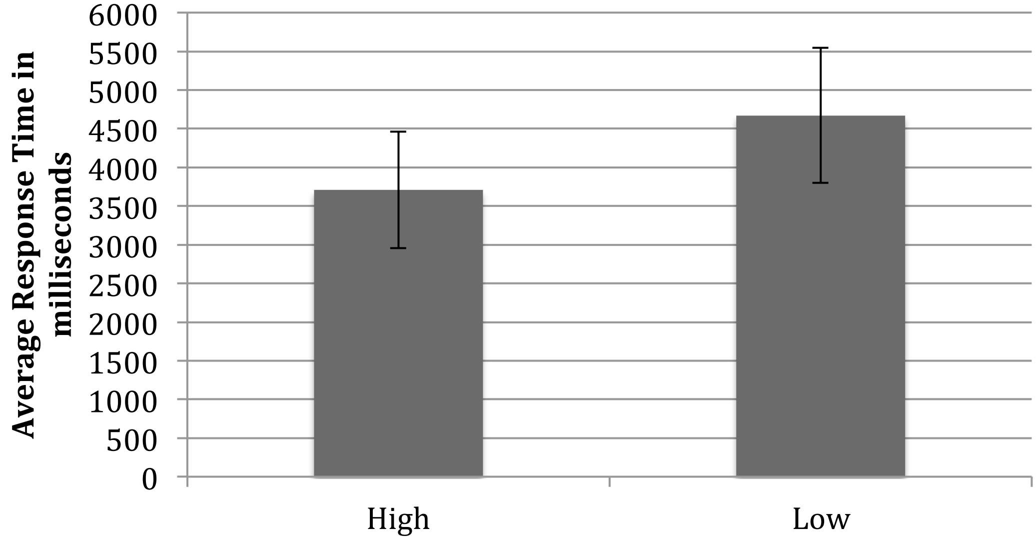

Figure 15: High and LMRA individuals exhibit equivalent response times on average. Error bars represent one standard deviation.

The within-group analysis of the average response times for both correct and incorrectly answered questions query if answer accuracy is reflected in shorter average response time. Correctly answered questions (mean ± 95% confidence interval) were found to be significantly briefer (HMRA: 3357.17 ± 163.66 ms, LMRA: 4224.83 ± 274.11 ms) than those questions answered incorrectly (HMRA: 4055.74 ± 163.66 ms, LMRA: 5114.31 ± 274.11 ms); $F(1,8) = 23.89$ ($p = 0.001$) (Partial $\eta^{2:}$: 0.749) (Figure 16).

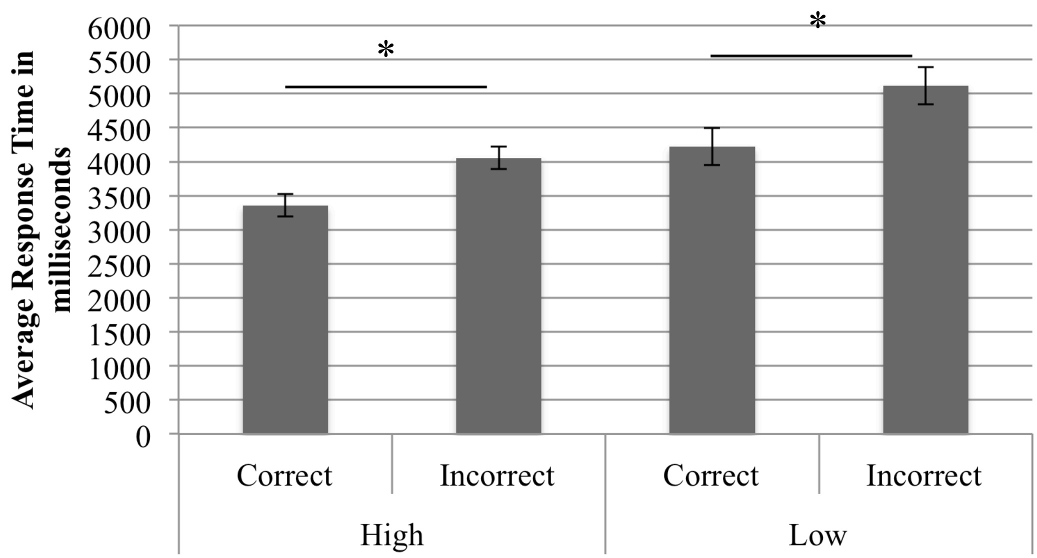

Figure 16: High and LMRA individuals show different response times based on accuracy. Error bars represent 95% Confidence Interval for within –group comparison.

The final eye movement related performance metric, average number of fixations per question, was also analyzed in the same manner as the previous two: via 2x2 (MRA x Accuracy) Mixed ANOVA to discern both group and participant level differences. Analysis suggests both MRA groups demonstrated equivalent average fixations per question (mean ± SD), (12.72 ± 2.99 and 14.27 ± 2.91) for H and LMRA respectively $F(1.8) = 0.853$ ($p= 0.383$) (Partial $\eta^{2:}$ 0.096) (Figure 17).

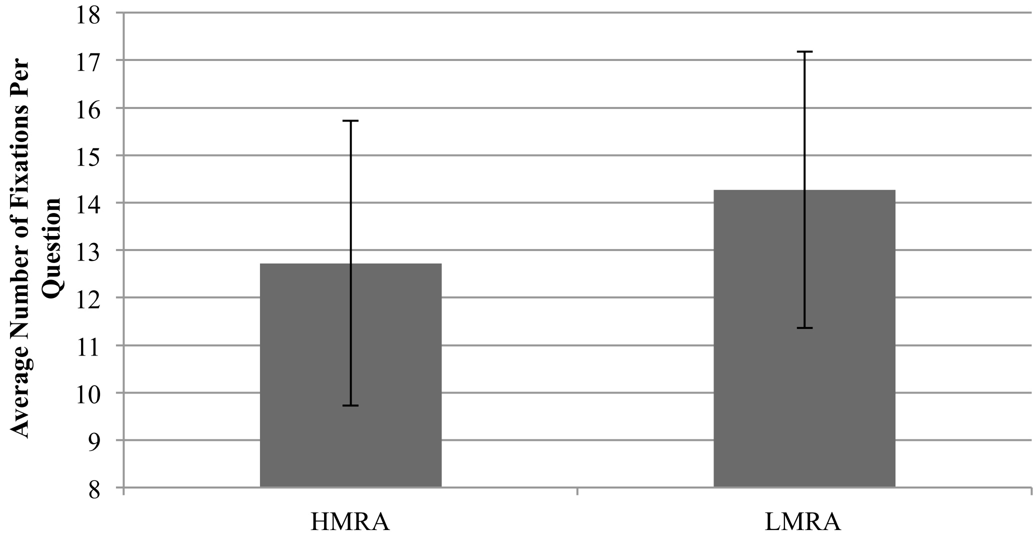

Figure 17: High and Low MRA Individuals are equivalent in terms of average number of fixations per question. Error bars represent one standard deviation.

With regard to the role that answer accuracy imparts on the average number of fixations per question, within-participant analysis was carried out to address the hypothesis that the average number of fixations per question is equivalent across both correct and incorrectly answered questions. However, analyses found that the average number of fixations per question of correctly answered questions (HMRA: 11.50 ± 0.65 and LMRA: 13.01± 0.94) was significantly lower than incorrectly answered questions (mean ± 95% confidence interval) (HMRA: 13.95 ± 0.65 and LMRA: 15.53 ± 0.94), F(1.8) = 18.12 (p=0.003) (Partial $\eta^{2:}$ 0.682) (Figure 18). The current results align with the aforementioned average response time results for accuracy, as with briefer overall response times, it is logical that fewer fixations may occur in a shorter time frame.

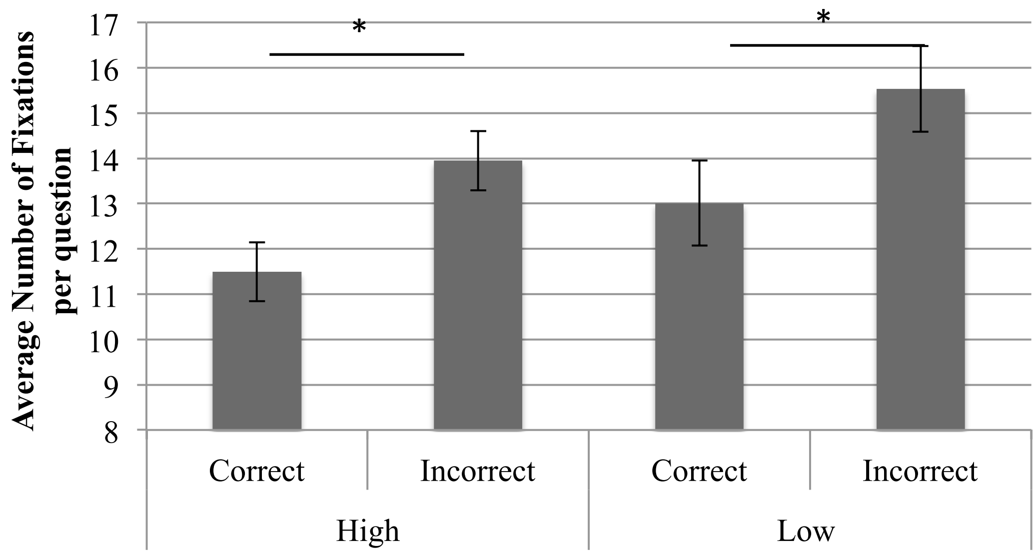

Figure 18: Correctly answered questions exhibit significantly fewer fixations per question than incorrectly answered questions. Error bars represent 95% confidence interval for within-group comparison.

2: Relating salience patterns to mental rotations ability

In addition to chrononumeric measures, the current experiment also sought to determine the level of attentional agreement for different regions of the target images according to spatial ability. A Fisher Exact Test distinguished the two groups based on the distribution across the six categories of salience (Fisher Exact Test: 12.47 (p = 0.018)) (Figure 19). The test suggests that H and LMRA individuals attended to different regions of salience at different frequencies. High MRA individuals attend preferentially to "Straight" regions, while LMRA individuals attend predominantly to "Bend 1" during problem solving.

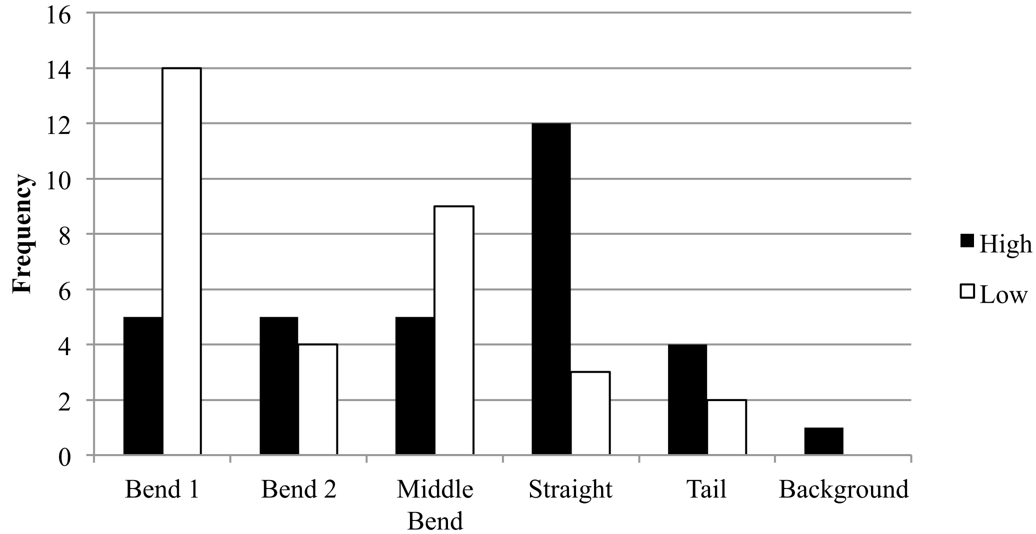

Figure 19: The dichotomy between High and Low frequencies across the categories of salience.

Further analysis was undertaken to establish a level of attentional agreement between HMRA and LMRA individuals on a question-by-question basis. Through application of Cohen's Kappa for Agreement, it was observed HMRA and LMRA individuals attended to the same region of salience ($\kappa = .20$) in only 34% of questions illustrating a poor agreement between the two groups[32] (Figure 20).

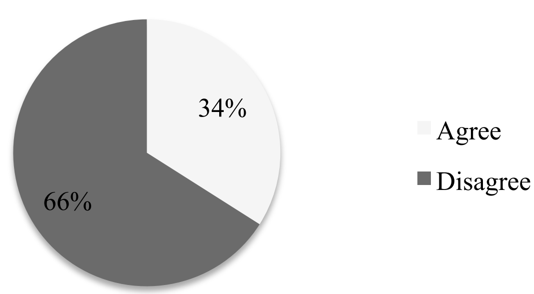

Figure 20: The two MRA Groups attend to the same salience category in only 34% of questions presented, illustrating a poor agreement on a question-by-question basis.

4.4 Discussion

Through correlational analyses, it was noted that a significant and strong positive relationship existed between individuals' EMRT and VKMRT scores; suggesting that scores obtained on the EMRT are an accurate representation of mental rotations ability. As a result, for applications requiring eye movement recording, it can be concluded that the timed EMRT provides a valid mechanism for the testing of MRA.

It was hypothesized that HMRA individuals would demonstrate shorter average fixation durations during problem solving. The average fixation duration of HMRA individuals was found to be significantly shorter than for LMRA individuals, suggesting that HMRA individuals are able to obtain information more quickly during visual tasks than LMRA. This finding is supported by literature that suggests that individuals of HMRA have a higher spatial working memory capacity, and are thus better equipped to hold spatial representations in their minds eye for comparison during problem solving[37–41]. Higher spatial working memory may enable quicker comparisons between the line structures and allow for a more consistently accurate problem solving process[42]. In terms of accuracy, average fixation duration was found to be consistent within both MRA groups regardless of answer accuracy, and in line with the findings of the results observed in Chapter 3, in an untimed environment. As a result, average fixation duration may be constant within individuals regardless of answer accuracy. However, whether the imposition of temporal limits caused a degradation of performance however, was beyond the design of the current study

As average fixation duration differs significantly across MRA groups, one could infer that this difference would also be manifest in the average response times and average number of fixations per question of the two groups. However in this experiment, no difference in average response time, or average number of fixations per question was noted between HMRA and LMRA. This findings lies in contrast to available literature on other tests of spatial reasoning, that suggest that apt individuals tend to perform spatial tasks with greater speed than those who struggle with spatial reasoning[26]. However, the same pattern of consistent average response time and average number of fixations per question across MRA groups was also presented in findings of Chapter 3. Indeed, when the same testing parameters (The EMRT) were employed without any time limits; both groups responded at approximately the same speed, and with the same number of fixations during problem solving, yet achieved different scores.

Further, the dichotomy of scores between the HMRA and LMRA individuals is not revealed when considering the accuracy of the question when evaluating the average response time and average number of fixations per question of individuals. For both groups, correctly answered questions were associated with significantly shorter response times, and significantly fewer fixations per question overall. Essentially, what can be inferred from these findings is that both groups complete the task in the same way. Questions that individuals answer correctly are done so quickly; while those that are not solved are puzzled over; directly supporting the findings observed in The Untimed Experiment under the untimed condition. Ultimately, the frequency with which the question is solved accurately is what represents the aptitude for spatial reasoning. If individuals differ fundamentally in average fixation duration, but not in terms of average response time and number of fixations, further inspection into the location of these fixations is warranted. Therefore, it is possible that where individuals direct their attention on spatial tasks may be more critical to success in problem solving, than the speed with which an individual views the stimulus.

It was hypothesized that HMRA and LMRA individuals would attend to different features of the EMRT while problem solving; potentially contributing to varied success on the task. Indeed, HMRA and LMRA individuals attended to different salient regions of the EMRT images. In fact, on a question-by-question basis, the two groups attended to the same location only 34% of the time. This finding suggests that although the individuals share similar average response times and fixation times within questions, differences between HMRA and LMRA exist as to where gaze is directed as they solve spatially complex problems. This observation suggests that there may be specific, task-relevant salient regions of spatially complex images, and that skill in identifying and attending to these areas is key to successful problem solving[43,44]. Furthermore, if specific salient regions are important to spatial reasoning, and are identifiable through salience maps, they may be translated as visual cues. These visual cues could be applied to train

LMRA individuals, direct their attention, and potentially improve their spatial reasoning skills through guidance.

Limitations

This study may have been limited by the use of repeated image pairs. By presenting each image pair in triplicate, there is a possibility that with each subsequent exposure, the participants could have experienced a familiarity with the exposure, and refer to previous conclusions. Thus, individuals may have been more reliant on short-term memory to solve the question, rather than actively reasoning spatially, or relying on their MRA. This effect could have thus influenced average response time and average number of fixations per question findings, and refer more to the individual's spatial working memory than to their MRA. However, as the test battery consisted of 16 unique image pairs, which were each visually similar (differing only by degree of rotation) and were assorted randomly to each participant, it is unlikely that memorization was employed. Finally, if some type of familiarity was detected by the participants they would still require some degree of MRA to correctly answer the question: that is, "Are the two presented blocks rotations of each other, or are they mirror images?"

Further, it is known that question difficulty increases with maximum angular disparity. As the EMRT employed increments of angular disparity only up to 80 degrees, it is possible that this test was not challenging enough to exacerbate substantial chrononumeric differences[17]. If greater degrees of disparity were employed across the test, it is possible that HMRA individuals would have solved the problems more quickly, and revealed group-wise differences on the test.

Additionally, this study may also have been limited by a small sample size. With each group consisting of only 5 individuals, it is possible that the lack of differences in average response time and average number of fixations per question may be the result of reduced statistical power. As a result, future studies that explore this chrononumeric relationship alone should seek to include a larger sample. This being said, other studies that include a larger pre-sample often exclude the results, or even further testing of intermediate scoring participants that lay about the mean plus or minus one standard deviation[9,19,27]. By studying the extremes of the spatial ability behavior we are better able to formulate hypothesis about the spatial ability in general.

Conclusions

When considering the process of spatial problem solving, there are fundamental differences in eye movement behavior between HMRA and LMRA individuals. HMRA individuals are able to quickly identify salient areas of the block figure that are most important to accurately solving the problem, while LMRA individuals attend to different areas of the block figure, fixating on these locations for longer periods of time, and ultimately reaching incorrect answers more frequently.

Therefore, there appears to be a fundamental difference in how individuals examine images, and presumably how they process the stimuli. Similar findings have been obtained in the field of laparoscopy, in which the eye movement patterns of expert and novice laparoscopists were monitored during the performance of standardized laparoscopic tasks[45–47]. Significant differences in the patterns of eye movements between the novices and experts were observed, and successful approaches held by the experts were defined[45,46]. As a result, a gaze-directed training tool based on the eye movements of expert laparoscopists was created to train novices on specific laparoscopic techniques. When evaluated, the gaze-directed approach proved to be an effective protocol to guide the attention of novices, and improve their performance on a the specific laparoscopic task[48].

This raises the question as to what directs these individuals' attention to these regions of interest? If LMRA individuals are directed to these task-relevant regions, will they have the cognitive capacity to interpret the information with greater facility and improve performance scores on tests of mental rotations? Moreover, could training using expert gaze be employed to facilitate knowledge acquisition in spatially complex disciplines, such as STEM?

Future studies should seek to construct visual guidance based on the salience patterns of HMRA individuals as an intervention to direct the attention of LMRA individuals in effort to elucidate if the direction of attention can improve spatial reasoning.

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Chapter 5

5 A Comparison of Eye Movements During Tests of Mental Rotation in Timed and Untimed Conditions

5.1 Introduction

Spatial ability, the trait responsible for an individual's aptitude for understanding the three-dimensional relationships around them, has occupied the interest of cognitive, psychological and educational researchers in recent decades[1–5]. As investigators aimed to explore and understand the polylithic trait of spatial ability, several schemas were brought forth to categorize its sub-factors[1–3]. In the subdivision by Linn and Peterson, three sub-factors of spatial ability were identified as discrete constructs: spatial perception, spatial visualization, and mental rotation[1]. The third sub-factor of spatial ability, mental rotation ability (MRA), is of particular interest, as it incorporates qualities of both spatial perception and visualization into a well-defined concept. Specifically, mental rotation can be described as an individual's ability to maintain a mental image of a two- or three-dimensional object as it revolves around an axis in space[6]. The ability to rotate objects mentally is measured via standardized tests such as the Vandenberg and Kuse Mental Rotations Test (VKMRT)[7,8], The Timed Electronic Mental Rotations Test[9] and the Card Rotation Test[10].

In effort to better understand the underlying processes that govern MRA, educational researchers have begun to develop explanatory hypotheses; of which one suggests that MRA may manifest in the finite and measureable movements of the eyes[11]. The theory posed by Just and Carpenter suggests that as an individual directs their visual attention to elements of a spatial task or stimuli, their attention is manifest in the fixations of their eyes; that is, the act of maintaining visual gaze on a single location[12]. Just and Carpenter suggest that each fixation of the eye is intimately involved with the ability to visually encode spatially distributed information[11,13]. Therefore, patterns in visible in an individual's fixations may represent the initial cognitive processes that occur as that visual information is being interpreted[11]. In Just and Carpenter's foundational eye tracking study significant differences in fixation patterns and response times of High and Low MRA (H and LMRA) were identified, and related to strategy and approach during the performance of an untimed test of MRA, based on the line drawings of Shepard and Metzler[14]. The results obtained by Just and Carpenter gave credence to the theory of a causal link between cognitive processing and eye movement in an untimed environment, and were later followed by additional confirmatory work in "Chapter 3: The Untimed Experiment" and "Chapter 4: The Timed Experiment". While the work of Just and Carpenter paved the road for the observation of differences in eye movements, and strategic problem solving of mental rotation tasks between groups, the paired experiments (The Untimed and Timed Experiments) of this study confirmed the dichotomy between H and LMRA using specific performance measures (average fixation duration, average response time and average number of fixations per question) and spatiotemporal salience measures, where a fixation may be considered the maintenance of visual gaze on a discrete point for a period of time exceeding 200 milliseconds. While the Untimed and Timed Experiments demonstrated interesting differences between the H and LMRA groups, the question remained: "What influence does a time restriction impose on cognitive processing within participants, vis-à-vis chrononumeric and salience measures, during mental rotations?"

In Lohman's sub-division of the factors of spatial ability, "mental rotations" is renamed "speeded rotations"[3,15], under the implication that individuals who are able to mentally rotate structures effectively, do so more quickly than those who are less proficient[16]. In fact, many accepted, validated tests of MRA have incorporated this assumption into their protocol, and impose stringent time limits on participants completing the test, including the Timed Electronic Mental Rotations Test (Timed EMRT) which requires participants complete each question within six seconds of exposure (Chapter 4: The Timed Experiment) and the gold-standard of MRA evaluation, The Vandenberg and Kuse Mental Rotations Test (VKMRT)[7,17] which allots a total of six minutes to answer twenty-four questions. Both tests are considered "speeded" tests, wherein the test is so temporally constrained, that most test takers do not have enough time to consider and answer all questions[18]. However, whenever tests impose a time limit, the rate at which students work will directly influence their performance[19]. Literature pertaining to test validation suggests that when test-taking ability is employed to establish sub-groups[20], some sub-groups will be less effective than others at allocating their time per item according to the difficulty of the item[21]. As a result, literature suggest that the application of time limits on tests may differentially impact the test scores of some sub-groups, for example high and low performers. Such a differential impact thus may be observed in the H and LMRA groups across timed, and untimed testing conditions. Given the dichotomy of performance, response time, and approach to questions in the sub-groups observed by Just and Carpenter in an untimed environment, and the results of the paired experiments of Chapter 3 & 4 in this study, the question arises: "How might the chrononumeric and salience measures associated with mental rotation performance differ across individuals, during different timing conditions?"

The current experiment explores how specific eye movements relate to mental rotation ability (MRA), during the completion of both an untimed (EMRT), and timed electronic test of mental rotations (Timed EMRT), to elucidate patterns associated with different levels of MRA.

Specifically, the current experiment aims to investigate the chrononumeric and salience patterns associated with an individual's gaze while performing mental rotations in both timed, and untimed environments. In this instance, the term "chrononumeric" refers to a group of eye- and performance-related measures collected during mental rotations, including the average number of fixations per question, average response time, and average fixation duration that were selected as indices of performance that represent individual behaviour during completion of the EMRT (Chapter 3: The Untimed Experiment). As this overarching aim is composed of two distinct, yet related components (chrononumeric and salience measures), they will be addressed separately.

1: Relating chrononumeric patterns to mental rotation ability

Through analysis of EMRT scores, the current study aims to distinguish how HMRA and LMRA individuals perform across timed, and untimed testing conditions. It is hypothesized that Timed EMRT Scores will be lower than Untimed EMRT Scores, for both high and low MRA groups.

Additionally, through analysis of the chrononumeric data collected during the completion of both the timed, and untimed EMRT, the current experiment aims to identify how these indices relate to MRA score when timing is a factor. Specifically, this study seeks to ascertain how average fixation duration, average response time, and average fixations per question each relate to both MRA score and timing. Additionally, the current experiment seeks to identify how average fixation duration, average response time, and average fixations per question vary as a function of answer accuracy in both timing conditions.

It is predicted that each chrononumeric metric relates to MRA in a different way and varies according to the accuracy of an individual's answer. It is hypothesized that average fixation duration will be shorter for HMRA individuals than for LMRA individuals, but will be equivalent across both levels of answer accuracy, and timing conditions. Like average fixation duration, it is anticipated that average response time will be shorter for HMRA individuals than for LMRA individuals, but will differ according to accuracy and timing condition; being shorter on correct answers, than on incorrect answers, and shorter in the timed condition than in the untimed condition. Finally, it is expected that average fixations per question will be consistent across both MRA groups, but differ according to answer accuracy and timing; being lower on correct answers, than on incorrect answers, and lower in the timed condition, than in the untimed condition.

2: Relating salience patterns to mental rotations ability

As video-based corneal reflection eye tracking yields spatiotemporal data during the performance of the EMRT, the current experiment aims to determine if an individual's attention to particular regions of salience is contingent on their MRA, and to observe how attention may change with time constraints. That is, do individuals of different MRA look at different areas of images while problem solving? And are these regions of spatial salience contingent on the amount of time available to solve the problem?

It is predicted that the regions of salience will differ between the two groups, as measured by the Fisher Exact Test, and illustrate that the two groups attend to different elements of the testing images during problem solving, during both the timed and untimed tests.

5.2 Materials & Methods

Participants*:* Participants were volunteer graduate students in the allied health sciences and anatomy and cell biology at The University of Western Ontario with normal, or corrected to normal vision by way of contact lenses. Interested volunteers were invited to participate in this study, under approval from the university's Research Ethics Board. Prior to testing, consenting individuals (n = 14; 9 F and 5 M) were classified according to their mental rotation ability, by completing a standardized electronic test of Mental Rotations Ability, the Vandenberg and Kuse Mental Rotations Test (VKMRT)[7,22]. The VKMRT was chosen because it displays high internal consistency (Kuder-Richardson 20 = 0.88) and test-retest reliability (0.83)[7]. Individuals with VKMRT scores in excess of one standard deviation above the sample mean were considered to be HMRA (n = 7; 3 F and 4 M), and those with VKMRT scores less than one standard deviation below the sample mean were considered to be LMRA (n = 7; 6 F and 1 M). Individuals scoring within one standard deviation of the sample mean were classified as having intermediate MRA, and were not included in this study. This approach was adopted to emphasize the distinction between HMRA and LMRA individuals[23].

Experimental Design: Qualifying participants completed both a timed, and untimed version of the EMRT (a secondary task of mental rotations ability, distinct from the initial VKMRT), while monocular gaze was monitored from the right eye using video-based corneal reflection-style eye tracking. Gaze metrics were collected according to the specifications detailed in Chapter 3: The Untimed Experiment, using eye-tracking equipment (EyeLink 1000-SR Research, Mississauga, Canada), recorded at 1000 Hz, and from a viewing distance of 40 cm. Ambient light in the testing room was held constant throughout all testing events. Participants each completed both the timed, and untimed tests on the same day, over a twenty-minute period, with a five-minute break between testing sessions. The chrononumeric metrics of interest included average question response time, average fixation duration, and average number of fixations per question, and the region of highest salience (Chapter 3: The Untimed Experiment) (Figure 21).

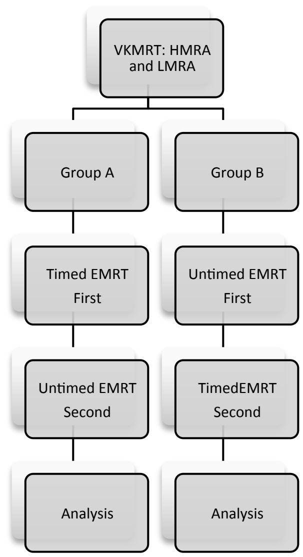


Figure 21: Schematic representation of experimental design and data collection in the experiment.

Target Images: The target images presented to the participants in both the timed, and untimed conditions each constituted an electronic Mental Rotations Test (EMRT) described initially in The Untimed, and Timed Experiments. This visual test requires participants to view two 3D block figures (a "block pair"), and determine if the pair is the same, or different by responding using two keyboard keys as quickly, and accurately as possible. A button-press of "1" indicated a "same" pair, while a "2" indicated a "different" pair.

The EMRT was selected for this study, over other tests of mental rotations for its clarity and ease of use in the context of eye tracking (Chapter 3: The Untimed Experiment). The task requires a comparison of only two images, and thus facilitates a straightforward analysis in the domain of visual salience, which stands in contrast with most other tests of MRA, which consist of as many as five target images requiring visual inspection, as is the case in the VKMRT, used to stratify the participants into HMRA and LMRA groups.

Through eye tracking, eye movements were quantified during the presentation of each question, for each participant, during each of the test conditions (timed and untimed). Salience maps for the right and left block for each image were created for each participant, in each condition, using a Gaussian overlaid upon each fixation[24]. Individual salience maps were then summed group-wise to yield salience maps representing the overall apprehension patterns of the group, for each question (Chapter 3: The Untimed Experiment).

The region of highest salience occurring on each salience map was then contrasted according to location between groups, and between timing conditions, as outlined in Chapter 3: The Untimed Experiment. Predefined location-based categories were employed by three blind observers to identify the regions of highest salience (ICC: 0.84). The classification facilitated the identification of which areas of the blocks drew the most attention, or salience, from the participants as they performed the test (Figure 22).

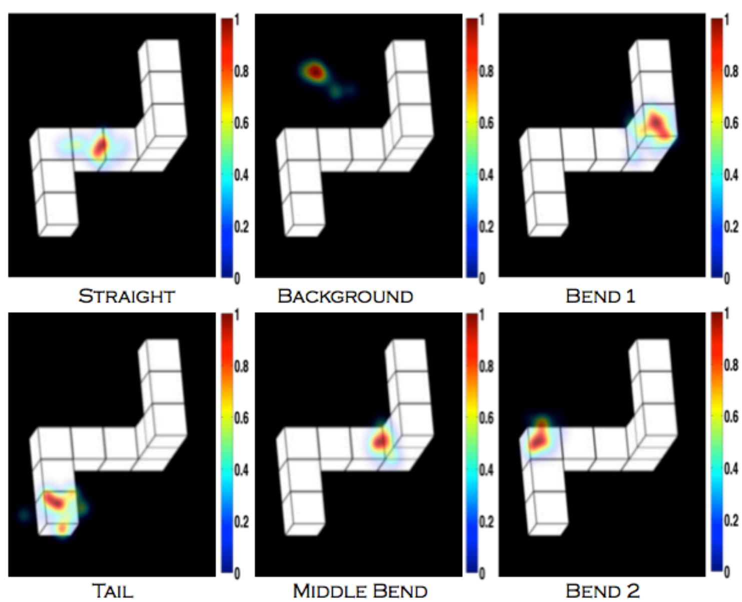


Figure 22: Diagrammatic representation of the six possible categorizations for the location of highest salience, derived from Chapter 3: The Untimed Experiment. The areas having the highest salience are presented in red, and indicate the most attended areas of the image

Data Analysis

Chrononumeric Analysis: First, timed EMRT scores were compared with untimed EMRT scores to illustrate the role that timing plays on spatial reasoning performance. Analysis was conducted via a 2(Timing) x 2 (MRA) Mixed ANOVA.

Additionally, data collected via eye tracking facilitated analyses of the relationship between MRA score and accuracy (correct v. incorrect answers), and timing (timed v. untimed) for each of the metrics of interest: average fixation duration, average question response time, and average number of fixations per question. This analysis was achieved by way of 2(MRA) x 2(Accuracy) x 2(Timing) Mixed ANOVA for each metric.

Analysis of Salience: The classification of the highest regions of salience allowed for comparisons between groups, and between timing conditions, across each category by frequency using the Fisher Exact Test[25]. This test was employed because it is robust to smaller sample sizes, and is specific to categorical data[25,26] such as salience location categories. Additional between- and within-group comparisons following the results of the Fisher were corrected using the Bonferroni correction method for reducing likelihood of type-1 error[25]. Comparisons of question-by-question agreement were also conducted using Cohen's kappa to determine how often the two groups attended to the same location on a given question, in each timing condition[27].

The EMRT and The Inclusion of the Low MRA Group

As this study sought to distinguish differences between HMRA and LMRA groups in timed, and untimed test conditions, it was necessary to include low functioning individuals in analysis, as was completed in The Untimed and Timed Experiments. This procedure, though common to literature on testing MRA, is often misunderstood, as there is the possibility that LMRA individuals will function at a level approaching chance when they attempt to solve spatial problems. As a result, critics will often suggest that individuals who perform poorly do so because of guessing, or inattention to the test. With this in mind, as some of the individuals occupying the LMRA group attained scores approaching 50%, further analysis was undertaken to ensure that these individuals were actively problem solving, rather than guessing. A Binomial Test[28] was employed, and concluded that the individuals of the LMRA group were performing at a level statistically higher than that expected by chance. The binomial test indicated that the proportion of correct answers obtained by the low group on the timed condition (0.63) was higher than that expected by chance (0.5), $p < 0.05^*$ (1-sided). This calculation was also performed for the untimed condition (0.82), and the same results were obtained ($p<0.001^*$). These findings re-affirmed our inclusion of the LMRA group, and confirmed that their low scores were not the result of guessing, but of reaching an incorrect answer following spatial problem solving.

5.3 Results

1. Chrononumeric Indices

Testing Scores and Times

The VKMRT served as a diagnostic test to allocate individuals into two MRA groups. Significant differences in score on the subsequent EMRT were observed between the two MRA groups overall $F(1.12) = 14.41$ ($p = 0.003$) (Partial η^2: 0.546). The significantly higher average EMRT score (Mean ± SD) demonstrated by the HMRA group reaffirms the between-group distinction that is key to the continued contrast between HMRA (41.29±4.65) and LMRA groups (34.71±6.93) (Figure 23).

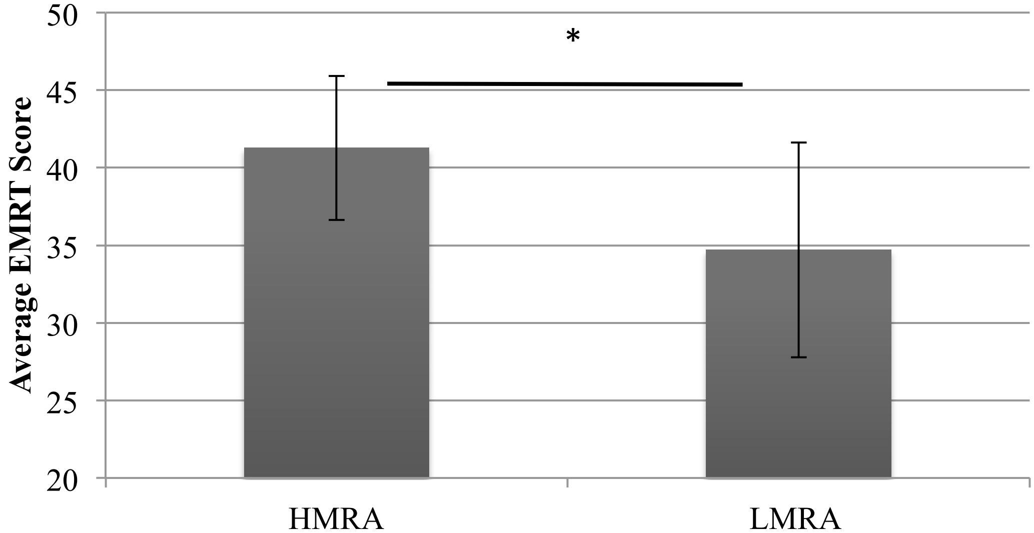


Figure 23: A between group comparison of performance (average EMRT score ± SD), regardless of timing condition. The HMRA group outperforms the LMRA group consistently and significantly F(1.12) = 14.41 (p = 0.003), confirming the significant difference between the groups.

Additionally, both H and LMRA groups demonstrated significantly higher EMRT scores in the untimed condition (Mean ± SD) (HMRA: 42.71±3.95, LMRA: 39.29±4.61), than in the timed condition (HMRA: 39.86±5.15, LMRA: 30.14±5.84) $F(1.12) = 9.09$ ($p = 0.011$) (Partial η^2: 0.431) (Figure 24). No interaction was observed between group, and timing condition $F(1,12)=2.49$ ($p = 0.14$) (Partial η^2: 0.172).

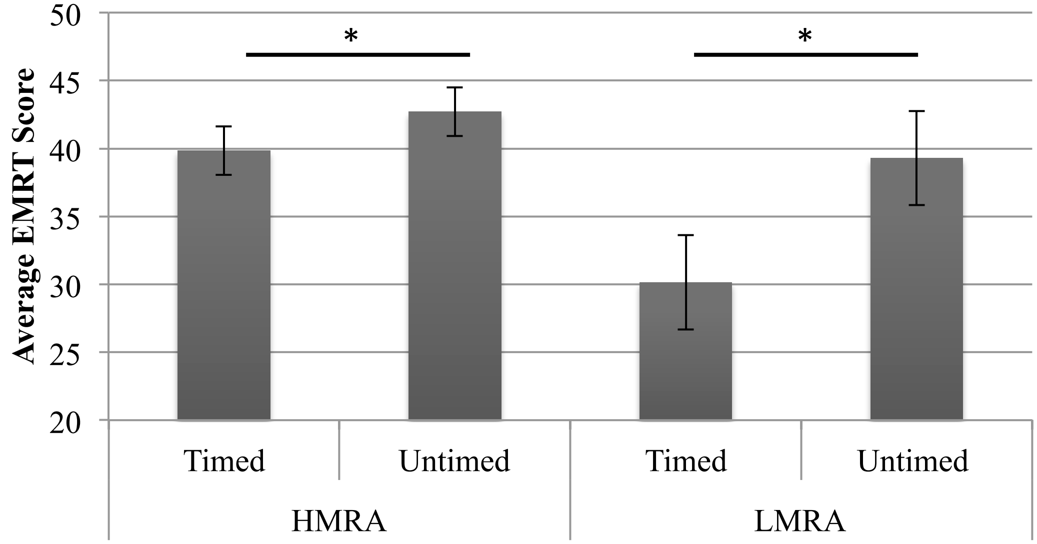


Figure 24: The performance (average EMRT Score ± 95% Confidence Interval) of both MRA groups for both timing conditions. Both groups show lower EMRT scores in the timed condition, compared to the untimed condition

Average Response Time

No difference exists in average response time (Mean ±SD) for HMRA (4975.21±2165.25 ms) and LMRA overall (5960.67±2465.95 ms) $F(1,12) = 1.92$ ($p=0.191$) (Partial η^2: 0138) (Figure 25).

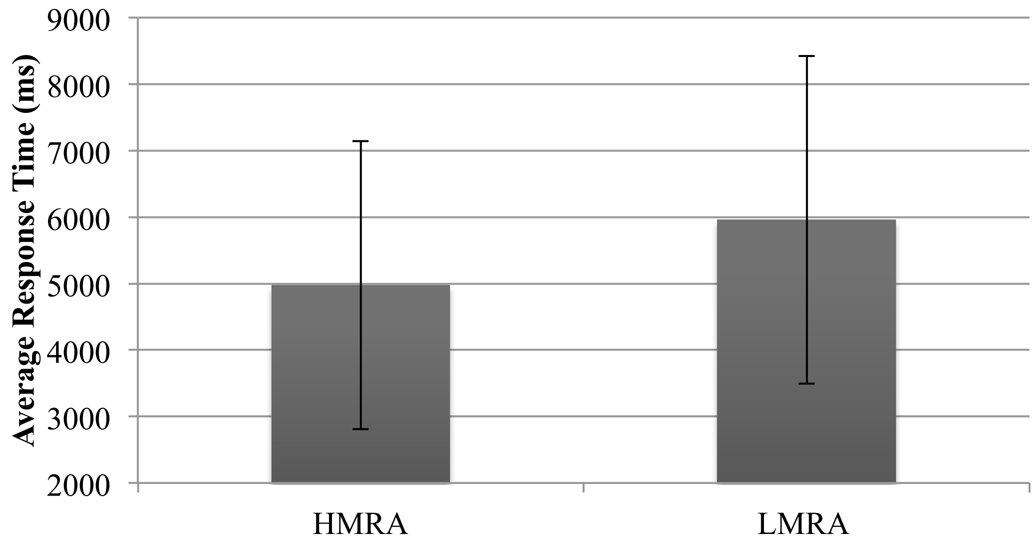


Figure 25: A between-group comparison of average response time (average response time ± SD), regardless of timing condition. There is no difference in average response time between HMRA and LMRA groups

Overall, correctly answered questions are answered with a shorter average response time: $F(1,12) = 23.27$ ($p = 0.001$) (Partial η^2: 0.66) (Mean ± 95% Confidence Interval) (HMRA: 4229.61±373.89 ms; LMRA: 5460.11±297.77 ms), than those that are answered incorrectly (HMRA: 5778.17±373.89 ms; LMRA: 6461.23±297.77 ms), for both groups $F(1,12) = 23.27$ ($p = 0.001$) (Figure 26).

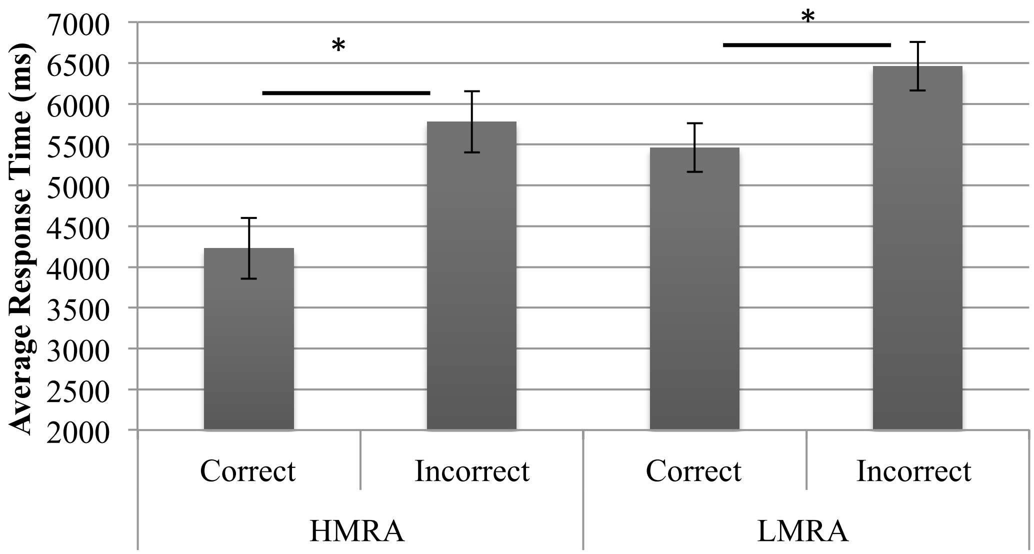


Figure 26: A within-participant comparison of average response time (average response time ± 95% Confidence Interval) across timed, and untimed conditions, for both MRA groups. There is a significant difference in average response time between timed and untimed conditions.

Additionally, average response time (Mean± 95% Confidence Interval) was significantly shorter in the timed conditions (HMRA: 4362.57±770.50 ms; LMRA: 4242.55±855.52 ms) than in the untimed conditions $F(1,12) = 12.96$ ($p = 0.004$) (Partial η^2: 0.519); (HMRA: 5634.98±770.50 ms; LMRA: 7678.80±855.52 ms) across both MRA groups $F(1,12) = 12.96$ ($p = 0.004$) (Figure 27). No interaction was observed between group, accuracy, and timing $F(1.12) = 2.11$ ($p = 0.172$) (Partial η^2: 0.149).

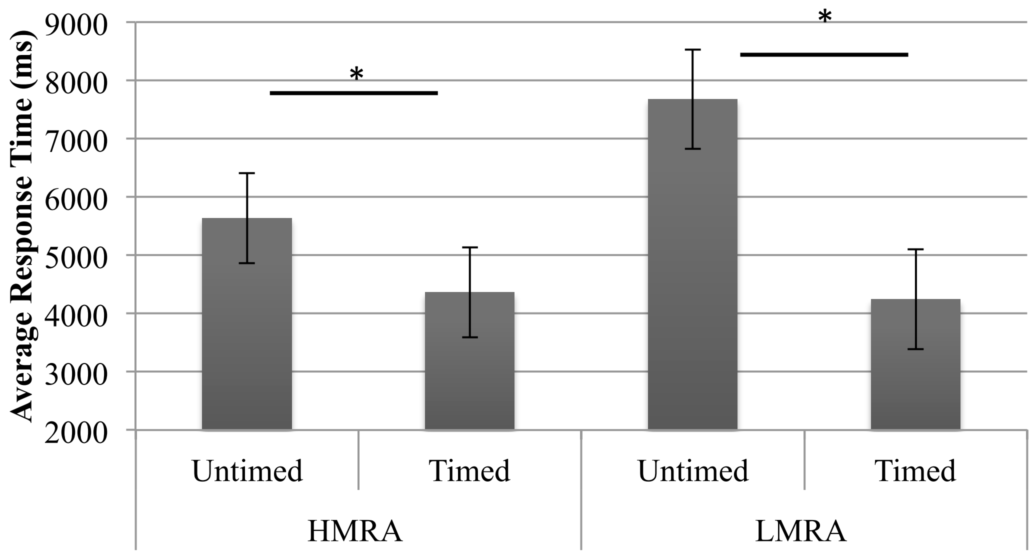


Figure 27: A within-participant comparison of average response time (average response time ± 95% Confidence Interval) across timed, and untimed conditions, for both MRA groups. There is a significant difference in average response time between timed and untimed conditions.

Average Fixation Duration

There was no significant difference in average fixation duration between the MRA groups (HMRA: 274.92±68.85 ms, LMRA: 252.73±23.30 ms) $F(1,12) = 2.61$ ($p = .132$) (Partial η^2: 0.179) (Figure 28).

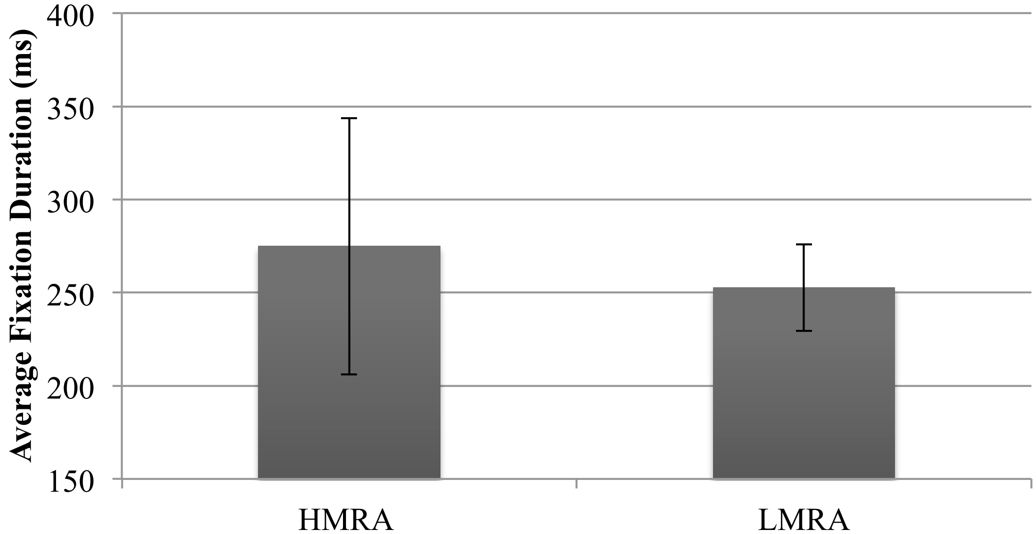


Figure 28: The between-group comparison of average fixation duration (average fixation duration ± Group SD). There is no significant difference in average fixation duration between HMRA and LMRA groups

It was observed that average fixation duration (Mean ± 95% Confidence Interval) was consistent, regardless of whether individuals answered the question correctly $F(1,12) = 3.55$ ($p = 0.084$) (Partial η^2: 0.228); (HMRA: 255.93±17.95 ms, LMRA: 244.28±10.48 ms) or incorrectly (HMRA: 295.37±17.95 ms, LMRA: 261.19±10.48 ms) (Figure 29).

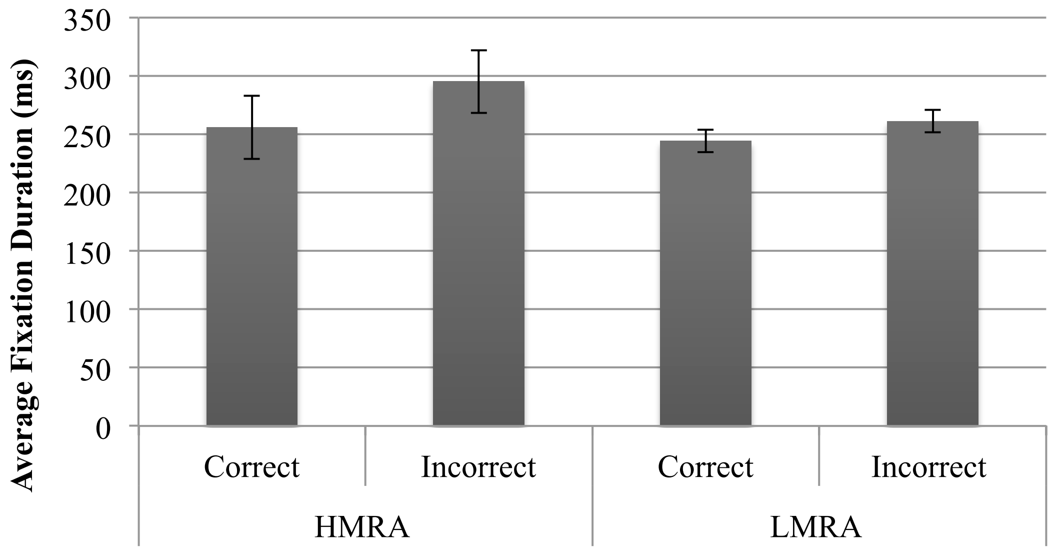


Figure 29: The within-participant comparison of average fixation duration (average fixation duration ± 95% Confidence Interval) across correct, and incorrectly answered questions. There is no significant difference between average fixation duration in correct and incorrect answers, for both groups.

Additionally, average fixation duration (Mean ± 95% Confidence Interval) was consistent across both timing conditions, for both groups $F(1,12) = 1.34$ ($p = 0.27$) (Partial η^2: 0.10); (Timed: HMRA: 285.70±13.04 ms, LMRA: 257.03±10.11 ms; Untimed: HMRA: 263.31±13.04 ms, LMRA: 248.43±10.11 ms) (Figure 30). No significant interactions were observed between group, accuracy and timing for average fixation duration $F(1,12) = 0.209$ ($p = 0.656$) (Partial η^2: 0.017).

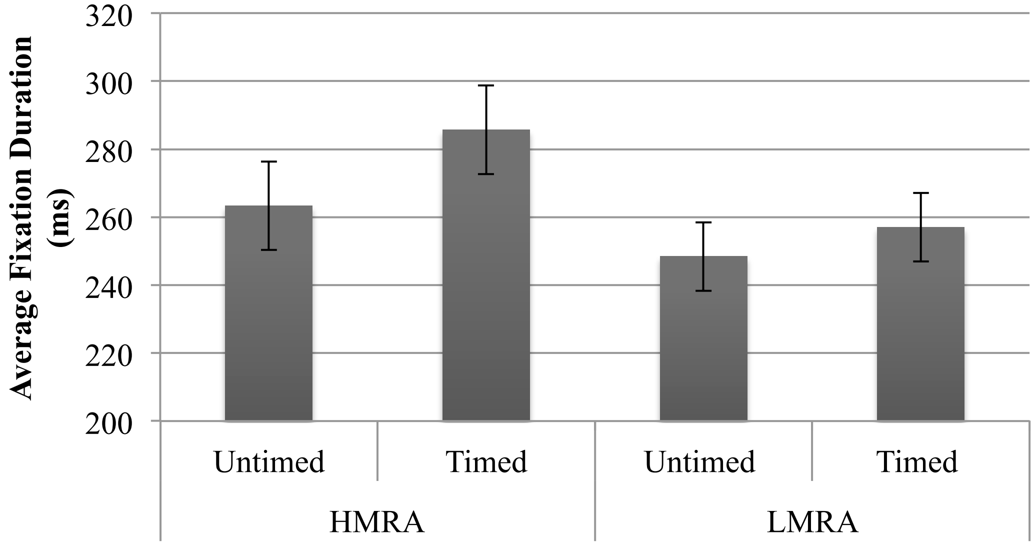


Figure 30: The within-participant comparison of average fixation duration (average fixation duration ± 95% Confidence Interval) across both timing conditions, for both MRA groups. No significant difference between average fixation duration was observed according to timed and untimed conditions.

Average Number of Fixations per Question

Both MRA groups demonstrated similar average fixations per question (Mean ± SD) overall (HMRA: 14.84±6.66 fixations; LMRA: 18.59±6.44 fixations) $F(1,12) = 2.5$ $(p=0.14)$ (Partial η^2: 0.173) (Figure 31).

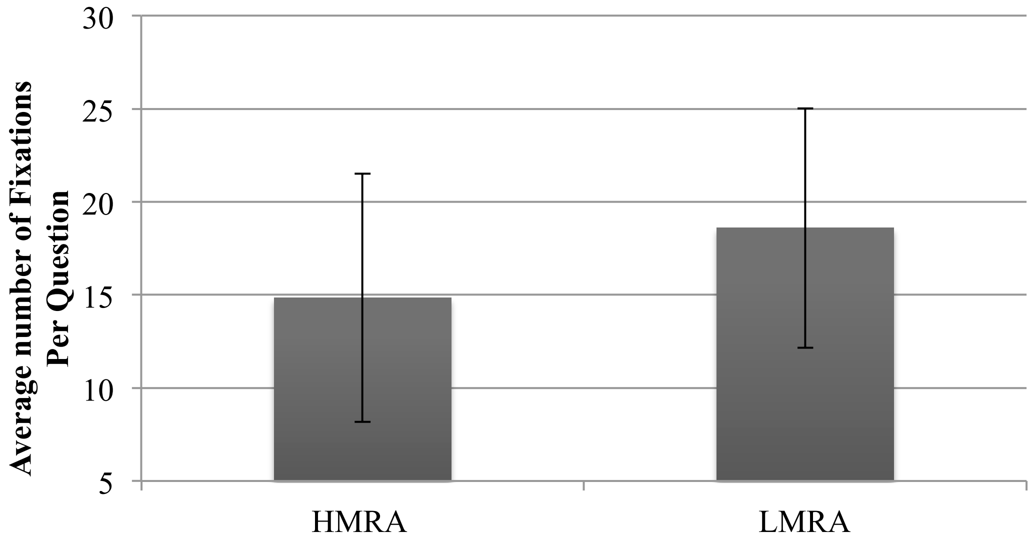


Figure 31: The between-group comparison of average fixations per question (average fixations per question ± SD) regardless of timing condition or accuracy of the answer. There was no difference observed in average fixations per question between HMRA and LMRA groups

Questions that were answered correctly showed significantly fewer fixations per question (Mean ± 95% Confidence Interval)(HMRA: 13.10±1.59 fixations; LMRA: 17.01±0.92 fixations) than those answered incorrectly (HMRA: 16.71±1.59 fixations; LMRA: 20.18±0.92 fixations), across both MRA groups $F(1,12) = 24.09$ ($p=0.001$) (Partial η^2: 0.667) (Figure 32).

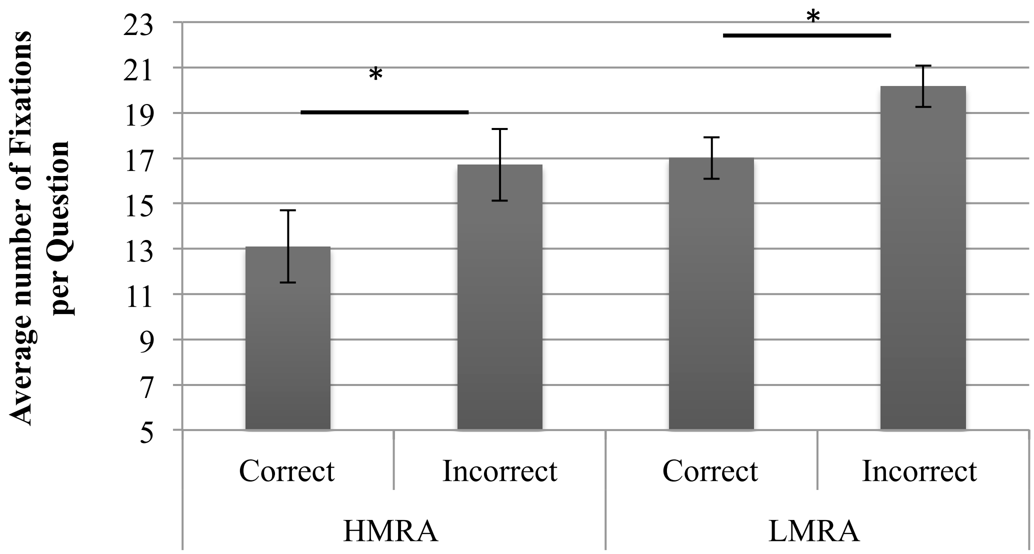


Figure 32: The within-group comparison of average fixations per question (average fixations per question ± 95% Confidence Interval) over correct and incorrectly answered questions, for both MRA groups. There was a significant difference noted in average fixations per question between correct and incorrect answers for both groups

Both groups demonstrate significantly higher average fixations per question (Mean ± 95% Confidence Interval) in the untimed condition (HMRA: 16.13±2.08 fixations; LMRA: 22.79±2.12 fixations) than in the timed condition (HMRA: 13.63±2.08 fixations; LMRA: 14.40±2.12 fixations) $F(1,12) = 9.97$ ($p = 0.008$) (Partial η^2: 0.454) (Figure 33). No significant interactions were observed between group, accuracy and timing for the measure of average fixations per question $F(1,12) = 3.52$ ($p = 0.085$) (Partial η^2: 0.227).

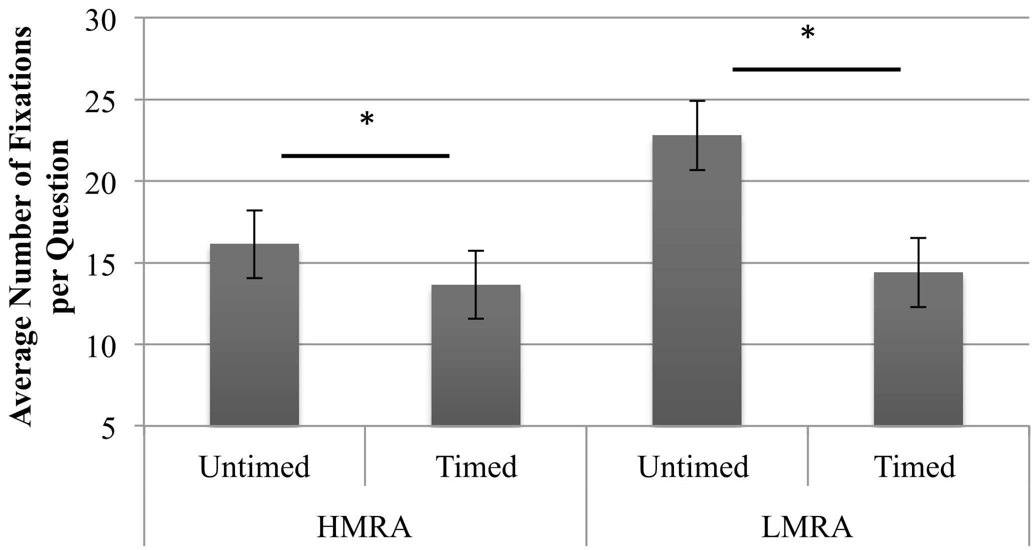


Figure 33: The within-group comparison of average fixations per question (average fixations per question ± 95% Confidence Interval) for both MRA groups, on the timed, and untimed conditions. There is a significant difference in average fixations per question between the timed and untimed conditions

2. Visual Salience

Analysis of the distribution of salience centers across the MRA groups, under the two timing conditions, yielded significant differences in where the groups directed visual attention during problem solving (Fisher Exact Test = 122. 18, $p < 0.001$) (Figure 34).

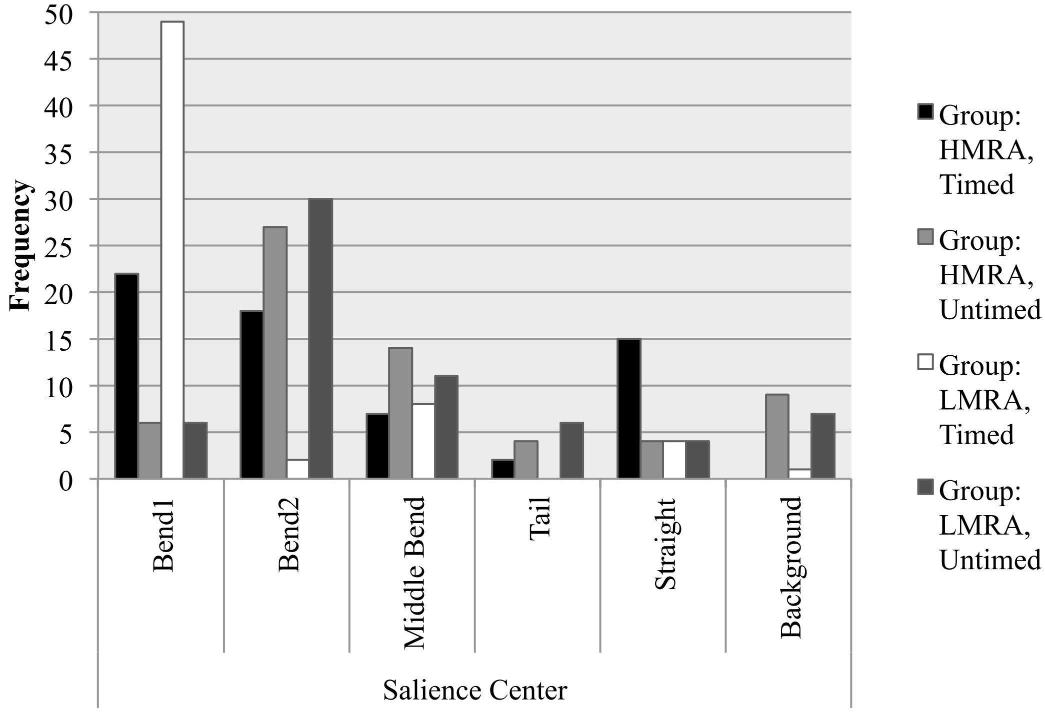
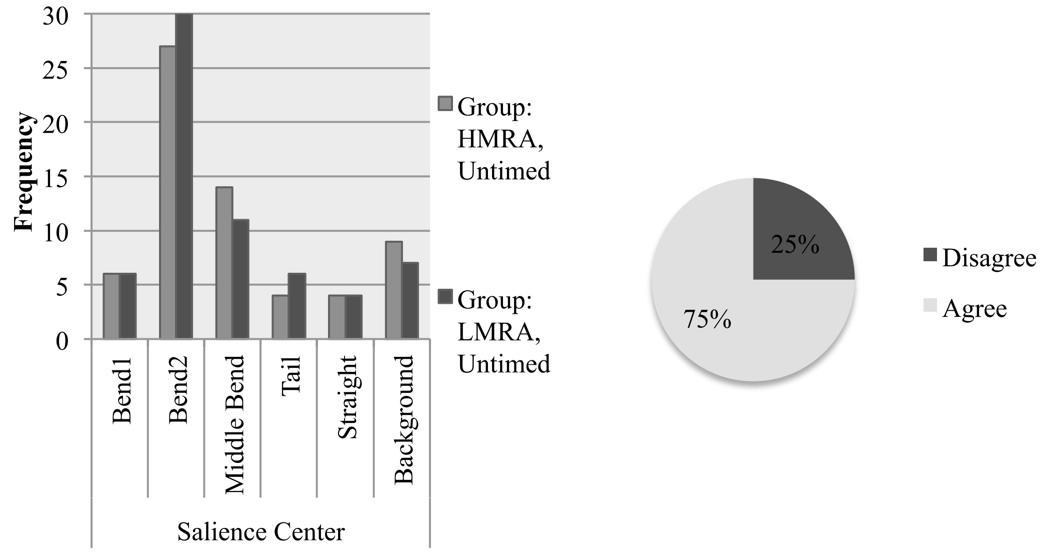


Figure 34: The between-group comparison of salience location frequency, for both timing conditions. There is a significant difference between the four groups: HMRA: Timed, HMRA: Untimed, LMRA: Timed and LMRA: Untimed (Fisher Exact Test = 122.18, p <0.001).

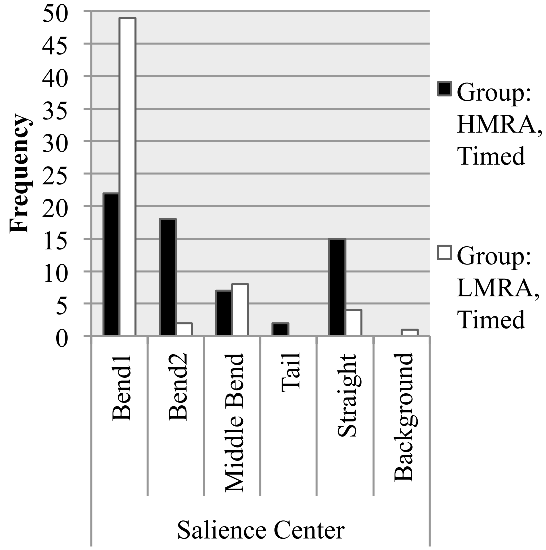
In untimed conditions, the two MRA groups showed similar salience patterns (Fisher Exact Test: 1.31, $p = 0.95$), and on a question-by-question basis, share the same salience in 75% of questions ($\kappa = 0.67$) (Figure 35).



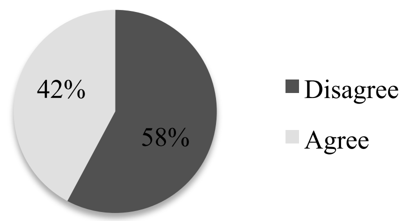
A B

Figure 35: A) The between-group comparison of salience center distribution in the untimed condition. There is no difference between the distribution of salience centers between the HMRA and LMRA groups (Fisher Exact Test: 1.31, p = 0.95). B) The between-group question-by-question agreement for the untimed condition. The groups share salience centers in 75% of questions, showing significant agreement between the groups during untimed testing (κ = 0.67).

However, in the timed condition, the distribution of salience diverges (Fisher Exact Test: 33.24, $p < 0.001$), and the question-by-question salience agreement is decreased to 42%, representing no agreement between the groups when chance is agreement is considered ($\kappa = 0.20$) (Figure 36).



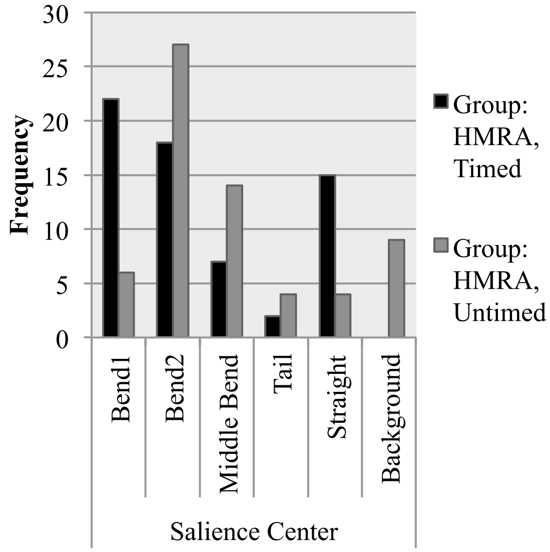
A



B

Figure 36: The between-group comparison of salience center distribution in the timed condition. There is a significant difference between the distribution of salience centers between the HMRA and LMRA groups (Fisher Exact Test: 33.24, p <0.001). B) The between-group question-by-question agreement for the timed condition. The groups share salience centers in 42% of questions, showing no agreement between the groups during timed testing (κ = 0.20).

Additionally, when a within-group contrast was conducted on the HMRA group, there were significant differences observed between the distribution of salience in the timed, and untimed conditions (Fisher Exact Test: 30.33, p <0.001). The within-group question-by-question salience center agreement was found to be 38%, representing a fair agreement between the timed and untimed conditions for the HMRA group (κ = 0.25) (Figure 37).



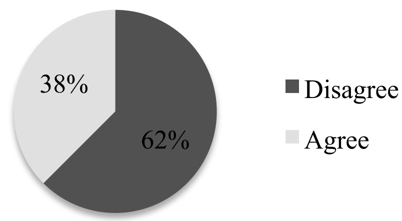
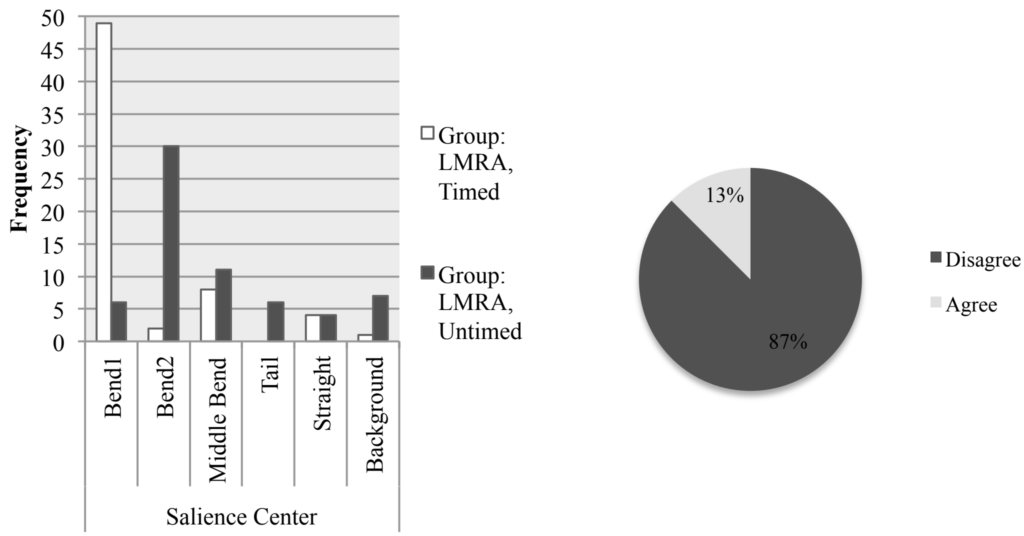


Figure 37: A) The within-group comparison of salience center distribution in the HMRA group. There is a significant difference between the distribution of salience centers between the timed and untimed conditions (Fisher Exact Test: 30.33, p <0.001). B) The within-group question-by-question agreement for the HMRA group. The group demonstrates the same salience centers in 38% of questions, showing fair agreement between the testing conditions (κ = 0.25).

Given the fair agreement found between the timed and untimed conditions for the HMRA group, the same analysis was conducted for the LMRA group. The within-group comparison of salience was found to be significantly different in between the timed and untimed conditions (Fisher Exact Test: 76.46, p <0.001). This difference was represented by a within-group salience center agreement of 13%, which represents no agreement in the LMRA group across the testing conditions (κ = 0.013) (Figure 38).



A B

Figure 38: A) The within-group comparison of salience center distribution in the LMRA group. There is a significant difference between the distribution of salience centers between the timed and untimed conditions (Fisher Exact Test: 76.46, $p < 0.001$). B) The within-group question-by-question agreement for the LMRA group. The group demonstrates the same salience centers in 13% of questions, showing no agreement between the testing conditions ($\kappa = 0.013$).

5.4 Discussion

Regardless of timing condition, HMRA individuals outscored LMRA individuals on the EMRT. As a result, it is clear that from the outset, the two groups varied significantly in their ability to reason spatially[23,29,30]. Further, it was observed through a lack of interaction between group and timing condition, that EMRT scores were significantly lower in the timed condition for both MRA groups when compared to the untimed condition.

While both groups were impacted significantly by the application of a time limit, the finding that LMRA individuals performed worse when restricted by time aligns with research by Weaver (1993). Weaver suggests that individuals of low ability are handicapped by time limits, and that extra time enables individuals to process the information fully, and then demonstrate their knowledge. As a result, the application of a time limit may mask an LMRA individual's ability to perform on a test[31]. However, the observation that the HMRA individuals also suffered as a result of the time constraint is not surprising, as literature on Scholastic Assessment Test (SAT) performance suggests that high-scoring students tend to benefit more than low-scoring students when additional time is allotted on tests[18], as low-scoring individuals often lack the reasoning skills to puzzle through the task, which are not always improved by additional time.

When considering the other effects that time constraints may have on individual performance, it was hypothesized that each of the chrononumeric metrics would relate to MRA in a unique manner, contingent on both answer accuracy and timing condition. In the context of average fixation duration, there was no observation of a relationship contingent on MRA, accuracy, or on timing. As a result, it could be considered that average fixation duration may be a fixed value that is not task, or ability specific; but possibly reflective of the individuals' working memory capacity. This hypothesis is supported by literature that suggests that HMRA is correlated with elevated spatial working memory, defined as the ability to hold representations of spatial relationships in their 'minds eye' whilst problem solving[32]. Consequently, higher spatial working memory may enable quicker comparisons (occurring through shorter fixations) between the block pairs, and facilitate a more reliable problem solving process.

Despite dichotomies in average fixation duration, differences in average response time were not observed between the two MRA groups when both timing conditions were considered together. When the timing condition was considered, a significant and predictable difference was observed across both groups; average response time was reduced when time limits were imposed. Similarly, when accuracy was considered, a significant difference was observed between correctly and incorrectly answered questions for both timing conditions. Questions that were answered correctly were done so more quickly, but both groups spent more time on those questions that were ultimately answered incorrectly. This relationship is in direct alignment with the findings of previous work completed using the EMRT. Like in the preceding chapters, the relationship between average response time and accuracy in the current study may be evidence of conflict monitoring, described broadly as the implicit allocation of more time or resources in effort to answer more challenging questions[33].

Similarly, the average response time relationships observed with MRA, accuracy, and timing condition are mirrored in those of average fixations per question. When the average fixations per question of HMRA and LMRA were contrasted without consideration of timing or accuracy, no difference was observed between the two groups. Similarly, the two groups responded similarly to both timing conditions, and across both levels of accuracy, as evidenced by a lack of interaction between accuracy, timing condition and group; suggesting that average number of fixations per question may not be reflective of differences in MRT. Like average response time, the results of the average number of fixations per question analyses were predictable. In the timed condition, both groups demonstrated fewer fixations than in the untimed condition, and correctly answered questions were characterized by fewer fixations than incorrectly answered questions. Again, like the patterns observed in average response time, it is possible that the patterns observed in average number of fixations per question are influenced by conflict monitoring, because as more time is allocated to answering a question, the eye will have more time to conduct more fixations, and inspect more information as a result. But why does this additional information taken up during extra fixations result in an incorrect answer more often for LMRA individuals? In effort to answer this question, the current experiment also explored the locus of fixations, via a nonparametric analysis of salience.

The analysis of salience employed in the current experiment was modeled after that conducted in The Untimed and Timed Experiments that investigated the MRA dichotomy under similar parameters involving the same MRA test, the EMRT. Significant divergences existed between the salience patterns of HMRA and LMRA groups across the two timing conditions (Figure 33), suggesting that individuals with different MRA attend to different structural elements of the images as they solve complex spatial problems, and that where they look is also contingent on the time available to solve the problem. These results align with those found by Wilson *et al*., in a study monitoring gaze and task performance in novice and expert laparoscopists; wherein it was observed that experts (akin to HMRA) show a more economical gaze pattern than novices[34]. Following further subdivision and comparisons, it was observed that when the data from the untimed condition was considered exclusively, the difference between MRA levels was no longer apparent. Individuals of HMRA and LMRA attended to the block pairs in the same distribution, and devoted attention to the same salient region 75% of the time; essentially appearing to view the structures identically. However, when the timed condition is applied and analyzed, the original dichotomy returns, and the two groups no longer attend to the same structures; sharing the same salience locations only 42% of the time. This finding aligns directly with literature that states that experts and novices attend to different structures during problem solving[35–42]. This distinction is exacerbated in conditions where timing is a factor, as the addition of a time limit applies pressure on performance, and favours individuals with high cognitive processing rates, as higher rates of processing yield more time to inspect more questions[43,44].

It is assumed that this variance may be attributed to differences in individual working memory capacity[45], and higher rates of mental processing. Research suggests a very strong correlation between an individual's ability to reason spatially, and their working memory capacity[46–49]. That is, individuals who are proficient at reasoning will typically have high working memory capacities, and rates of mental processing, and vice versa. With this in mind, when tasks are considered speeded, and the burden on working memory is high, the rate of mental processing becomes critical to performance.

It is possible that the imposition of a time constraint may directly influence where individuals' attend during problem solving, and as a result, may impact their ability to perform the test accurately. The within-group analysis of salience supports this hypothesis, as both groups demonstrate significant differences between their salience distribution patterns between the timed, and untimed conditions. The HMRA group attends to the same location on 38% of question across the two timing conditions, while the LMRA group diverges even further, attending to the same locations in only 13% of questions on the two tests. As a result, it is clear that the two groups respond to the addition of a time limit in different ways, and that response may manifest in how they approach solving the problems.

Further analysis of the distribution of salience across and between the two groups provides interesting insight into the allocation of attention for the groups, and timing conditions, and may present information regarding how these individuals differ in terms of how they approach mental rotation type problems. In the untimed condition, both groups attended to the various domains of the image (Bend 1, Bend 2, Middle Bend, Straight, or Background) in the same proportions; however in the timed condition, it is apparent that the two groups diverge, and no longer inspect the domains in the same proportion. That is, the high MRA group attends to various features of the image, while the low MRA group tends to direct their attention to the Bend 1 structure preferentially for each question.

Moreover, upon inspection of the within-group differences across the two timing conditions, more differences in approach are revealed. Notably, the high MRA group attends preferentially to Bend 2 during the untimed condition, but when a time limit is applied, the high MRA group becomes more flexible in their visual assessment of the image; directing their attention to more features of the image across the test. This stands in contrast to the low MRA group, who like the high MRA group, attend to a single feature during the untimed iteration (Bend 2) and continue to allocate attention to a single feature in the timed condition (Bend 1). In essence, it appears that this group attempts to direct their search around a single feature, regardless of the orientation of the image. This essentially suggests that the low MRA cannot identify that the task-relevant salient domain images differ based on the orientation of the block pairs, and instead adopt a "feature-matching" or analytic approach to problem solving. The analytic approach, characterized by Geiser is described as a non-spatial approach to mental rotation[50], because no actual mental rotation takes place. This approach is reported to be the least effective method to complete tasks of mental rotation, and is often adopted by the lowest performing individuals[50.]

Conclusions

It appears that on the basis of MRA, there are few discernable differences held within the chrononumeric measures of average fixation duration, average response time and average fixations per question during mental rotations. Though these measures do vary with timing and answer accuracy, they do so equally across both levels of MRA. However, substantial differences have been discovered within the realm of visual salience, and how patterns of salience differ across levels of timing. It is apparent that these two groups approach spatial questions differently; as HMRA individuals are able to identify that different domains of the block images are pertinent to solving questions in different spatial orientations, while LMRA individuals appear to use a single feature as a landmark for each question, regardless of its task-relevance. Further, in the context of attention allocation, it appears that the effect of time limitations also differs across the groups. High MRA individuals are able to more consistently identify regions of task-relevant salience across both time conditions than Low MRA, who show very inconsistent agreement across the timing conditions. With this in mind, it is possible that where individuals are attending during problem solving may be essential to their ability to reason spatially.

If LMRA individuals are guided to the same loci that are prescribed by their HMRA peers, could the capacity to interpret the stimuli be transferred? And as a result, could this manifest in improved performance on tests of spatial reasoning? Future work should aim to develop and evaluate such strategies, as methods of intervention may hold the key to facilitate spatial reasoning in LMRA individuals.

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Chapter 6

6 The Effects Of Visual Guidance On Success In Tests Of Mental Rotation Ability

6.1 Introduction

Each day, humans are challenged to think spatially as they navigate the three-dimensional world that surrounds them. They must encode the spatial information presented to them, transform it, match it, and often recall it after time has passed. The aptitude with which individuals carry out these spatial tasks is termed "spatial ability"[1]. Loosely defined in the literature, spatial ability is a polylithic construct, encompassing multiple factors [2]. Psychometric studies have revealed several distinct spatial ability factors, including spatial relations[1,3–5], an ability known more commonly as mental rotation ability (MRA)[6–9].

Shepard and colleagues[7,8] have conducted a series of studies focusing on mental rotations ability, and defined it as an aptitude for rotating two or three dimensional figures rapidly and accurately[6]. Following the studies conducted by Shepard *et al.* (1978), a test was created to measure spatial ability via MRA, referred to as the Vandenberg & Kuse Mental Rotation Test (VKMRT)[10]. This test has been applied across literature to gauge an individual's aptitude for spatial reasoning, and serve to classify individuals as having high, intermediate or low spatial abilities[11–13].

The implications of spatial ability have extended beyond success on individual psychometric tests and are found to correlate significantly with success in the STEM disciplines[14,15], success in surgical skill acquisition[16–20], military flight training[21] and anatomical science[12,22,23]. As a result, initiatives have sought to train this ability, and subsequently enhance performance in related disciplines[24–31]. In a recent meta-analysis conducted by Uttal and colleagues, 217 research studies were investigated to determine if spatial training and experience could serve to improve spatial abilities, and if the effect of training was both durable and translatable to other related spatial tasks[2]. The meta-analysis revealed that the effects of training were stable, and consistent, regardless of latency between training and post-testing. Further, it was also observed that the effect of training was transferred to other novel spatial tasks that were not directly trained[2].

A hypothesis posed by Just and Carpenter (1971) suggested that the movements of the eyes may serve as indicators of the cognitive processes associated with spatial abilities; specifically mental rotations ability[32,33]. While Just and Carpenter were unable to display concrete evidence identifying the underlying processes that govern spatial ability, they demonstrated a difference in response latency and eye-fixation patterns between high and low spatial individuals during a mental rotations test. This finding suggests that where individuals look while problem solving may be key to their ability to interpret spatially complex information. This early hypothesis was expanded upon and studied in detail in the preceding chapters of this study, and revealed that spatial ability does vary with time limitations and that the distribution of visual saliency was marked different between high and low spatial individuals (Chapter 5). The poor performance in mental rotation by individuals of low MRA may be linked to their inability to identify task-relevant locations, and adoption of an inefficient "feature matching" approach to problem solving, while the success of the high MRA individuals may be attributed to their more flexible approach to viewing spatial problems[35].

If the movements of the eyes can serve as behavioral correlates of mental events[33], then a gaze-based methodology for training of spatial ability vis-à-vis MRA may be a novel answer to improving spatial reasoning. There is evidence to suggest that scores on perceptual tasks will be enhanced through employment of expert eye movements to guide an individual's attention during perceptual tasks such as the tumors-and-laser radiation problem[36], chest x-ray analysis[37], and conceptual tasks such as cardiovascular system comprehension[38]. This evidence hinges on the premise that experts, or individuals with higher levels of expertise on perceptual tasks tend to focus faster and proportionally longer on task-relevant salient structures than their less-experienced peers, while disregarding information that is irrelevant to the completion of the task[39–42]. This behavior is in contrast to less-experienced individuals, who typically attend to visual information that is irrelevant to successful task completion[41,43]. By highlighting, or cueing regions attended to by the experts, visual attention may be drawn to task-relevant information, by making these areas more visually salient[44].

The success of these expert-guided, eye-movement based, training protocols provide insight into the potential application of a strategy for the training of MRA. If the eye movements of expert spatial problem solvers can be elucidated, then they may prove useful as a mechanism to train MRA. As such, the current experiment aims to apply EMME (Eye Movement Modeled Examples) to direct the visual attention of Low MRA (LMRA) individuals to task-relevant salient structures during spatial problem solving. Specifically, this experiment intends to identify if, and by what magnitude, the addition of EMME improves scores on the EMRT for LMRA individuals, to discern if the effects of EMME are maintained on an unguided iteration of the EMRT, and to determine if LMRA individuals' attention patterns mimic High MRA (HMRA) when guided by EMME.

It is hypothesized that LMRA individuals will achieve higher scores on the EMRT when guided using EMME, than without EMME guidance, and that LMRA scores on the Guided EMRT will be maintained in the short term, on the unguided EMRT. Further, it is thought that there will be a high level of agreement between HMRA EMME exemplars and LMRA salience location on the Guided EMRT.

6.2 Materials & Methods

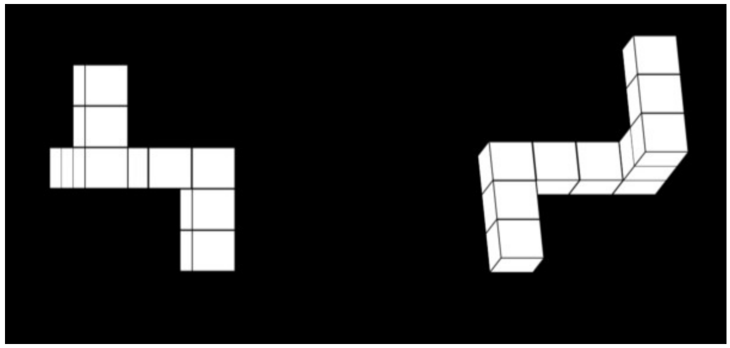
Participants: Participants were thirty-three volunteer graduate students in the allied health sciences and anatomy and cell biology at The University of Western Ontario with normal, or corrected to normal vision by way of contact lenses, who were invited to participate in this study, under approval from the university's Research Ethics Board. Consenting individuals (n = 33; 24F and 9M) completed a standardized electronic test of Mental Rotations Ability, the Vandenberg and Kuse Mental Rotations Test (VKMRT)[10,45] to allow classification according to MRA. Individuals achieving a score of less than 7/24 on the initial VKMRT were invited to participate in the training study. The threshold of 7/24 was selected based on the mean of previous MRA studies (The Untimed, Timed and Crossover Experiments), in which a score of 7/24 represented a value of 1 standard deviation below the mean VKMRT score. As a result, individuals scoring less than 7/24 may be considered to have LMRA.

Experimental Design

Creating The EMMEs

In Chapter 5: The Crossover Experiment, individuals designated as either L or HMRA by way of the VKMRT completed both the Timed and Untimed Electronic Mental Rotations Test as quickly, and accurately as possible while their eye movements were monitored using video-based corneal reflection-style eye tracking. These data were acquired, and the eye movement data specific to correctly answered questions on the Timed EMRT by the HMRA group were extracted. The positional fixation data for each correctly answered question was then mapped for each HMRA individual. A Gaussian distribution was then overlaid upon each fixation (defined as the maintenance of gaze on a spatial location for a period exceeding 200 milliseconds) and scaled according to fixation duration[48] to yield a Salience Map. Each individual salience map was then summed group-wise to yield an HMRA group salience map for each test question. The protocol for salience map creation is described in detail in Chapter 3: The Untimed Experiment. The salience map for each question was then employed to quantify the region of highest salience, or region containing the highest number of fixations, with the longest fixation durations, for the right and left blocks, on each question. Each region of highest salience was then mapped onto the test images using a magenta-colored Gaussian overlay from the Timed EMRT. This overlay of the region of highest salience described by the HMRA group onto the test image would serve as an expert eye movement modeled example (EMME). All sixteen EMMEs were then combined, and administered randomly in triplicate under a six-second time limit to constitute the Guided EMRT (Figure 39).

Unguided EMRT Image



Guided EMRT Image (With EMME Guidance)

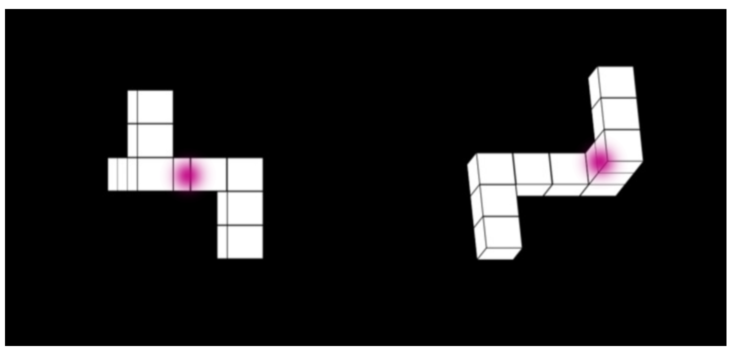


Figure 39: Exemplar of EMME Guidance Test Question

Test Administration

In this experiment, all individuals completed a combination of two EMRT tests, which differed according their group allocation (A: Unguided /Guided EMRT, B: Guided /Unguided EMRT or C: Unguided /Unguided EMRT) (Figure 40). Each group was comprised of 3 Males and 9 Females. The instructions for completing the each test were held consistent regardless of the participant's group allocation. The Unguided EMRT was presented with the instructions to

"Complete this test as quickly, and accurately as possible. Your goal is to determine if the two images are the same (rotations) or different (reflections of each other, and non-superimposable). To answer "Same", press "1" and to answer "Different" press "2" on the keyboard in front of you. Each question will be presented for six seconds. When six seconds has passed, the test will automatically advance to the next question. There will be 48 questions in total."

The Guided EMRT included the same verbally administered instructions as the Unguided EMRT, with an additional instruction: *"You will notice coloured indications present on the block images. These coloured indications represent areas attended to by experts during problem solving. Pay careful attention to these areas as you solve the presented problems."*

As participants completed both EMRT tests, their monocular gaze metrics were collected according to the specifications detailed in The Untimed Experiment from the right eye, using video-based, corneal reflection-style eye-tracking equipment (EyeLink 1000-SR Research, Mississauga, Canada), recorded at 1000 Hz, and from a viewing distance of 40 cm. Ambient light in the testing room was held constant throughout all testing events.

Testing occurred according to a counterbalanced crossover design wherein individuals were exposed to both approaches in different order. The application of a crossover design allowed for the investigation of whether scores obtained on the Guided EMRT were maintained in the Unguided EMRT. In so doing, it was possible to answer the question "If individuals are presented with EMME first, do they continue to attend to salient areas in the absence of EMME prompting?"

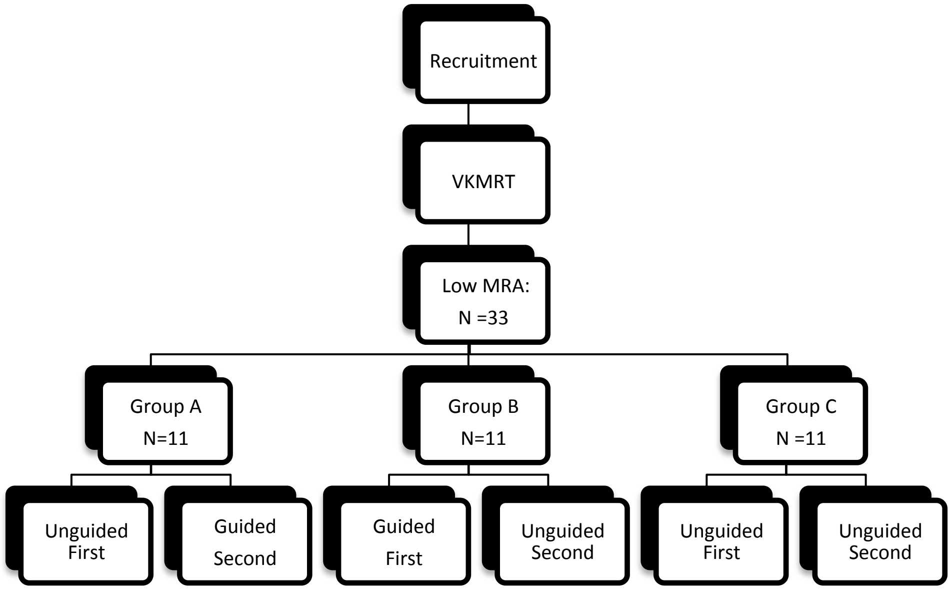


Figure 40: Schematic of Experimental Design

Analysis

As in previous studies concerned with the salience patterns of groups (The Untimed, Timed and Crossover Experiments) salience maps were generated for each individual for each of the Guided and Unguided EMRT sessions. Comparisons between the EMME salience locations and LMRA salience locations on the Guided EMRT were analyzed on a question-by-question basis using Cohen's Kappa. Additionally, the same agreement tests were employed to analyze the relationship between the Guided and Unguided EMRT for the each of the groups to illustrate how their gaze patterns were altered across the two test iterations.

As all participants completed the test twice, a 2-way mixed ANOVA was applied, where the within-groups variable was "Iteration" (1: Test 1, or 2: Test 2), and the between-groups variable was condition (1: Unguided First, 2: Guided First or 3: Control).

The dependent variable (EMRT Score) was contrasted across the groups to ascertain the effect of guidance on performance, and if the effect was maintained when the unguided presentation followed the guided presentation of the test, beyond the potential effects of the experience bias reflected in tests of MRA.

6.3 Results

Individuals achieving a score of less than 7/24 on the initial VKMRT were invited to participate in the training study. The threshold of 7/24 was selected based on the mean of previous MRA studies in which 7/24 represented a value of 1 standard deviation below the mean VKMRT score. As a result, individuals scoring less than 7/24 may be considered to have low MRA (LMRA).

Prior to testing, each group was found to have equivalent mean VKMRT Scores: Group A (5.45 ± 1.86 (SD)), Group B (5.45 ± 1.64) and Group C (4.36 ± 2.25) ($F(2,30) = 1.17$, $p=0.32$). All groups demonstrated an increase in EMRT scores on their second iteration of the test ($F2, 30) = 28.29$ ($p<0.001$) (Partial η^2: 0.485); however an interaction was observed between treatment group and time $F(2, 30) = 4.22$ ($p = 0.024$) (Partial η^2: 0.220) (Figure 41).

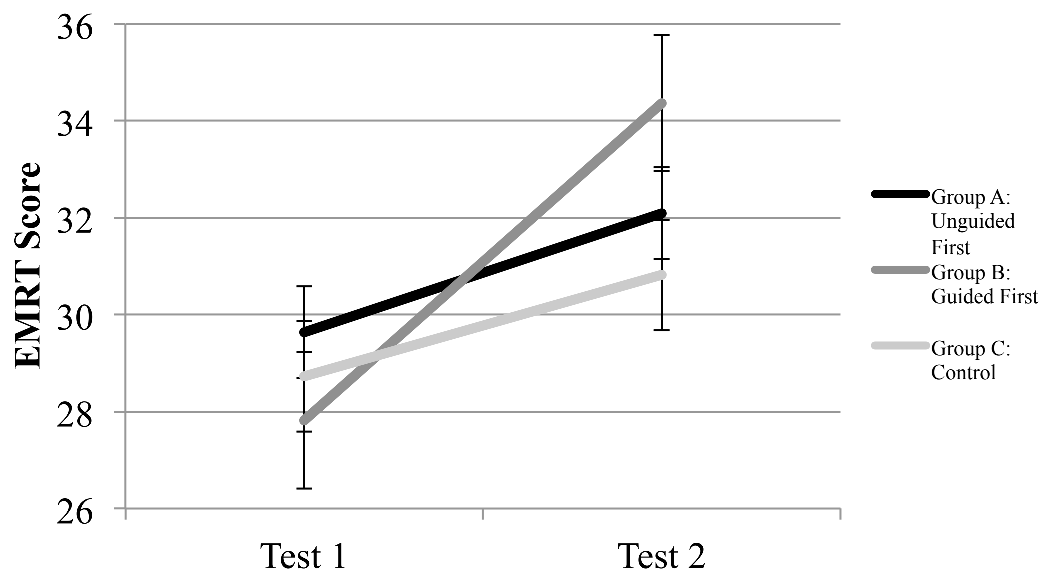


Figure 41: Within-group contrast of EMRT scores ± 95% CI across the two tests, for each test group. A significant interaction was observed between Test and Group, F(2, 30) = 4.22 (p = 0.024).

The mean EMRT score (± 95% CI) on Test 1 was 29.64 ± 0.95 for Group A, 27.82 ± 1.41 for Group B, and 28.73 ± 1.14 for Group C. The mean EMRT score on Test 2 was 32.09 ± 0.95 for Group A, 34.36 ± 1.41 for Group B, and 30.82 ± 1.14 for Group C (Figure 42).

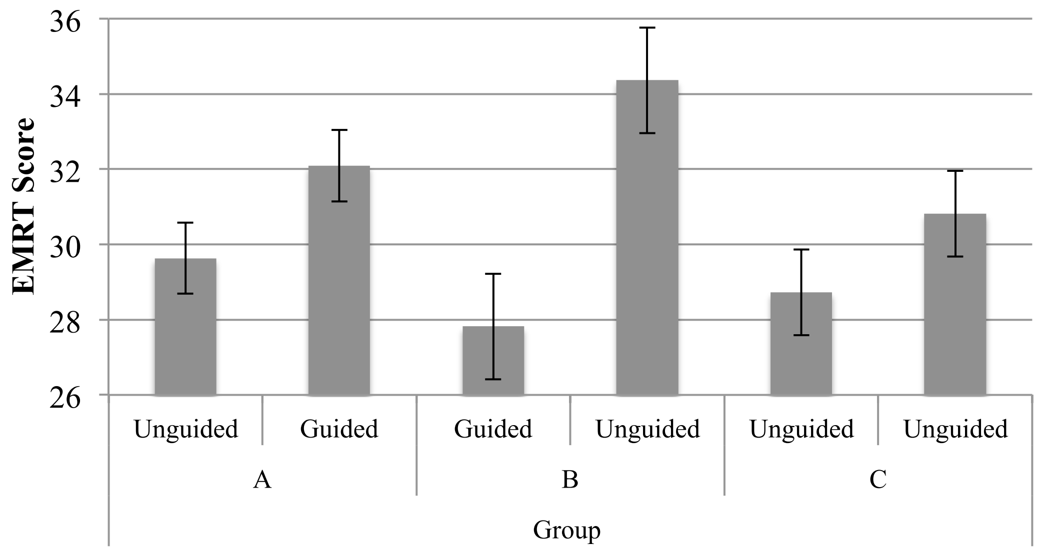


Figure 42: Within-Groups contrast of Mean EMRT Scores ± 95% CI across the treatment groups.

A post-hoc analysis of the mean differences between scores on test 1 and test 2 was conducted to illustrate the within-group change in EMRT score, across the three treatment groups (Figure 43).

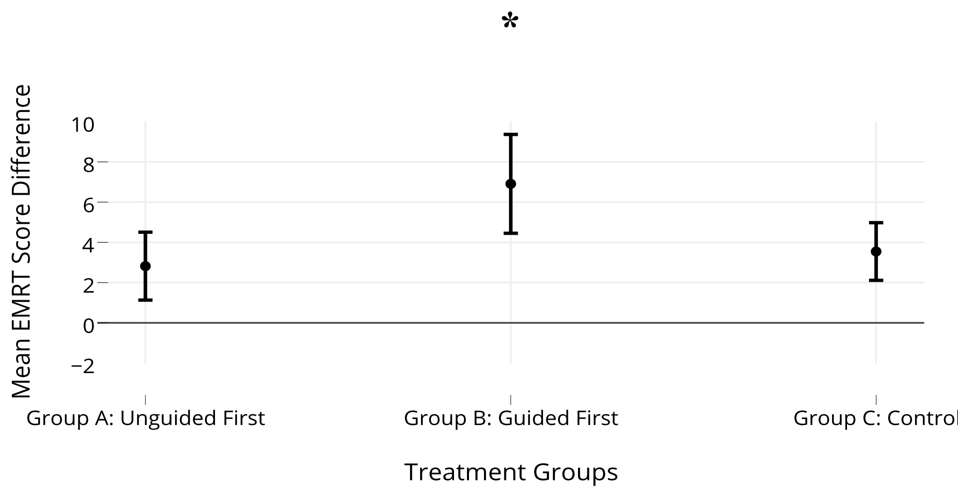


Figure 43: Between-Group Contrast of Mean Differences between EMRT Tests ± 95% CI across treatment groups

Post-hoc analysis demonstrated a significant difference between the EMRT mean differences across the groups. Group B (mean difference ± 95% CI: 6.91 ± 2.46) was found to be statistically greater than both Group A (2.82 ± 1.69) and Group C (3.55 ± 1.43); ($t(10) = -3.78$, $p = 0.004$) (η^2: 0.39) and ($t(10) = 2.58$, $p = 0.028$) (η^2: 0.129) respectively (Figure 43).

Analysis of agreement between the salience patterns demonstrated by the LMRA individuals and the EMME guidance cues was conducted via Cohen's Kappa. In Group A, individuals showed an agreement of $\kappa = 0.11$ with the EMME guidance on the Unguided EMRT, and $\kappa =0.25$ on the Guided EMRT: corresponding to 22% and 37% agreement, respectively. In Group B, individuals showed an agreement of $\kappa = 0.11$ with the EMME guidance on the Unguided EMRT, and $\kappa =0.33$ on the Guided EMRT: corresponding to 22% and 44% agreement, respectively. In Group C, individuals showed an agreement of $\kappa = 0.33$ and 0.09 on the first and second Unguided EMRT: corresponding to 44% and 25% agreement respectively (Figure 44).

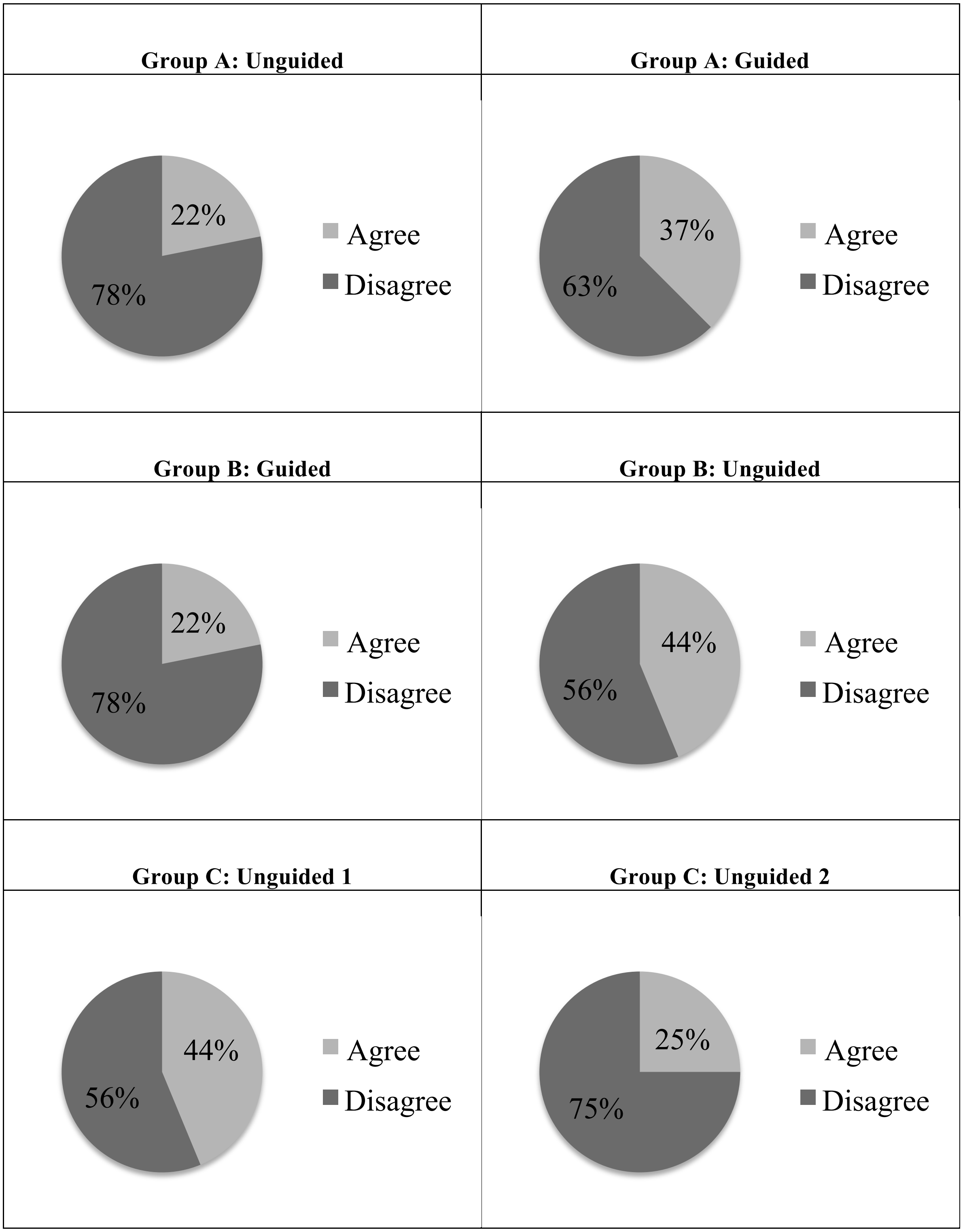


Figure 44: The visual salience agreement between EMME exemplars and the LMRA groups

6.4 Discussion

In effort to train spatial ability in low mental rotation ability (MRA) individuals, an eye-movement modeled example (EMME) based visual guidance protocol was created. The EMME protocol was then evaluated using 33 low MRA (LMRA) individuals in a counterbalanced crossover design; wherein individuals were exposed to both guided and unguided EMRT approaches in different orders. The application of a crossover design allowed for the investigation of whether scores obtained on the Guided EMRT were maintained in the Unguided EMRT.

It was observed that the effect of EMME guidance was contingent on when the EMME guidance was applied. When EMME guidance was applied at the outset of training, the observed differences in score were significantly greater than that expected based on repetition alone. The effect of early training was manifest in Group B (Guided First), who demonstrated a greater mean EMRT score difference between tests than the control group (repetition alone). This finding aligns with the results obtained by Nalanagua *et al.* (2006), who under the paradigm of circuit board inspection, found that a novice's accuracy scores improved when guided by the eye-movements of experts in a feed-forward design[49]. This finding is also supported by similar results observed by Sadasivian *et al*., under the paradigm of aircraft inspection[50], and by Litchfield *et al,* in the case of novices identifying pulmonary nodes on information-rich static chest x-rays[37].

Literature suggests that the eye movements of experts and novices reveal differences in visual search strategies, and how these patterns change as a function of expertise[51–54]. The measures of agreement supported this claim, in the current paradigm of EMME and LMRA, as a greater percentage of attention was aligned with the EMME exemplars in the Group B Unguided test; suggesting that when the guidance is removed, the LMRA individuals are better able to assess the task-relevant spatial regions that are key to problem solving. When considering the inversion of agreement scores observed in Group C, the feature-based approach adopted by LMRA individuals discussed in Chapters 3, 4 and 5 when unguided is evident. When LMRA individuals are unassisted, they tend to employ a consistent approach of feature matching that is not reliant on spatial orientation, while when assisted or guided, that strategy can be improved to a more task-relevant, flexible approach with some lasting effects.

The approach adopted by LMRA individuals can be likened to the ineffective search strategies of the novice, who attend to task-relevant areas less frequently than experts[52,55,56]. The observed differences in search strategy, and reliance on feature matching may result from individual differences in spatial working memory. Individuals with LMRA have less spatial working memory resources available than their HMRA peers[57], and as such, may not be able to represent or process the information presented in a given image in one instance. In work by Just and Carpenter, LMRA individuals completing mental rotation did report that images often "fell apart" while they were attempting to rotate the image mentally[32]; supporting the hypothesis that LMRA individuals lack spatial working memory resources, and as a consequence use parts of the images or features, for comparison. [35].

Limitations

The current experiment was limited in two domains: by a brief testing period, and a brief inter-test period. As the design of this study only required two test iterations, it is not possible to determine what effect would have resulted from repeated Guided EMRT exposure, and how scores in Group A would change following the Guided EMRT. Further, it is possible that the influence of the EMME guidance was minimized due to the brief period of time that was allotted for learning to occur between test iterations.

Future Directions

Future experiments should seek to investigate how a third iteration of the test impacts EMRT scores, as it is hypothesized that given a third test iteration, scores in Group B would be further improved, and the scores in Group A would see the same elevation that was observed in Group B initially. Further, given the results of the current study, continued examination into how training MRA can be translated to success on other tests of spatial ability, and academic success in spatially complex disciplines is merited. Moreover, as controversy still surrounds the underlying mechanisms that govern MRA, neuroscientific approaches should be applied in effort to continue to better understand this cognitive skill.

In summary, despite the short intervention duration of this study, promising results have been obtained. If EMME is applied at the outset of training, meaningful differences in mean EMRT score are observed, beyond that expected by repetition alone. By applying EMME, LMRA individuals are cued to salient regions of images, and despite limitations of working memory, or spatial ability, are better able to perform on tests of spatial reasoning when tested in unguided environments.

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Chapter 7

7 Discussion

The current series of experiments sought to determine if eye movements could serve as indicators of success in mental rotation tasks, and if eye movements associated with successful completion could be applied to strategically improve mental rotation ability. Individuals of high and low mental rotation ability (MRA) were tested in both timed and untimed environments to reveal how the addition of urgency impacts the ability to solve complex spatial problems, and how differences in timing can influence apprehension patterns (in terms of chrononumeric and salience measures), and accuracy in both groups. The apprehension patterns of high MRA individuals were then applied as a training mechanism to guide low MRA individuals visually during a timed mental rotation test.

The first experiment in this study (Chapter 3: The Untimed Experiment) sought to explore the relationship between eye movements and MRA during the completion of an Untimed EMRT. While the two groups differed significantly in mental rotation ability, no relationship was observed between the chrononumeric metrics and EMRT score on the untimed test. It was noted that the average response times of high MRA individuals were more variable than low MRA individuals across correct and incorrect questions. This variability may have been reflective of increased flexibility in the underlying cognitive processing associated with spatial task completion, via conflict monitoring. In theory, the process of conflict monitoring includes the evaluation of perceived stimuli by the anterior cingulate cortex for conflicting information, and the transmission of signals to neighboring cortical centers to carry out compensatory adjustments to better control cognitive processing[1]. These compensatory adjustments may take the form of increased processing time, which could account for increased average response times on questions perceived to be challenging (and ultimately answered incorrectly) in the high MRA group. In essence, high MRA individuals may possess better conflict monitoring systems than the low MRA, who do not demonstrate this pattern variability in response time.

In addition to the chrononumeric variability findings, distributions of visual attention were also compared across the two groups. It was observed that on a question-by-question basis, the two groups attended to different features of the block images during test completion, showing no agreement on a question-by-question basis ($\kappa = 0.21$). Literature supports this finding, as individuals with higher spatial ability may demonstrate different visual search patterns compared to lower spatially able individuals[2]. Individuals of low MRA may adopt a less effective search pattern when viewing images for comparison, because they have difficulty identifying the task-relevant salient structures associated with task completion, or possibly because they struggle with the ability to hold an exemplar image in their working memory while problem solving[3]. This finding is supported by the work of Just and Carpenter, who argued that during mental rotation, subjects first encode sections of stimuli individually, and then the subjects must recall where and how each component previously fit together, theoretically requiring the resources of spatial working memory[4].

Moreover, the dichotomy of the two groups' approach to visual search is also exemplified by the Kappa coefficient for agreement. The finding that the two groups show little agreement mirrors the findings of Wilson *et al.,* who contrasted the visual search patterns of novice and expert laparoscopists[5] and that of Zumwalt *et al.,* who observed eye movement patterns of experienced and naïve anatomy students[6]. In these similar search paradigms, more experienced (akin to high MRA) individuals demonstrated very specific direction of gaze to focal regions of the target image, while novices directed their gaze non-specifically[5] to areas of the image not associated with success in the task. As a result, it appears as though individuals of high and low MRA view identical images in different ways, and reach different conclusions. As such, it is possible that eye movement data-driven approaches and gaze-directed instructional methods may present an opportunity for education and training of spatial reasoning.

However, as many MRA tests occur under a time limit, the findings of the Untimed Experiment may not be reflective of typical MRA testing environments, and further research into timed testing environments was merited. The second experiment (Chapter 4:

The Timed Experiment) sought to expand on the findings of The Untimed Experiment by applying a six-second per question time limit. In essence, this experiment sought to further explore how eye movements relate to MRA during the completion of a timed EMRT. It was predicted that as MRA is often measured by speeded tests, the application of a time limit, and the stressors associated with speeded test completion, may exacerbate the dichotomy between high and low MRA. Like the Untimed Experiment, the Timed Experiment yielded little in terms of the chrononumeric metrics of interest. In terms of answer accuracy, the Timed experiment did reveal that correctly answered questions were characterized by fewer fixations per question, and shorter average response times than incorrectly answered questions; reinforcing the theory that individuals who perform well on tasks of spatial reasoning do so with both speed and accuracy[7]. This finding aligns with the conflict hypothesis, that suggests that in timed conditions, the monitoring of response conflict may serve to activate neural mechanisms responsible for overcoming conflict and elevate performance[1]. As a result, the act of conflict monitoring may be attributed to the uniformly elevated response times[1] and average fixations per question observed on incorrectly answered questions.

Further, the distributions of visual attention were again compared across the two groups. The application of the time limit did produced a greater divergence in the agreement between the high and low MRA groups, who attended to the same regions only 34% of the time ($\kappa = 0.20$). As a result, it can be suggested that individuals with an aptitude for performing spatial problem solving are readily able to identify salient areas of presented images, while those who lack this aptitude struggle in identifying task-relevant features. Other eye tracking research paradigms suggests that experience in perceptual tasks influences where individuals attend when viewing imagery, such as in cases of hazard detection, identification of fish locomotion patterns, and visual search and memory recall of art pieces[8–10]. In each context, experienced individuals demonstrated different search patterns than their inexperienced peers. As a result, the ability to rapidly select information that is task-relevant may be key to streamlining problem solving in LMRA individuals.

While The Timed Experiment explored how different individuals responded to a time limit during the EMRT, the design of The Timed Experiment did not reveal how individual differences manifest across the timing conditions. That is, how does an individual's performance of the EMRT differ across both timing conditions? The third experiment in this study (Chapter 5: The Crossover Experiment) sought to build on the observations garnered in the first two experiments and investigated how eye movements differed during the completion of both the Untimed, and Timed EMRT for both MRA groups. A significant difference in EMRT score was observed between Low and High MRA groups, regardless of timing condition. No remarkable differences were observed between the metrics of average response time, average fixation duration and average fixations per question, between the MRA groups, but two of these metrics did vary uniformly across both groups with respect to timing condition and accuracy. Both groups demonstrated elongated average response times in the untimed condition, and on incorrect answers. Likewise, both groups demonstrated elevated average fixations per question in the untimed condition, and on incorrect answers. This finding is also supported by the conflict hypothesis, as more mental resources and effort are dedicated to more challenging questions[1].

The observed behaviour stands in contrast to available literature pertaining to the gender dichotomy that is often considered to parallel high (male) and low (female) ability. In a recent meta-analysis of mental rotation ability across the sexes, the prevalent theory that males outperform females on mental rotation tests was confirmed[11]. In the same meta-analysis, Voyer further explored the differential role that time limits impose on the sexes, and found that the well-established sex difference in mental rotation score is actually diminished in instances of time-limit relaxation[11]. Voyer suggests that females are more prone to anxiety in cases of time restriction[12], which could ultimately negatively effect test outcome[11], while in time-relaxed conditions, females may be able to work more slowly and cautiously than males, and may be able to keep their effort level sustained for improved accuracy[11]. These observations do not align with the EMRT score results of the Crossover Experiment, as both groups respond similarly to the removal of time limits, and the gap between high and low MRA was maintained.

Additional research in test design literature has yielded similar findings when evaluating the effect of time limits on reasoning tests and suggests that when tests are speeded, a great variability in the success of test-takers will be observed.

The findings of Voyer's meta-analysis of time limits and sex differences in mental rotation do align with the salience observations of the Crossover experiment. In the Crossover Experiment, examination of the distributions of visual attention yielded significant differences across the groups as a function of timing condition. In analyses on a question-by-question basis, the salience distributions of HMRA were more consistent across timed and untimed conditions ($\kappa = 0.25$), than the LMRA ($\kappa = 0.013$). This finding directly parallels the finding that males (akin to high MRA) show more consistency across timing condition than females (low MRA).

It appears that high MRA individuals are able to identify that specific domains of the block images are pertinent to solving questions in when the blocks are positioned in different spatial orientations, while low MRA individuals seem to use a single feature consistently to base their judgments, regardless of its task-relevance. Additionally, it seems that the effect of time limits also differs across the groups. Individuals of high MRA are able to consistently identify regions of task-relevant salience across both timing conditions, while low MRA show very inconsistent agreement across the timing conditions. As this finding aligns with the group-wise findings of Voyer's meta-analysis, it is possible that the low MRA group may, like the female group, experience test-related anxiety, and this anxiety may directly impact their ability to interpret task-relevant, salient information. Test related anxiety, or Cognitive Test Anxiety[13], is a particular variety of anxiety in which worry mixes with fear in situations of individual evaluation, particularly in an academic context[14,15]. Typically, females demonstrate greater test anxiety than their male counterparts[14,16], and subsequently anxious females demonstrate lower academic performance[15]. Research suggests that the anxiety may prevent effective use and communication of the pertinent information and result in failure[17]. As a result, visual cueing that directs visual attention, and potentially reduces test anxiety through guidance could serve to direct attention of low MRA individuals experiencing test anxiety to task-relevant salient domains, and potentially improve task performance[18].

Finally, the fourth experiment in this study (Chapter 6: The Guidance Experiment) sought out to train MRA through the application of a visual guidance protocol derived from the eye movements of High MRA individuals (EMME) on the timed EMRT. It was observed that the effect of EMME guidance on EMRT score was contingent on when the EMME guidance was applied. When EMME guidance was applied at the outset of training, the observed differences in score were significantly greater than that expected based on repetition alone. The effect of early training was manifest in the "Guided First" group, who demonstrated a greater mean EMRT score difference between tests. This result is supported directly by the work of Nalanagula et al., who observed that by using feed-forward training based on expert eye movements, the visual search strategies of novices were altered to show improvements in score that were maintained on unguided, untrained circuitry board inspection tests[19]. This finding suggests that by guiding LMRA individuals where to look during spatial problem solving at the outset of training, better search approaches may be adopted and improvements in EMRT performance may be observed.

The findings of The Guidance Experiment also align with the results obtained in the literature, where studies have observed that the accuracy of novices improves when guided by the eye-movements of experts during circuit board inspection, aircraft inspection, and pulmonary nodule identification[19–21]. Pertinent literature suggests that patterns of visual search change as a function of experience[22–25]. The results of The Guidance Experiment support and expand upon this trend in the literature, as a greater percentage of the LMRA group's attention aligned with the EMME in the Group B Unguided Test, suggesting that when the guidance was removed, the LMRA individuals are better prepared to identify task-relevant regions of the image. If one considers the reciprocal finding in the control group, one can surmise that in the absence of visual guidance, the LMRA individuals maintain an inefficient, single-feature based approach to problem solving.

The inefficient approach to problem solving may be explained by individual differences in working memory capacity[26] or inefficient visual search strategies, including the "analytical" feature-matching approach that is often adopted by LMRA individuals. As individuals with LMRA have a reduced capacity for working memory[27,28], than their high MRA peers, any reductions in working memory load may manifest in score differences[29]. By directing vision specifically to salient areas, part of the burden associated with visual search may be alleviated, and may "free up" cognitive resources to process the task at hand[29]. This claim is supported by the model described by Postle, wherein the model of working memory storage is maintained as a series of networks in the posterior cortices[30]. Postle suggests that the storage of spatial and object related material in visual working memory executed by the posterior regions of the dorsal and ventral processing streams[31,32]. As a result, if one considered that the dorsal and ventral streams are burdened by processing of complex information, their execution of visual search may be impeded, or vice-versa. If these cortical regions are previously occupied by completing a complex activity such as mental rotation, removing the additional activity of visual search may expedite the processing of the complex stimuli. Further, by visually cueing the task-relevant domains of the block pairs, this may have identified salient feature of the block-images for the LMRA group, who often adopt an inefficient and unsuccessful analytic approach to problem solving[33]. This may have prevented the LMRA's initial urge to adopt a feature-matching approach and instead employ an assisted mental rotation. As such, through the addition of visual guidance, the LMRA may have been able to adopt more the flexible, orientation-specific search patterns that were demonstrated by the high MRA individuals, and contribute to improvements in EMRT score.

The current research attended to a previously unaddressed niche in eye-movement and spatial ability training literature. In a larger sense, because of its implications associated with visual information presentation, visual guidance and the observation of a dichotomy between novices and experts, the current research provides data and insight into the use and placement of content in instructional multimedia in education. Additionally, the current research serves as a foundation to cultivate methods of honing and improving spatial skills in the general population.

Within the context of spatial ability research, the findings of the current dissertation speak to the malleability of mental rotations ability, and spatial ability. A prevalent topic in the literature[34] many groups have aimed to evaluate the efforts to train mental rotations ability to varied success[35–37]. However, none have sought to apply EMME and visual guidance to address deficits in the LMRA population. The findings of this study confirm that mental rotations ability is malleable, and that the designation of an individual as "LMRA" may be a dynamic classification if the appropriate training protocols are applied. Though the findings of this study are specific to mental rotations ability, further research should seek to explore how EMME protocols can be applied to the other aspects of types of spatial ability tests, to better reveal how spatial ability as a whole may be manipulated in individuals.

The research presented in the current study has direct implications for the spatially complex discipline of anatomy. Success in anatomy is reliant on a firm understanding of the interactions of three-dimensional structures in the visually complicated environments of the human body [6,7,38]. As a result, efforts to train mental rotations ability may directly inform how anatomy educators should augment their approach to instruction. With the consideration that anatomical science is rampant with key terms, clinical pseudonyms, multiple systems, spatial relationships and individual variation, it can be suggested that the intrinsic cognitive load of anatomical material is relatively high[39].

If students are incapable of interpreting spatial information because they lack working memory resources, adequate conflict monitoring, or efficient problem solving strategies, it could be recommended that anatomy instructors be informed of new approaches available to support student learning; particularly through mechanisms that reduce cognitive load, and alleviate cognitive resources. Specifically, instructors may seek to apply instructional techniques that minimize the extraneous cognitive load burden imposed on student's cognitive resources[40] as well as via visual guidance, or relaxation of rigorous timing limits.

More broadly speaking, the findings of this study may be translated beyond anatomy and spatial reasoning tasks to the spatially complex STEM disciplines or into technical training. Literature has demonstrated significant correlations between spatial ability and success in the STEM fields[41]. Indeed, while considering the fact that the American National Research Council has called for continued research into the malleability and trainability of spatial ability, the importance of this construct cannot be overstated. The NRC report suggests that through training spatial reasoning, countries could modify their population and "Maximize their human capital" by honing elevated spatial skills[42]. The NRC goes farther to hypothesize that populations with aptitudes for spatial reasoning could encourage considerable growth in the scientific, technological, engineering and mathematical sectors, and could drive an economical shift to more sustainable, renewable human intellectual resources[42].

Limitations

This study may have been limited by the use of repeated image pairs in the EMRT. By presenting each image pair in triplicate, there is a possibility that with each subsequent exposure, the participants could have experienced a familiarity with the exposure, and refer to previously drawn conclusions, rather than puzzling through it anew. As a result, it is possible that individuals may have been more reliant on their short-term memory to solve the question, rather than actively employing their MRA. Retrospective analysis of data did not reliably show any such pattern of learning, or improvements in accuracy across the triplicate presentation of the images. However, despite no differences in overall accuracy, familiarity may have influenced the results of average response time and average fixations per question findings on the first three experiments, and contributed to the chrononumeric findings observed. Further, the first three studies may have been hindered by small sample size. As each group consisted of only five (The Untimed and Timed Experiments) and seven (The Crossover Experiment) participants, it is possible that the lack of statistical differences in the chrononumeric metrics across the MRA groups may be the result of insufficient power, secondary to small sample size.

In addition to small sample size, this research may also be limited by its specificity. The results draw linkages to many cognitive processes in addition to mental rotations, including spatial working memory, strategy, test-taking anxiety, and conflict monitoring, but this study does not empirically measure any cognitive processes beyond mental rotation. As such, any direct linkages are only inferential, and further study employing tasks such as the N-Back Task[43] (working memory), the Stroop Test[44] (Conflict Monitoring) and scales of test anxiety (such as the Cognitive Test Anxiety Scale[13]) should be employed as covariates in future work.

Moreover, this research may be limited by the design of the main test metric, the EMRT. The EMRT was designed to facilitate evaluation of mental rotation in an eye tracker, and employed block rotations occurring in increments of twenty degrees, from ten to ninety degrees of disparity. While these levels of angular disparity do provide complex spatial arrangements, it is possible that greater levels of disparity could have yielded even more challenging spatially complicated questions[4], and served to further dichotomize the groups, exacerbate the differences between them, and potentially yield significant differences in terms of chrononumeric metrics.

The EMRT may also have been limited by the design, in using the 2-AFC style common to Shepard and Metzler type tests. In applying a 2-AFC-type test[45], it is difficult to control for participant guessing, given the binary nature of response. This may have artificially driven up the EMRT scores. However, given the post-hoc analysis of the binomial test, it is apparent that despite the adoption of the 2-AFC style, individuals did respond at a level exceeding chance, and were not guessing throughout the entirety of the EMRT. Further, the EMRT may have been limited not only by the adherence to the 2-AFC style, but also by its usage of a single block (and its reflected reciprocal) for evaluation for each question. In an effort to prevent non-rotators from relying on feature matching, only one block was employed[33]. As a result, if feature matching was employed, participants would conclude that all of the responses would be "same" regardless of the angular disparity or inclusion of a reflection. This fact may have driven up scores in low MRA individuals who adopted an analytic approach to problem solving, rather relying on their ability to rotate mentally[46].

Finally, while this study found significant effects of training mental rotations ability through EMME visual guidance on the EMRT, this study only explored the first level of generalization testing, using identical stimuli. This study did not explore if these effects can be translated to other standardized tests of mental rotations ability or spatial ability (second level generalization) or the real-world environment (third-level generalization). While other studies have found significant transfer effects of spatial training on untrained tasks, this study did not explore how EMME guidance on the EMRT may transfer to other, novel tasks of MRA or spatial ability. As a result, it is possible that these effects are not generalizable, and recognized only in the paradigm of the EMRT. With this in mind, despite the significant effect, there is no guarantee at this stage that the effects observed in this study can be translated directly to success in anatomy, or other spatially complex disciplines. Moreover, the current study makes references to differences in working memory, based on relationships presented in literature that suggest a significant correlation between spatial ability and working memory capacity. However, as the current study did not evaluate working memory capacity directly, firm conclusions regarding the relationship between working memory, visual guidance and performance on tests of MRA cannot be made at present.

Future Directions

Continued work in this area should seek to expand upon the findings of this study, and elaborate on the use of EMME in other paradigms, particularly other spatial tasks, and anatomically relevant spatial tasks. If the effects of EMME guidance are observed in such a task, the findings may serve to reveal a new paradigm for instruction in not only the anatomical sciences, but the wider spatially complex STEM disciplines as well. Further research may also consider building on the work of Zacks (2008) and endeavor to quantify the underlying neural processes of mental rotations ability[47], working memory, and spatial ability, and examine if these processes differ across high and low MRA individuals. If differences do exist in neural activation patterns of these groups, what role does EMME guidance play, if any, in the augmentation of neural activation patterns?

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B. Research Ethics Board Approval

Western Research

Research Ethics

Use of Human Participants - Ethics Approval Notice

Principal Investigator: Dr. Tim Wilson
File Number: 103970
Review Level: Delegated
Approved Local Adult Participants: 60
Approved Local Minor Participants: 0
Protocol Title: The Path More Travelled: defining gaze-based approaches to spatial tasks in anatomy.
Department & Institution: Schulich School of Medicine and Dentistry\Anatomy & Cell Biology,Western University
Sponsor:
Ethics Approval Date: July 31, 2013 **Expiry Date:** August 31, 2015
Documents Reviewed & Approved & Documents Received for Information:

Document Name	Comments	Version Date
Protocol		2013/06/10
Western University Protocol		2013/06/18
Board Recommendations	Response to Board Requirements	2013/07/22
Other	Demographic Questionnaire	2013/07/22
Other	Follow Up Questionnaire	2013/07/22
Instruments	SAMPLE OF SPATIAL TASKS	2013/07/10
Revised Letter of Information & Consent	REVISED LETTER OF INFORMATION/CONSENT	2013/07/10
Other	LETTER OF RECRUITMENT THIS LETTER WILL BE EMPLOYED AS A VERBAL SCRIPT TO RECRUIT INTERESTED HEALTH SCIENCE STUDENTS (IN-CLASS)	2013/07/10
Recommendations Form	Recommendations	2013/07/05

This is to notify you that The University of Western Ontario Research Ethics Board for Health Sciences Research Involving Human Subjects (HSREB) which is organized and operates according to the Tri-Council Policy Statement: Ethical Conduct of Research Involving Humans and the Health Canada/ICH Good Clinical Practice Practices: Consolidated Guidelines; and the applicable laws and regulations of Ontario has reviewed and granted approval to the above referenced revision(s) or amendment(s) on the approval date noted above. The membership of this REB also complies with the membership requirements for REB's as defined in Division 5 of the Food and Drug Regulations.

The ethics approval for this study shall remain valid until the expiry date noted above assuming timely and acceptable responses to the HSREB's periodic requests for surveillance and monitoring information. If you require an updated approval notice prior to that time you must request it using the University of Western Ontario Updated Approval Request Form.

Members of the HSREB who are named as investigators in research studies, or declare a conflict of interest, do not participate in discussion related to, nor vote on, such studies when they are presented to the HSREB.

The Chair of the HSREB is Dr. Joseph Gilbert. The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

Curriculum Vitae

Name	Victoria Roach
Post-secondary Education and Degrees	Laurentian University Sudbury, Ontario, Canada 2009 B.Sc. (Hon.)
	The University of Western Ontario London, Ontario, Canada 2011 M.Sc.
	The University of Western Ontario London, Ontario, Canada 2016 Ph.D.
Honors and Awards	Francis Chan Award for outstanding extracurricular involvement, mentorship of junior students and humanitarian conduct. June 2015
	Social Sciences and Humanities Research Council of Canada (SSHRC) Doctoral Fellowships September 2014- August 2016
	American Association of Anatomists (AAA) Educational Research Platform Presentation Award Finalist April 2014
	Ontario Graduate Scholarship (OGS) – Declined September 2014- August 2015
	Western Graduate Research Scholarship (WGRS) September 2009- August 2015
	Schulich Graduate Scholarship (SGS) September 2009-2011
Related Work Experience	University of Western Ontario Sessional Instructor Continuing Studies at Western Financial Aspects of Clinical Trials Management 2015-2016

The University of Western Ontario
Teaching Assistant
Medical Gross Anatomy, School of Physical Therapy, School of Occupational Therapy, Dental Gross Anatomy, Undergraduate Systemic Anatomy.
September 2009- December 2015

Publications

2015 **Roach VA**, Fraser GM, Kryklywy J, Mitchell D, Wilson TD.. Perfect Timing: How do time limits impact eye movements during spatial reasoning? Anatomical Sciences Education [Under Review].

2015 **Roach VA**, Fraser GM, Kryklywy J, Mitchell D, Wilson TD. Do The "Eyes" Have It? How Eye Tracking Can Reveal Accuracy In A Timed Test Of Spatial Reasoning. Cognitive Science [Under Review].

2015 **Roach VA**, Fraser GM, Kryklywy J, Mitchell D, Wilson TD. The Eye of the Beholder: Can patterns in eye movement reveal aptitudes for spatial reasoning? Anatomical Sciences Education [Accepted].

2014 Van Nuland SE, **Roach VA**, Wilson TD and Belliveau DJ. Head to head: The role of academic competition in undergraduate anatomical education. Anatomical Sciences Education. 8(5):404-12

2014 **Roach VA**, Mistry MR , Wilson TD. Spatial visualization ability and laparoscopic skills in novice learners: Evaluating stereoscopic versus monoscopic visualizations. Anatomical sciences education. 7(4): 295-301.

2013 Martin CM, **Roach VA**, Nguyen NT, Rice CL, Wilson TD. Comparison of 3D reconstructive technologies used for morphometric research and the translation of knowledge using a decision matrix. Anatomical sciences education. 6(6): 393-403.

2013 Mistry MR, **Roach VA**, Wilson TD. Application of stereoscopic visualization on surgical skill acquisition in novices. Journal of surgical education. 70(5): 295-301.

2012 **Roach VA**, Brandt MG, Moore CC, Wilson TD. Is three-dimensional videography the cutting edge of surgical skill acquisition? Anatomical sciences education. 5(3):138-45.