ANGULAR DISPARITY AND DIMENSIONALITY IN MENTAL ROTATION: CHARACTERISTICS OF SACCADIC EYE MOVEMENT AND ELECTROENCEPHALOGRAM

Ph.D. Thesis

By

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DEPARTMENT OF BIOSCIENCES AND BIOMEDICAL ENGINEERING

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ANGULAR DISPARITY AND DIMENSIONALITY IN MENTAL ROTATION: CHARACTERISTICS OF SACCADIC EYE MOVEMENT AND ELECTROENCEPHALOGRAM

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **ANGULAR DISPARITY AND DIMENSIONALITY IN MENTAL ROTATION: CHARACTERISTICS OF SACCADIC EYE MOVEMENT AND ELECTROENCEPHALOGRAM** in the partial fulfillment of the requirements for the award of the degree of **DOCTOR OF PHILOSOPHY** and submitted in the **DEPARTMENT OF BIOSCIENCES AND BIOMEDICAL ENGINEERING, Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the time period from July 2015 to July 2021 under the supervision of Dr. Sanjram Premjit Khanganba, Associate Professor, Indian Institute of Technology Indore and Dr. Ram Bilas Pachori, Professor, Indian Institute of Technology Indore.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

Akanksha Tiwari
16/07/2021

(AKANKSHA TIWARI)

This is to certify that the above statement made by the candidate is correct to the best of my/our knowledge.

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AKANKSHA TIWARI has successfully given her Ph.D. Oral Examination held on **February 25th, 2022**.

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To

My Grandfather

LIST OF ABBREVIATIONS

MR	Mental rotation
AD	Angular disparity
CA	Convex angle
RA	Reflex angle
2D	Two-dimensional
3D	Three-dimensional
RT	Response time
EEG	Electroencephalography
MRI	Magnetic Resonance Imaging
LI	Laterality index
CWL	Cognitive workload
BEM	Boundary Element Model
DICS	Dynamic imaging of coherent sources

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ABSTRACT

Mental rotation is an essential aspect of visuospatial processing in playing computer-games. Computer gaming is one of the most common activities that individuals are indulged in their usual activities concerning interactive system-based entertainment. During computer-games, mental rotation ability can be used as a proper strategy for understanding and fulfilling specific requirements, like area measurement tasks, composing and decomposing two- or three-dimensional objects, proving symmetry, finding missing parts of an object, etc. The gaze behavior and neural activities can unfold plenty of valuable links and understanding about an individual's cognitive state of mind during engagement in cognitive processing. Here, as the focus revolves around objects' visuospatial characteristics and their processing during mental rotation, this dissertation provides insights on gaze parameters and neural activities during a mental rotation computer-game involving 2D and 3D isomorphic objects with varying angular disparity. Along with dimensionality (2D vs. 3D) of the object, angular disparity also has two levels, convex angle (between 0^0 to 180^0) vs. reflex angle (between 180^0 to 360^0). This dissertation comprises three different thematic analysis approaches for four groups with the unique combination of angular disparity and dimensionality with 60 healthy participants.

The first theme of the analysis is focused on saccadic gaze behavior and provides insights on saccadic characteristics in gaming task performance that involves 2D and 3D isomorphic objects with varying angular disparity. Gaze behavior data of all participants were recorded during task execution and analyzed to find the changes in spatiotemporal characteristics of saccades associated with the variation in angular disparity and dimensionality. Results indicate that the spatial characteristics of the object affect the temporal aspect of the saccade (duration), whereas the spatial aspect of the saccade (amplitude) is influenced by the objects'

dimension. A longer saccade duration indicates a prolonged suppression of spatial information processing during the MR tasks with objects at convex range angular disparities. Therefore, the MR tasks with convex angular disparity become more complex to process compared to the tasks with reflex angular disparity. MR process is faster and more accurate with 3D objects than 2D objects. Hence, during the MR task, the longer saccade duration implies that the tasks with convex angular disparities become comparatively more challenging. Also, the lower saccadic amplitude for 2D objects indicates difficulties in processing due to deficient visual features.

The second theme of the focus investigates how dimensionality and angular disparity affect spatio-spectral characteristics of electroencephalogram (EEG) during mental rotation in computer-games. Hemispheric laterality and significant clusters were identified using spectral power for the frequency range of 3.5–30 Hz EEG signals. The results indicated higher alpha desynchronization during mental rotation compared to baseline. Overall, the results showed different hemispheric lateralization dominance with respect to object characteristics in such a way that right hemispheric lateralization for convex angular disparity and 3D objects, whereas left-hemispheric lateralization for reflex angular disparity and 2D objects in the parietal region. Further, higher neural active areas as no. of clusters elicited by convex angular disparities and 3D objects in the game compared to the reflex angles and 2D objects.

The next analysis focuses on how the objects' visuospatial characteristics (i.e., angular disparity and dimensionality) in an MR-based computer-game influence the cortical activities in dorsal-ventral visual pathways. The source reconstruction was done for ~3000 sources inside the brain using the Dynamic Imaging of Coherent Sources (DICS) beamforming method for $\theta 1$(4–5.75), $\theta 2$(5.75–7.5), $\alpha 1$(7.5–9), $\alpha 2$(9–11), $\alpha 3$(11–13), $\beta 1$(13–17.25), $\beta 2$(17.25–21.5) Hz frequency sub-bands. The

reconstructed neuronal sources were segmented into 68 functionally parcellated brain regions, and the percentage of active sources for each region was computed. Further, the differences across the 68 regions among the four gaming conditions were evaluated using the percentage of active sources. The differences in activation for the dorsal-ventral pathways and some additional brain regions were observed among the four groups. The game with 2D objects and convex angular disparity showed higher activation than that with 3D objects and reflex angular disparity. The dorsal pathway was more active in contrast to the ventral pathway. The findings suggest that angular disparity and dimensionality in MR influence the engagement of dorsal-ventral visual pathways in such a way that angular disparity has a greater impact on cortical activation across this region than dimensionality. Also, higher activation for convex angular disparity than reflex angular disparity irrespective of dimensionality reflects the complexity of spatial information processing under the convex category. Similarly, greater activation was seen for 2D objects than 3D, indicating difficulty in information processing due to deficient visual features.

The findings enlighten the association of dependent and independent parameters in the MR task, which can be considered for making the strategies for improving the performance in a task involving visuospatial manipulation. The findings may further help in developing/enhancing computer-games for several applications, e.g., MR training, brain entrainment, rehabilitation. This study also has potential applicability in modeling human cognitive processes, especially visual and spatial features.

Keywords: Mental rotation, Angular disparity, Dimensionality, Computer-games, Saccadic gaze behavior, EEG spatio-spectral characteristics, Hemispheric laterality, Channel-clusters, Source localization, DICS beamformer, Dorsal-ventral pathway.

Chapter 1

Introduction

1.1. Background of the Study

Visuospatial processing is a primary essential aspect of human cognition, which belongs to a complex network. Some specific cognitive processes involved in dealing with visuospatial information are coding, retrieval, and perception. Perception is the process that consists of organization, identification, and interpretation of sensory information in order to represent and comprehend the presented information or environment (Schacter & Daniel, 2011). Our capacity to reach for objects in the visual field and change our gaze to different locations in space, both are dependent on visuospatial perception. Thus, visuospatial processing functions refer to cognitive processes necessary to identify, integrate, and analyze the visual and spatial form, details, and structure in more than one dimension. Visuospatial skills are crucial for the perception of movement, depth, distance, and spatial navigation (Dickerson & Alireza, 2014). By utilizing these skills, we can judge the distance between two objects, which can be helpful, for instance, to monitor the space between the vehicle and the surrounding obstacles while parking a car. Further, we also utilize visuospatial skills when imagining the location or surroundings that someone discussed earlier or when mentally rotating objects to imagine what they might seem like before actually doing it. Visuospatial impairment can lead to various problems, for example, low driving ability due to incorrect distance judgments or trouble navigating in space, such as bumping into things (Dickerson & Alireza, 2014). Mental rotation is one of the major visuospatial skills that is significantly utilized in our day-to-day activities in many ways. It is suggested as a cognitive operation in which a mental representation of an object or image is created and mentally rotated into a different orientation in space at various angular disparities. Usually, such a process needs to strategize the cognitive manipulation and spatial transformation of objects in either a two-dimensional or three-dimensional model. Further, interestingly, it may also include the rotation of body parts or shapes with embodied effects. (Guillot et al., 2012). The mental rotations test is probably the most general way of investigating mental rotation processing, as well as spatial skills in general. Arguably, it has been utilized to investigate spatial cognition not only in the behavioral and neurocognition field but also in most of the science disciplines as well (Castro-Alonso & Atit, 2019), like human anatomy (Jang et al. 2017; Berney et al. 2015; Stull et al. 2009; Garg et al. 2001); human surgery (Wanzel et al. 2002); human dentistry (Kozhevnikov et al. 2013; Hegarty et al. 2009); general chemistry (Hinze et al., 2013); organic chemistry (Stull et al., 2018); physics (Kozhevnikov & Thornton 2006; Peters et al., 1995); geology (Resnick & Shipley 2013; Atit et al., 2013); and zoology (Imhof et al., 2013). A prominent association of spatial ability, including mental rotation, with functional learning, is also a great implementation. In the domain of the medical field, the learning of functional anatomy and surgical procedures has been considered already (e.g., Garg et al., 2001). Higher spatial and mental rotation abilities are associated with greater learning and retention of functional anatomy information, as well as better surgical outcomes, than lower skills.

On the other hand, training and improving visuospatial skills are often associated with computer/video gameplay. Previous research suggests that, depending on the type of video/computer game, it can help to equalize individual disparities in spatial skill performance. Computer-games must be extensively investigated for their utilization beyond entertainment due to complex information processing requirements and the fast-growing gaming industry. Computer-games with mental rotation processing can significantly improve visuospatial performance and other associated cognitive skills (Green & Bavelier, 2006; Feng et al., 2007, Cherney, 2008; Trisolini et al., 2018; Petilli et al., 2020), such as judgment and evaluation, decision-making.

1.2. Context of the Problem

Visuospatial skill is the ability that includes the representation, analysis, and mental manipulation of objects. When it comes to visuospatial abilities, there are two key principles to remember. The first is spatial relations, which refers to the ability to visualize and mentally manipulate two-dimensional objects. The second is spatial visualization, which is the ability to visualize and mentally manipulate three-dimensional objects. One of the best utilization of such types of skills can be seen in computer games. Nowadays, computers in our daily lives are widespread because they are no longer a tool that only experts can use, and computer literacy must start from an early age. Computer and video games are commonly acknowledged as entertainment platforms, but they also provide an excellent learning environment (Prensky, 2005). Computer games could affect the development of abilities such as spatial visualization (Green & Bavelier, 2003), communication skills (Herz, 2001) critical and logical thinking (De Castell & Jenson, 2004). Studies have also established relationship among mental rotation, computer games, and spatial skills (De Lisi & Wolford, 2002). Oei and Patterson (2013) suggested that the frequent training of a specific cognitive skill also reflects in another task if they both share common underlying demands. Meneghetti et al. (2016) also reported a similar phenomenon, suggesting the transfer effects of mental rotation training in the task requiring spatial skill. In this way, it can be utilized in a controlled manner to track individuals' cognitive performances due to a particular parameter. Understanding the driving parameters in the mental rotation process would certainly help to improve a computer-game for training the mental rotation abilities.

1.3. Purpose of the Study

Computer-games are composed of complex visuospatial information with patterns requiring rotation (usually require fast responses), and the MR ability plays an essential role while executing the task efficiently. Though these games have been growing in recent years primarily for entertainment, recent studies have been supporting their usefulness and effectiveness in training cognitive abilities (e.g., Green & Bavelier, 2006; Feng et al., 2007, Cherney, 2008; Trisolini et al., 2018; Petilli et al., 2020). Here, the object characteristics significantly contribute to performance during MR processing in computer-games. Two main characteristics of objects, i.e., angular disparity and dimensionality, have been studied in MR tasks with different object types and contexts (Zacks & Michelon, 2005; Kessler & Thomson, 2010; Thomas et al., 2013). Computer-games requiring mental rotation ability could effectively train spatial abilities, considering their fast-growing access to everyone through smartphones and other multimedia devices. Thus, it can provide a covert tool to train a cognitive skill silently behind a computer-game. These reasons motivated us to investigate how the driving components of the mental rotation process in a computer-game impact the human brain. Using the isomorphic objects in 2D and 3D models with the combination of specific angular disparity categories, i.e., convex angular disparity and reflex angular disparity in the form of a computer game, is an exploring thought behind this study. The current research intends to gain a scientific understanding of the underlying relationships between characteristics of isomorphic objects (angular disparity and dimensionality), saccadic gaze behavior, and spatio-spectral characteristics of EEG during mental rotation computer-game.

This dissertation explores the visuospatial processing of objects' spatial and appearance information and addresses three problems by utilizing gaze data and EEG data during the MR processing in a computer-game. Available literature indicates that behavioral, physiological, and neuronal activity variation during mental rotation is influenced by the object appearance information and the information about its location in space, but the strategy or approach followed, the category of objects and the context of the task also play a crucial role to show their impact on them (Alivisatos & Petrides, 1997; Zacks et al., 2003; Zacks, 2008). In this context, the first problem addressed the saccadic gaze characteristic of the eye movement with the angular disparity of isomorphic 2D and 3D objects' mental rotation. Another approach explored the EEG spatio-spectral characteristics during visuospatial processing in mental rotation with different dimensionality and angular disparity combinations. The next problem turned into the brain's visuospatial information processing pathways and explored the dorsal-ventral visuospatial pathways with object characteristics by utilizing beamformer neuronal source-level analysis of EEG.

1.4. Significance and Objectives of the Study

The current study has significance in improving visuospatial skills by computer-game when the utilized characteristics of information presented in the game can be managed in controlled ways. It can be utilized as a therapeutic tool to enhance other associated cognitive skills. Previous research in health science education has supported the idea that students in various scientific and medical areas may benefit with the spatial ability and mental rotation training (Garg et al., 2001; Hegarty et al., 2009). The ability of object rotations may be transferred to mental rotation tasks requiring egocentric transformations, allowing students' potential for success in anatomy to be assessed using spatial ability and mental rotation tests (Guillot et al., 2007). The impact of mental rotation training on anatomy learning and the internal mechanism of such a transfer has also been investigated (Hoyek et al., 2009), concluding that having a high mental rotation skill may help acquire, learn, and retain anatomical knowledge. Spatial skills like mental rotation also have a significant implication in military training. In order to make mission-critical judgments, mental rotation facilitates a soldier to "see" the target and associated regions from different angles. It allows the soldier to design an efficient strategy using the resource-favorable path (Spencer, Beehner & Thomas, 2018). Another potential significance of mental rotation can be easily seen in luggage scanning at security points. It enables the monitoring personnel to efficiently identify any suspicious object hidden in complex carry-on luggage by mentally rotating the objects at various angles (Krüger & Suchan, 2016). Further, a transfer effect of mental rotation abilities from a task demanding rotation of two- or three-dimensional objects to a task involving the transformation of body segments and complicated anatomical systems was discovered in the study (Hoyek et al., 2009). Transfer between mental rotation abilities to complex motor skills, such as body rotations and directional changes, might be useful as well. In theory, if mental rotation and motor performance share comparable mental processes, improving mental rotation ability or its sub-processes could be transferred to the physical execution of a given action, contributing to performance enhancement.

Apart from this, there is a category of games called ‘serious games’ developed for the specific purpose (to treat a particular issue like healthcare, education, motivation, etc.) with a high possibility of cure. Fleming et al. (2017) suggested six major categories of applied games (serious games) - Virtual reality, Cognitive behavior therapy-based games, Biofeedback-based games, Cognitive training games, Entertainment games, Exergames. Different methods for research with these interventions are used- method for immediate and long-term effect, physiological measures-based method, and questionnaire/ survey-based method. The benefits of computer or video game training on the cognitive and emotional skills of the healthy adult population and their efficacy have been shown not just for non-commercial video games or commercial brain-training programs but also for commercial games. But the inference that genuinely drives the enhancement of cognitive skills within a game needs to be understood. Because of the involvement of several complex variables in gaming mechanism, the outcome of any particular one is difficult to detect. So, if we control a specific cognitive variable in a computer-game, such a guided game can be utilized to train the associated cognitive skills. Thus, the findings of the current study can further help to develop/improve computer-games for several applications, e.g., MR training, brain entertainment. Since computer-games are getting more common via handheld devices, there are possibilities to utilize them as a covert tool for training our cognitive skills silently behind entertainment. Overall, the current dissertation focuses on two specific object characteristics, i.e., the angular disparity in two categories (convex angular disparity and reflex angular disparity) with two categories of dimensionality (2D and 3D) of isomorphic objects in parity judgment-based MR processing. This study has utilized the computer-game environment and presented the MR in the form of a computer-game to the participants to evaluate MR processing in an interactive and impactful manner.

Notably, the present research explores the role of unique combinations of angular disparity and dimensionality with isomorphic objects in mental rotation computer-game using the saccadic characteristics of gaze behavior and brain signals, i.e. (EEG) electroencephalogram. Three research questions were addressed with the following specific objectives to attempt these scientific observations:

A. Saccadic Characteristics of Gaze

1. To investigate the effect of object characteristics (angular disparity and dimensionality) in MR computer-game on saccade duration.

2. To investigate the effect of object characteristics (angular disparity and dimensionality) in MR computer-game on the saccadic amplitude.

B. Spatio-spectral characteristics of EEG rhythms

1. Utilizing a clustering approach to evaluate the changes in spatio-spectral features of EEG rhythms during MR computer-game with varying dimensionality and angular disparity of an object.

2. To investigate hemispheric laterality changes during MR computer-game with specific conditions of dimension and angular disparity of objects utilizing spatio-spectral features of EEG rhythms.

C. Activities in Dorsal-ventral Pathways and other Associated Regions

1. To study the source level activation in the brain while MR during the computer-game.

2. To investigate the cortical networks associated with MR computer-game with specific conditions of dimension and angular disparity of an object.

3. To investigate the dorsal-ventral pathways of the brain associated with MR computer-game with specific conditions of dimension and angular disparity of an object.

1.5. Parity Task: Isomorphic and Non-isomorphic Objects

Among the experiments previously carried out in mental rotation, the parity tasks are the most common where an individual had to match and find the pair of visual patterns from the given choices by mentally rotating them. Shepard and Metzler (1971) first analyzed mental rotation with pairs of rotating block stimuli/objects using their classic mental rotation parity judgment task. When information concerning an object's handedness, or parity, has to be accessible, the imagined rotation of a visual representation from one orientation to another is referred to as mental rotation. For example, determining whether a misoriented letter is printed in its original shape or has been mirror-reversed necessitates mental rotation to the upright before making this parity decision (Cooper & Shepard, 1973). Parity judgment tasks are widely used to explore the eye movement and neural mechanisms underlying mental rotation (Carpenter et al., 1999; Koshino et al., 2005; Zacks, 2008; Xue et al., 2017; Moen et al., 2020).

During parity judgment-based tasks, dimensionality also plays a crucial role. Different 2D and 3D object types have been used to study the MR in the parity task. However, when both types of dimensionalities have been compared in the previous studies, the two different object types have usually been utilized, whereby the use of isomorphic stimuli is missing. The term "non-isomorphic" means not having the same form or structure. Using the non-isomorphic objects (i.e., two different objects type) to compare the effect of dimensionality is an essential concern because the object category (stimulus type) also could influence the selection of strategy to process MR. The point is that if objects are non-isomorphic, there is a concern related to experimental control. In other words, the effect may not be only because of dimensionality, but also the factor concerning non-isomorphic objects itself could play a role. The isomorphic objects can be referred to as identical or similar forms, shapes, or structures. The interest in isomorphisms lies in that- the characteristics of two isomorphic objects are identical (excluding further information such as additional structure or names of objects). The current study has used isomorphic objects, allowing better experimental control in studying the 2D vs. 3D aspects of dimensionality.

1.6. Thesis Outline

This chapter has highlighted the background and the context of the study. It has also specified the purpose and objectives of the current study. Chapter 2 discusses the available literature specifying the role of visuospatial information processing during mental rotation and the association of mental rotation with computer-games, saccadic gaze behavior, and spatio-spectral characteristics of EEG rhythms. Chapter 3 explains the methodology in detail used in the current dissertation. Further, chapters 4-6 reports three different thematic analysis approaches of the study. Chapter 4 reports the behavioral analysis approach, which investigated how the saccadic characteristics of gaze behavior are affected by the angular disparity of an isomorphic 2D/3D object in MR computer-game. Chapter 5-6 report physiological analysis approaches by utilizing EEG signals. Chapter 5 focuses on investigating how the specific combinations of angular disparity and dimensionality of an object affect spatio-spectral characteristics of EEG rhythms. On the other hand, Chapter 6 reports the involvement of the brain region associated with dorsal-ventral visuospatial pathways recruited during the processing of object characteristics is investigated in MR computer-game. Finally, chapter 7 provides a general discussion based on the study's findings, and chapter 8 presents a consolidated account of the findings, discusses the limitations and the implications of this research, and describes the scope for future research.

Chapter 2

Review of Literature

2.1. Visuospatial Processing

To process any information, our visuospatial ability plays a major role, and visuospatial information processing is a rudimentary characteristic in human cognition. In their working memory model, Baddeley and Hitch (1974) proposed that the working memory system consists of central executive, visuospatial sketchpad, and the phonological loop. The visuospatial sketchpad contains visual and spatial information received through the senses or obtained from long-term memory (LTM). According to Logie (1989), visuospatial sketchpad division is also possible in two components- the first is ‘the visual cache’ and the second is the ‘inner scribe’. The visual cache saves information about shape and color, whereas the inner scribe retains the spatial and movement information. In addition, the information gets rehearsed by the inner scribe in the visual cache, and further, it gets transferred to the central executive. Research demonstrates that the brain's visual regions are split into two different pathways (Milner & Goodale, 1995), the dorsal and ventral pathways, or spatial and object pathways. The ventral stream or object pathway is also called the ‘vision-for-perception’ pathway, which plays a significant role in in the identification and differentiation of visual forms and objects, whereas the dorsal stream, also known as the "vision-for-action" pathway, is primarily involved in visually directed processing of object spatial position and orientation. (Hebart, & Hesselmann, 2012).

The ability to interpret visual information about spatial characteristics of objects and their parts and conduct mental spatial transformations and manipulations is referred to as ‘spatial visualization’. So, mental rotation processing is the appropriate cognitive function in terms of spatial visualization. Mental rotation involves dorsal stream spatial operations on the representations stored in the object working memory subsystem of the ventral stream (Hyun & Luck, 2007). The mental rotation has its specific aspects, like angular disparity and dimensionality, which is necessary to identify any object’s appearance, spatial orientation and location (Cooper, 1975; Metzler, 1973; Metzler & Shepard, 1974; Shepard & Metzler, 1971; Vandenberg & Kuse, 1978; Ganis & Kievit, 2015; Bałaj, 2015). Mental rotation performance may improve not just as a result of an adequate representation being encoded but also due to the improved process of mentally rotating the representation. In mental rotation tasks, the angle of disparity (0–180 degrees) between the two items varies between trials. The angular disparity causes the response time (RT) to rise. The longer the RT should be, the more likely it is that the individual is rotating a mental representation of the stimuli to match the other stimulus (Shepard & Metzler, 1971). It is anticipated that as mental rotation abilities improve, the slope of the RT should decrease. In addition, on mental rotation trials, there is more activation in regions of the visuospatial network/VSN (e.g., superior parietal lobe) and motor areas (e.g., primary motor and premotor areas) than nonrotation control trials, and this activity linearly increases with increasing angular disparity (Logie et al., 2011; Leek & Johnston, 2009; Zacks, 2008; Zacks et al., 2003; Carpenter et al., 1999). As a result, the RT slope may decrease as mental rotation abilities improve, but activity in the VSN and motor regions may rise.

Besides angular disparity and dimensionality, several other factors can influence an individual's mental rotation ability. For example, Mohler reviewed that the mental rotation of a person is affected by brain physiology, gender, age, socio-cultural factors (Mohler, 2008).

2.2. Mental Rotation and Computer-games

Visuospatial skills training like mental rotation is often accomplished with video/computer game play. Research suggests that individuals can benefit from playing video/computer games to enhance their spatial abilities (Subrahmanyam & Greenfield 1994; McClurg & Chaillé 1987; Dorval & Pepin 1986). By providing extended mental rotation training to the students, Terlecki and Newcombe (2005) noticed that the students were still enhancing their mental rotation skills after a semester of work with no indication of leveling off. The researchers suggested that after playing video games that include spatial skills, children performed better in mental rotation tasks in post-test than pre-test. Feng, Spence, and Pratt (2007) reported that playing an action video game would minimize gender disparities in mental rotation skills, and the mental rotation efficiency of participants also improves. The connection between spatial abilities and video games has also been explored. The significant discrepancies in the mental rotation performances were also reported between videogame players and non-players (Quaiser-Pohl et al., 2006), with the poorer performance of the non-players group than that of the players group. The similar trend was reported by Sims and Mayer (2002) also as they attempted to investigate the influence of video game play on spatial skills. They observed higher mental rotation ratings in video game players.

In terms of mobility, there are two categories of computer and video games, i.e., two-dimensional (2D) and three-dimensional (3D) games. In a

2D game, the player can only move a character across x-y axes in 2D plane, i.e., left-right or up-down; whereas in a 3D game, the player can also move forward-back (Gagnon, 1985). The impact of 2D/3D computer-game playing on spatial abilities has also been investigated in several studies. For example, Cherney (2008) investigated how practice and delivery of 3D and 2D computer games influenced the performance on mental rotation tests and suggested an improvement in the score for both types of games. Furthermore, the findings indicated that with limited computer game practice, spatial abilities could be enhanced. However, a significant difference was reported in favor of 3D players. Similarly, Green and Bavelier (2003) explored the influence of playing video games on visual ability. According to their findings, the focus and visual skills of 3D video games players were substantially increased. In other words, this can be stated that mental rotational skills are stronger in habitual 3D computer game players with enhanced spatial processing skills than in 2D computer game players and non-players. Dorval and Pepin (1986) analyzed the ability to discern the 3-D structure of a 2-D object and tested how the same object would appear if rotated in space. The trained group had considerably higher spatial ability ratings than the control group after training with the video game, indicating that spatial visualization can be improved through video/computer game play. Further, the ability to deduce an object's three-dimensional structure from a two-dimensional depiction is critical for architects and engineers. Increases in spatial abilities like mental rotation, mental folding, etc., might also benefit many other professions, such as pilots, mechanics, machine operators, and draftsmen (Gagnon, 1985). A connection could exist between the playing and learning of video games. Spatial abilities may play an essential role in the learning process and an individual’s work performance.

2.3. Eye-movements and Saccadic Characteristics

Eye movements and their understating are critical for processing any visual and/or spatial information. They are the real-time measures of cognitive processes in any given situation. Even when concentrated and fixed at one point, the eyes are never entirely still; they make frequent fixational eye movements. The photoreceptors and ganglion cells are involved in this fixational eye movement. A persistent visual stimulus tends to render the photoreceptors or the ganglion cells unresponsive; a changing stimulus, on the other hand, would not. Therefore, eye movement continuously alters the stimuli on the photoreceptors and ganglion cells, rendering the image clearer (Carlson & Heth, 2010).

Eye movement comprises the voluntary or involuntary movement of the eyes, which helps in acquisition, fixation, and tracking to visual stimuli. The brain holds primary control over both types of eye movement, whether voluntary or involuntary. Numerous brain regions contribute to both these types of eye movements, along with the muscles' movement. These cortical areas include the regions associated with the conscious perception of vision and areas that facilitate tracking. Three forms of voluntary eye movements are used by primates and many other vertebrates to track the object or scene of interest: smooth pursuit, vergence shift (Pierrot-Deseilligny et al., 2004), and saccades (Krauzlis, 2005). A small cortical area in the brain's frontal region appears to be the source of these movements (Heinen & Liu, 1997; Tehovnik et al., 2000). Saccades are the quick movement the eyes used when visual information is scanned. For example, while reading, the eyes do not move smoothly across the written paper as per our subjective impression. Instead, they create short and quick movements referred to as saccades (Wayne, 2003).

There are some major parameters of saccadic eye movement, which are as follows: (a) *Saccadic amplitude* – It refers to the size of the saccade, which is commonly expressed in degrees or minutes of arc. The amplitude influences saccade accuracy and is sometimes expressed using "gain," where the gain is defined as the actual and desired saccade amplitudes ratio. (b) *Average saccadic velocity*- Average velocity over a movement is related to the amplitude and duration by the classical equation ($v=\theta/t$). Average Saccadic velocity is an average of velocities over the entire saccade duration measured in degree/sec. The velocity profiles of saccades are generally symmetrical, at least for small and medium-sized saccades. So, identifying the peak is usually straightforward. While the size of saccades remains quite precise in some circumstances, the saccade velocity is considerably reduced, resulting in so-called slowed saccades. (c) *Saccade duration* – It is referred to as the time utilized to complete the saccade, and it's simple to calculate using the velocity profile. Most saccades are completed in a few tens of milliseconds (ms), partly due to the high velocity involved. (d) *Saccade latency* - This is the time it takes for a target to appear and for a saccade to commence in reaction to it. It is also measured in milliseconds (ms).

Saccades are shown to be very stereotyped, and relatively fixed relationships is suggested between its amplitude, duration, and peak velocity. The correlations between saccade amplitude, saccade length, and saccade velocity are sufficiently consistent that they may be used to determine whether or not a given eye movement is a normal saccade. As a result, saccades have a "main sequence," and these parameters and their relationships are referred to as main-sequence parameters and relationships.

For healthy individuals, the relationship between amplitude and duration of saccade is reasonably linear (Carpenter, 1988).

In mental rotation processing, the piecemeal approach is the most prevalent. The stimulus is visually perceived in individual segments by subjects and internalizes the pieces to represent the whole stimulus. It includes decomposing the stimulus structure into many pieces, mentally rotating the one piece to align it with the target figure to compare, and then repeating the process with the remaining segments to ensure parity. During mental-rotation processing, eye fixation patterns also reflect a piecemeal strategy (Just & Carpenter, 1976; 1985). Just and Carpenter suggested that participants first rotated one piece of the stimulus and later determined whether the other pieces were rotated into congruence. Another study (Noton & Stark,1971) reported that cognitive focus on the angles of the visual stimulus plays a major role in the creation of an internal representation of the stimulus, and a similar fixation pattern is used on the matched stimuli when an original stimulus is perceived and interpreted by matching; specifically, subjects fixate on the matching item's similar lines, corners, or angles in the same sequence as while encoding the preceding stimulus.

A typical mental rotation task involves determining whether two things presented together are rotated versions of the same object. This necessitates the encoding and then rotation of a representation of the first object to match the second object. Following that, a comparison between the rotated mental image and the second object prompts a decision (Larsen, 2014). Learning to mentally rotate the encoded representation more efficiently can therefore help to enhance spatial reasoning and thinking skills. When a complete representation of the stimulus is encoded, mental rotation performance and efficiency increase (Heil & Jansen Osmann, 2008), especially when multiple object parts and spatial relationships between them are incorporated (Erdogan et al., 2016).

Saccades are one way of estimating the extend of encoding. These are the eye motions between fixations, and the distance between two successive fixations on an object is the amplitude of a saccade. An increase in this distance indicates that a larger region of the visual stimulus/object is being processed, and a more comprehensive representation of the objects is being formed. For instance, when looking at someone's face, if the initial fixation is on their forehead and the second fixation is on their eye, this is a brief saccade, implying that only a tiny portion of the face was encoded during the first fixation. However, if the second fixation occurs on their lips or chin, there would be a long saccade between fixations, indicating that the first fixation encoded a greater face area. When there is a fewer number of saccades between objects, which represents fewer encode–rotate–compare iterations and a longer distance between subsequent fixations, i.e., saccade amplitude (Davitt et al., 2014; Larsen, 2014; Irwin & Brockmole, 2000), indicate the encoding of a complete image of an object.

Therefore, the role of object/stimulus' spatial and appearance information like dimensionality and the angular disparity is critical during the encoding and rotation processing in mental rotation. It influences the approach or strategy followed in processing the presented information and the cognitive engagement accordingly. To explore the role of mental rotation in eye movement directional control, De' Sperati (1999) studied the saccadic behavior of the participants. In the result of the study, there was no difference between rotated and visually guided saccades in terms of the amplitude, duration, velocity, and curvature. Further, it is surmised that the frontal/prefrontal cortical areas contribute to rotating saccades by reorienting the intended saccadic direction, similar to mental rotation tasks requiring reaching arm movements. An increase in saccade duration has been associated with more complex tasks (Smit et al., 1987; Vuori et al., 2004) as well as a reduced processing capacity (Bestelmeyer et al., 2006; Green & Fornborough, 1986; McGregor & Stern, 1996; Lehtinen et al., 1979). Further, the saccadic amplitude is one of the most used measures of eye movement. Paeye and Madelain (2014) have studied the variability of saccadic amplitude in a visual search task and suggested that it is an actively controlled process that highlights the relevance of reinforcement contingencies in active vision and offers ways to improve training and rehabilitation. The size of the stimulus image influences the mean and median saccadic amplitude (Von Wartburg et al., 2007). Zangemeister & Liman (2007) observed that saccadic amplitudes are shorter with visual imagery than during real picture viewing. However, Humphrey and Underwood (2008) found the opposite trend when comparing amplitude from imagery to picture encoding. Another parameter, saccadic velocity, has been used to measure cognitive activation level, often called arousal level. Low vigilance decreases saccadic velocity (Galley, 1989), and so does tiredness (McGregor & Stern, 1996; Becker & Fuchs, 1969). Saccadic velocity increases as the task's difficulty increases (Galley, 1993) and decreases with an increasing time on task (McGregor & Stern, 1996). When the task requires a higher saccadic rate (greater frequency of saccades), the saccadic peak velocity increases (Lueck et al., 1991).

2.4. Electroencephalogram and its Spatio-spectral Characteristics

The electrical activity of the brain produced by the dendrites of neurons adjacent to the cortical surface is called an electroencephalogram (EEG). It is recorded by placing several electrodes on the scalp according to the 10-20 electrode placement system. EEG signals are measured in microvolts (µV). The EEG signals contain five frequency ranges, namely, delta (1–4 Hz), theta (4–8 Hz), alpha (8–12 Hz), beta (15–30 Hz), and gamma-band oscillations (>30 Hz) (Lally et al., 2014). The brain waves show the brain maturation process in humans, and it is also a reflection of the evolutionary past. EEG rhythms with different frequencies that appeared during specific goal-directed behavior probably reflect different aspects and impacts of the same cognitive processes. The spatio-spectral characteristics of EEG signal display not only the spatial and spectral properties of frequency bands (δ, θ, α, β, γ), but also different brain networks involved during any task/function.

Brain waves in different frequency bands are associated with emotion, attention, and higher cognitive processes. It implies that investigating the pattern of these frequency bands in EEG signals in terms of specific parameters can provide valuable information about how participants process or respond to a different type of task and stimuli. There are cognitive aspects also linked with EEG frequency bands. Delta wave tends to be the highest in amplitude and the slowest waves, and it is often associated with drowsiness, sleep, and states of altered consciousness. The theta oscillations have been found during the encoding of information during analytic and investigational activities and spatial navigation (Knyazev, 2007). An increase in frontal midline theta power with a decrease in parietal alpha power in mental rotation tasks suggests increased utilization of visuospatial representation processing and working memory, respectively (Gardony et al., 2017). Alpha waves are usually detected in the posterior areas of the head on both sides, with the dominant side having a higher amplitude. In terms of the role of alpha oscillations in human EEG, it can be deduced that inhibitory processes or other activities linked with alpha rhythm oscillations, such as working memory and mental representation of objects and events, are crucial for developing higher brain functions (Knyazev, 2007). During the task that requires visual attention, like the mental rotation task of noncorporeal objects, alpha-rhythm desynchronizes (Michel et al., 1994). Increasing the power of high-frequency EEG rhythms is associated with alpha-rhythm desynchronization during mental activities (Nikolaev & Anokhin, 1998).

Beta activity often appears in an alert state, and it shows the connection with the regulation of processing states. These rhythms are most commonly studied in relation to sensorimotor behavior. Decreasing pattern in beta band power has been found during the preparation and execution of voluntary movements, and it disappears after the termination of the task/activity (Nam et al., 2011). Further, the gamma rhythm is liked with object maintenance, memory, and various cognitive processes. Different properties of objects, events, or any information are encoded and processed by different parts of the brain, and gamma oscillations play an essential role in perceiving coherent representations (Tallon-Baudry & Bertrand, 1999). Another study (Nikolaev & Anokhin, 1998) suggests that certain changes in the power of the gamma range (35-45 Hz) may reflect the fact that the gamma frequency band is more closely associated with perception and recognition processes than with the mental image transformation.

The human Brain has mainly divided into four regions, frontal, parietal, occipital, and temporal, and all four regions are associated with different mental, physical and cognitive activities. The combination of different brain regions creates two visual streams, i.e., dorsal and ventral streams, to deal with Visuospatial information. The dorsal stream is proposed to be engaged in the guidance of actions and recognizing 'where objects are in space'. It is also called the "where" stream, or the "how" stream. The ventral stream is usually described as the "what" stream and it is associated with object recognition and representation in terms of color, shape, size etc.

Previous studies have studied functional neuroanatomy in terms of functional connectivity, hemispheric lateralization, etc., during mental rotation using different neuroimaging techniques like EEG, MEG, fMRI, etc., to explore these brain regions and their functioning (Zacks, 2008). The brain signal properties and the involvement of brain regions can be influenced by many factors in a task. In mental rotation processing, the object/stimulus characteristics like angular disparity, dimensionality, type of object/stimulus, strategy or approach (e.g., egocentric/allocentric, holistic/piecemeal) utilized to process the information play a significant role to influence the functioning of brain signals and regions (Zacks, 2008; Milivojevic et al., 2009). The participation of posterior parietal, inferior temporal, frontal, and motor areas and other areas associated with visual dorsal-ventral stream have been reported during mental rotation processing (Koshino et al., 2005; Jäncke & Jordan, 2007; Schendan & Stern, 2007). For example, it is suggested that mental rotation was done for external objects (such as letters) in an allocentric reference frame (object-based transformation) before judging them. In contrast, instead of rotating the object, a mental self-rotation is conducted before defining it in an egocentric reference frame (egocentric perspective-taking) for scene and human shapes (Kozhevnikov & Hegarty, 2001; Zacks & Michelon, 2005; Kessler & Thomson, 2010).

Diverse findings have been highlighted the engagement of brain regions and anatomical structures during mental rotation processing. One research found that mental rotation of external items activated the left parietal cortex and the right caudate head (Alivisatos & Petrides, 1997). Another study discovered activation of the left and right parietal cortices, as well as the associative visual cortex (Brodmann area (BA) 19) (Kosslyn et al., 1998), while others found the only activation of the right parietal cortex (Núñez-Peña & Aznar-Casanova, 2009; Zacks et al., 2003; Harris et al., 2000). In some other studies (Kosslyn et al., 1998; Parsons et al., 1995), mental rotation of the hands has been linked to activation of the left primary motor and insular cortices, as well as BA 6, 7, and 9; however, another study observed activation in both parietal regions, extrastriate, and premotor cortices (Vingerhoets et al., 2002). Further, some research indicates right-hemispheric dominance for mental rotation (e.g., Heil, 2002; Harris et al., 2000; Yoshino, Inoue & Suzuki, 2000), whereas some other research shows left-hemispheric dominance (e.g., Alivisatos & Petrides, 1997; Mehta & Newcombe, 1991), while some imply bilateral activation (e.g., Podzebenko et al., 2002; Jordan et al., 2001; Just et al., 2001).

These various findings suggest that mental rotation is a complicated cognitive activity requiring several sub-processes distributed across the brain. In mental rotation processing, the involvement of some specific brain regions is more than others, indicating the differential specialization of cortical areas for specific mental rotation activities. As complexity increases, the size (and a number of participating areas) of the cortical networks gets smaller, and the reduced size is accompanied by relatively strong separation of the cortical networks. A study (Jäncke & Jordan, 2007) suggested that the networks grew bigger under more complicated mental rotation settings, sharing more brain regions and having a lower degree of separation. As task complexity increased, there was a higher functional connection between the ventral and dorsal streams, indicating more synchronization between the dorsal and ventral systems. Thus, more brain areas are recruited to solve the mental rotation problem with increasing workload.

2.4. Cognitive Workload

The cognitive workload is defined as a quantitative measure of the amount of mental effort needed to perform a task (Gevins et al., 1997). In other words, the level of measurable mental effort exerted by an individual in response to one or more cognitive activities is referred to as cognitive workload. It is usually considered to be a property of an individual instead of a property of the task. Originally "workload" word was used to describe a job and referred to the amount of work needed to be done ('the work'), usually within a specified span of time ('the load'). Usually, the subjective measures based on interviews or questionnaires are utilized to evaluate the cognitive workload, in which the participants assessed the amount of mental effort being used in the particular task (Kruger & Doherty, 2016). The term cognitive workload has become "human-centered instead of task-centered" with the advent of the NASA-TLX Task Load Index. Mental demand, physical demand, temporal demand, performance, effort, and frustration level are the six aspects (subscales) of NASA's TLX. The first three dimensions of the scale (mental demand, physical demand, and temporal demand) are related to the demands of the task put on the task performance, whereas the last three (i.e., performance, effort, and frustration level) are related to the engagement of the participant with the task.

Another way to evaluate the cognitive workload is physiological and neuroimaging measures like eye movement, EEG, MEG etc. If neural activities reflect the capacity utilization, then the higher brain activity should entail a more demanding visuospatial transformation task performance than a less demanding task. Along with that, with increasing visuospatial competence, brain activity in this system should decrease. As assessed by several neuroimaging measurements, an increase in the demand for specific types of visuospatial functions often leads to higher brain activity in a network of associated regions. The amplitude of the brain signal, the Power Spectral Density (PSD), and time-frequency characteristics are used to identify mental tasks and mental states in cerebral interfaces, particularly those based on EEG data. Generally, as mental workload increases, the theta activity increases in the frontal region, whereas alpha activity decreases in the parietal regions (Hankins & Wilson, 1998; Holm et al., 2009). On the other hand, beta wave activity was shown an association with changes in complexity level (Brookings et al., 1996), i.e., the variation in the cognitive workload. A study (Michel et al., 1994) utilized the mental rotation task in which some sorts of trials needed more rotation than others and manipulated the task demand in visuospatial processing. To measure the resulting variation in brain activities, they used magnetoencephalography (MEG), and the demand is quantified as the size of the rotation angle across which a mental representation must be turned or as the processing of a computational model of task performance (Just & Carpenter, 1985). Carpenter et al. (1999) utilized fMRI to show that in a

Shepard-Metzler rotation task, the activation volume in the parietal lobule rises with the degree or size of the rotation angle. According to the theory, larger angular disparities need more resources to compute more intermediate orientations and maintain representations of both stimuli under comparison. The cortical systems that deal with spatial processing exhibit higher activity with greater demand in mental rotation (Just et al., 2003).

Eye movement parameters can also provide a sensitive measure of cognitive workload. Early studies have reported significant findings, suggesting blink and, especially, pupil size/diameter as indices of mental workload in a different type of tasks (e.g., Van Orden et al., 2001; Veltman & Gaillard, 1998; Brookings et al., 1996; Kramer, 1991; Stern et al., 1984; Beatty, 1982). However, since it is responsive to various processing activities (e.g., perceptual, cognitive, and response-related demands), the pupillary reaction has gained more prominence than a blink. While blink appears to be responsive to cognitive workload, its pattern between various studies is often inconsistent. Studies using search tasks, for instance, have also shown that the blink rate reduces as more items are to be scanned (Chen et al., 2011a; Irwin & Thomas, 2010; Van Orden et al., 2001). Whereas, the increase in blink rate has been reported in arithmetic tasks (Chen et al., 2011b; Recarte et al., 2008; Veltman & Gaillard, 1998) and in conversations and mental rehearsals (Stern et al., 1984). During spatial thinking activities such as mental rotation, pupil size variation can be a useful measure of capacity demand. In their study, Just and Carpenter (1995) monitored pupil size of the participants with a higher or lower spatial skill who performed a mental rotation task and judged whether two irregular two-dimensional hexagons portrayed the same figure (with a minor disparity in orientation) or mirror-image figures. According to a 3CAPS computational model, good performance demands more computation and storage as angular disparity increases, resulting in a rise in capacity utilization with angular disparity. The pupillary response was reported to increase monotonically on the 'Same' trials with increasing angular disparity. Participants with low spatial skill had significantly larger variations in pupil size than the participants with high spatial ability, indicating that capacity utilization was higher for those with less ability for the same operation. Further, their study suggests that the pupillary response is an indicator of capacity usage rather than an indicator of the participant's absolute processing/storage requirement. A dynamic system, such as the 3CAPS cognitive simulation of mental rotation, presents numerous different resource consumption indicators that might reasonably approximate to the aggregate demand measured by pupillary dilation. The function that assessed the proportion of total activation consumed by the model's processing function was the one that best suited the pupillometric data across rotation situations.

Chapter 3

Methodology

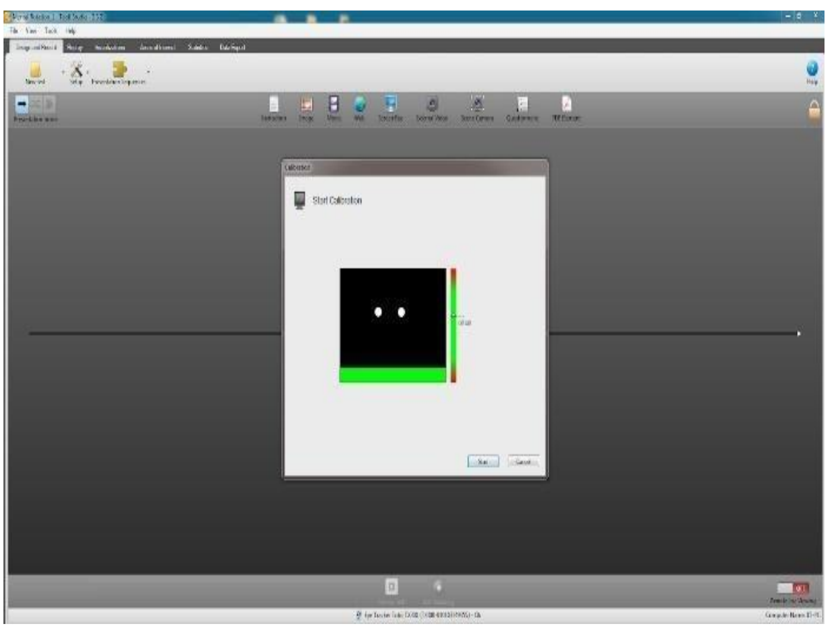
3.1. Experimental Setup

The experiments were conducted in an isolated and noise-free environment specially designed to conduct research involving human participants to prevent noise and distraction. The experimental room was equipped with an acoustic soundproof wall and proper lighting and ventilation to provide a comfortable environment during the experiment. An eye-tracker and multichannel EEG systems were used for acquiring neurophysiological changes during the study. The experimental setup and the data-acquisition systems utilized in the study were appropriately arranged in the room. The room, as well as all the used instruments, were properly sanitized before each session.

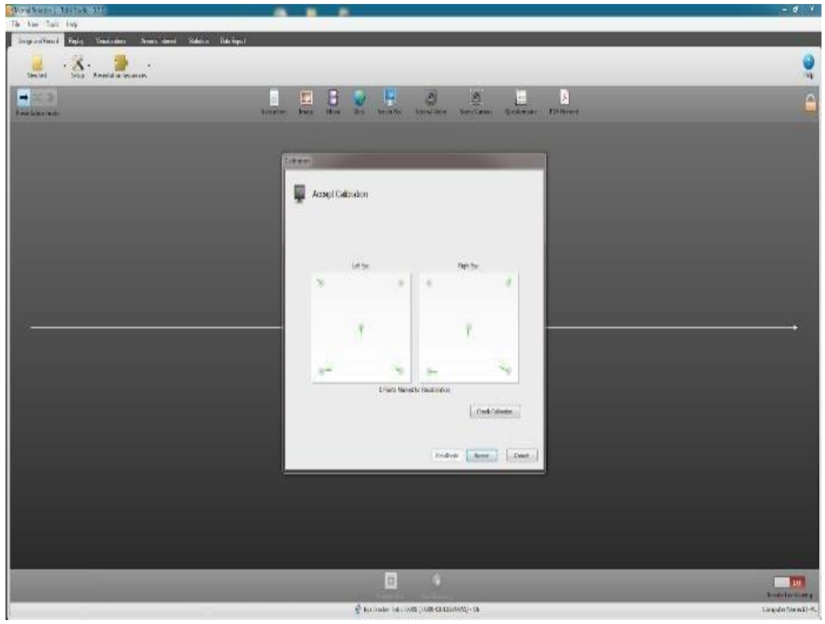
3.1.1. Eye-tracking System

The Tobii TX300 eye tracker is a state-of-art eye tracker for studying natural behavior in depth. With a recording rate of 300 Hz, its broad head movement box allows the subject to move during tracking while preserving accuracy and precision. Furthermore, it implies that saccades and brief fixations may be investigated without the need for a chinrest. The TX300 contains a built-in user camera and speaker, allowing for recording subjects' responses to stimuli and sound playback. With multiple software and stimulus setup options, the Tobii TX300 provides maximum versatility. It includes the eye tracker unit and a removable 24" monitor. Calibration of this system with participants' eyes is required at the beginning of each gaming session. Calibration includes a few moving dots on the screen, and it takes 2-5 minutes. Tobii Studio software is utilized to present the game and record the eye movement data in the video and MS excel format.

(a)



(b)



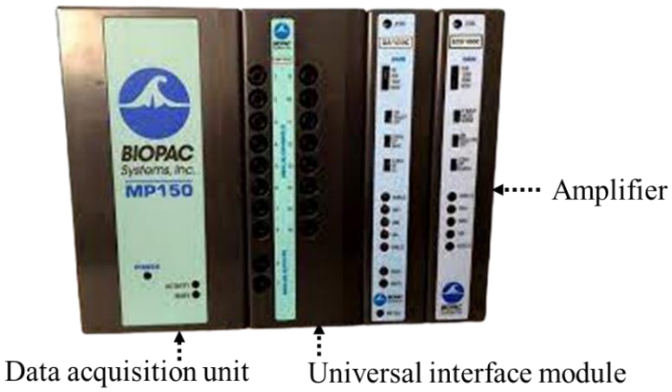
(c)

Figure 3.1 (a) Tobii TX-300 eye tracker (b–c) Eye-tracker calibration steps with participant’s eyes

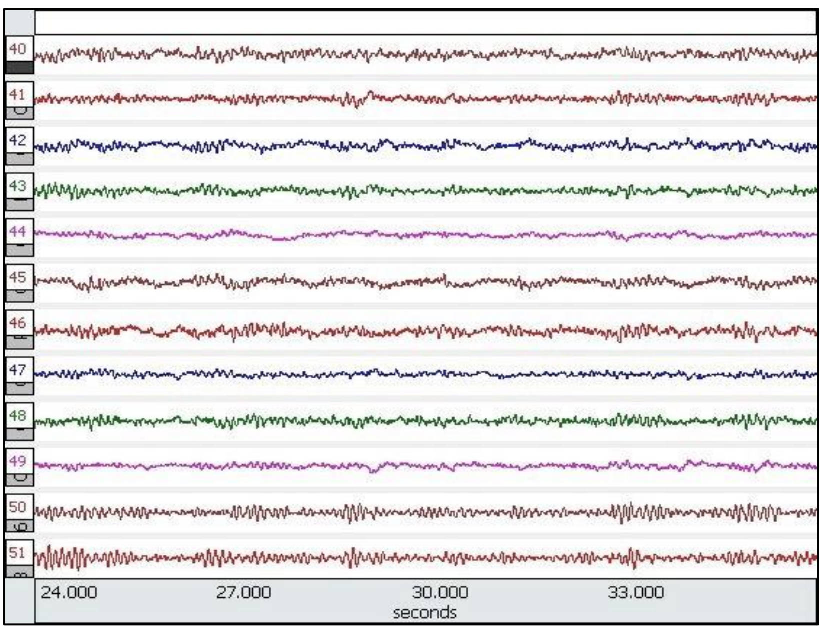
3.1.2. Electroencephalogram System

3.1.2.1. MP 150 EEG System

A 10-channel MP 150 system along with AcqKnowledge® software (BIOPAC Systems Inc., CA, USA) was used with a 2 kHz sampling frequency in the unipolar mode to acquire EEG data from 10 scalp positions- FPz, FC1, FC2, C3, Cz, C4, CP3, CP4, Pz and POz. The individual gold-plated electrodes were pasted at the ten pre-marked positions after measuring 10–20 international standards using EEG conductive paste.



(a)

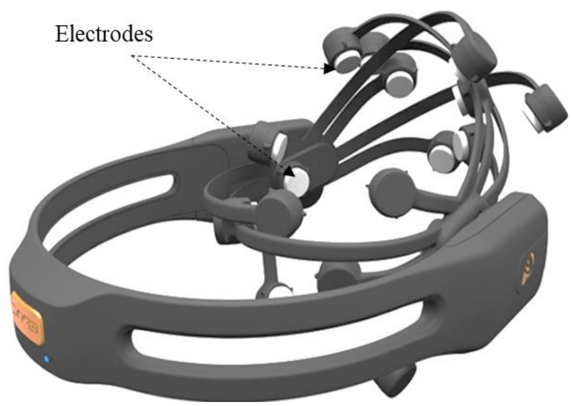


(b)

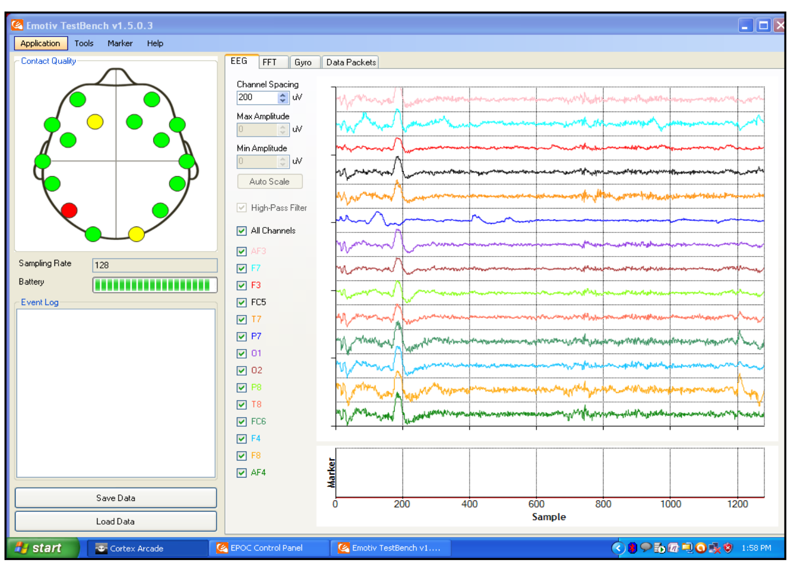
Figure 3.2 MP-150 EEG system, a) System hardware (Image courtesy BIOPAC Systems Inc); b) Data acquisition view in AcqKnowledge® software.

3.1.2.2. Emotiv Headset

A portable, high resolution14-channel Emotiv Epoc headset with 128 Hz sampling frequency was used to acquire EEG data from 14 scalp positions—AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, and AF4. Electrode placement was according to 10-20 international EEG standards.



(a)



(b)

Figure 3.3 Emotiv headset EEG system, a) System hardware (Image courtesy Emotiv EPOCH); b) Data acquisition view in Emotiv TestBench® software.

3.1.3. StimTracker®

To synchronize the EEG and eye tracker device and the computer-game, the experimenter uses the StimTracker® device from Cedrus. When biometric data (from an EEG or an eye tracker) adds markers that indicate when certain events happened, it becomes much more helpful. StimTracker® detects the onset of these events in behavioral research, transmits them to several recorders simultaneously, and does so autonomously to avoid operating system delays.

Figure 3.4 Cedrus StimTracker®

3.2 Hypotheses

In the light of available literature discussed in chapter 2, the following points are expected from this study:

1. (a) Longer saccadic duration is expected involving convex angular disparity as compared to reflex angular disparity, (b) Higher saccadic amplitude is expected for 3D objects as compared to 2D objects.

2. (a) Alpha desynchronization is expected along with higher active areas for convex angular disparity and 2D objects in contrast to reflex angular disparity and 3D objects, respectively, (b) The hemispheric laterality dominance is expected reflecting right-hemispheric laterality for convex angular disparity and 3D, however left-hemispheric laterality for reflex angular disparity and 2D.

3. (a) Spatial information (angular disparity) plays a much more influential role than the visual ones (dimensionality); while utilizing the dorsal-ventral pathways in MR, the dorsal pathway is expected to be more engaged than the ventral ones. (b) Also, higher activation in the dorsal-ventral pathway for convex angular disparity and 2D objects is expected than reflex angular disparity and 3D objects.

3.3. Ethical Clearance, Design, and Experimental Set-up

3.3.1. Ethical Clearance

The current research was approved by the *Institute human ethics committee* of IIT Indore, and all the recruited participants took part voluntarily by providing their consent. After the experiment, all the participants were given a token of thanks with a t-shirt for their participation. The risk involved in this study is no greater than that of interacting with computers in day-to-day activities. There is no prospect of any possible injury during experimentation. Participants do not have any specific benefit or risk with respect to this study. The findings of the study are expected to have implications in game design for improving cognitive skills. Participants have the privilege of knowing our research results and matters pertaining to published or unpublished contents derived from the study through official communication with experimenters.

3.3.2. Design

This experiment employs a factorial design with angular disparity (AD) and dimensionality (D) having two conditions each, i.e., 2 (AD: convex vs. reflex range) x 2 (D: 2D vs. 3D objects) between-groups design. The convex angular disparity lies between 0^0 to 180^0, whereas reflex angular disparity lies between 180^0 to 360^0. As shown in Fig. 3.5, there are four groups, and, in each group, objects from four categories of the varying number of arms (4, 5, 6, and 7 arms) were presented twice for each of the four angles of rotation. Therefore, each of the four groups included 32 (4: arms x 2: repetitions x 4: angular disparities) trials altogether. The computer-game involving the above-mentioned MR tasks was designed in the Unity3D game engine (Haas, 2014). The isomorphic 2D and 3D multi-arms objects, like the previous studies (Shepard and Metzler, 1971; Vandenberg and Kuse, 1978), were designed using Blender's Python API (application programming interface) (Blender Online Community, 2017). The 2D objects were obtained by removing the depth of their 3D counterparts. The game was developed for the Windows platform and presented on a 24-inch display with a 1920x1080 screen resolution. The gaming task had multiple successive trials. In each trial, the player had to identify a multi-arms object presented on the left side of the monitor and from a group of five look-alike objects (distractors) on the right side. The distractors were rotated at a fixed angle. Based on the angle of rotation and dimensionality of the objects presented, the complete game was divided into four sections:

I. CA_2D: 2D objects with convex angular disparities.
II. CA_3D: 3D objects with convex angular disparities.
III. RA_2D: 2D objects with reflex angular disparities.
IV. RA_3D: 3D objects with reflex angular disparities.

The four convex type angular disparity conditions for sections (I) and (II) were $AD1_{CA}$ (=40°), $AD2_{CA}$ (=80°), $AD3_{CA}$ (=120°), and $AD4_{CA}$ (=160°) whereas, the four reflex type angular disparity conditions for sections (III) and (IV), were $AD1_{RA}$ (= –40° or 320°), $AD2_{RA}$ (= –80° or 280°), $AD3_{RA}$ (= –120° or 240°), and $AD4_{RA}$ (= –160° or 200°). The angles for $AD\#_{RA}$ were the reflection of their convex counterparts from $AD\#_{CA}$ across the 0° line in Fig. 3.5, where '#' represents the index of the rotation. The objects were rotated in XY-plane (the plane of the monitor screen), considering Z-axis normal to the plane.

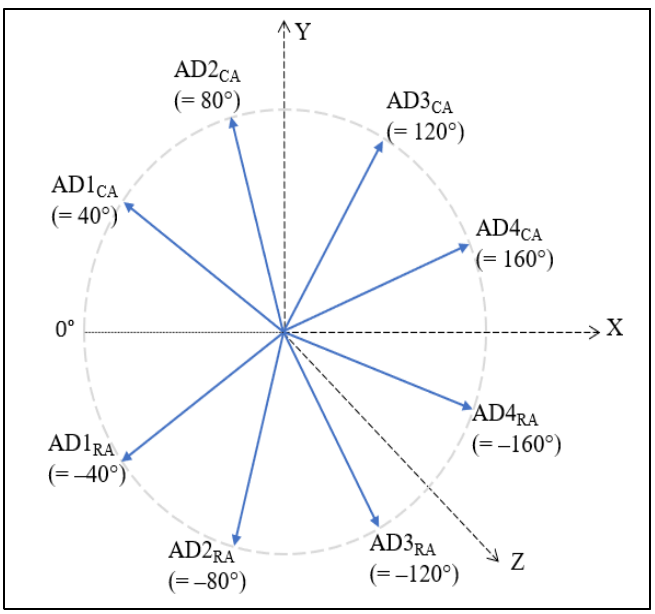


Figure 3.5 The angular disparity conditions for CA and RA

The location of the correct answer was randomized, and the player had to identify the match and click the mouse button as soon as possible for proceeding to the next trial. The trials were not time-limited so that a player could take time to respond as per their convenience, and the time was recorded as *response/reaction time*. One score for each correct answer was accumulated and displayed on the right upper corner of the screen throughout the gaming. Fig.3.6 a–b shows the setting window and login window of the game, while c–d shows the snapshots of the task at any arbitrarily chosen time point during the game for a 2D and a 3D section. We also integrated event-markers at the start and endpoints of each session to identify the synchronized eye-tracking and EEG data for the corresponding sessions.

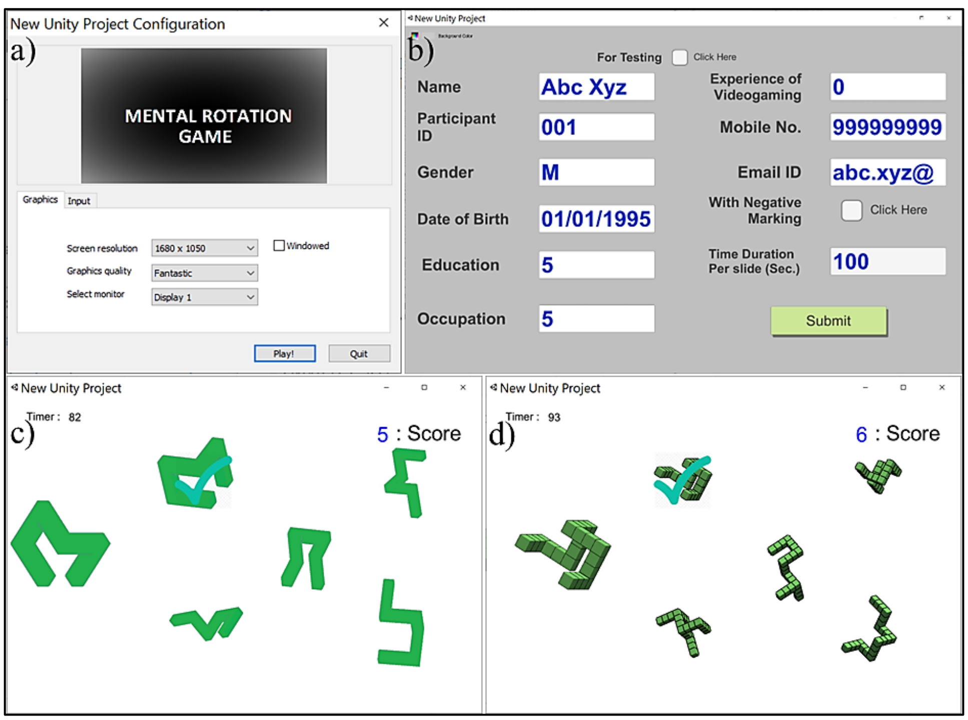


Figure 3.6 a) Game monitor setting window, b) Participants log in window, c) 2D representation of objects in the tasks, and d) 3D representation of objects in the tasks

3.3.3. Participants and Experimental Setup

A total of 72 healthy engineering students (Mean = 22.3 years; Standard deviation = 3.61; range = 18–32 years) voluntarily participated in the experiment. The data for 12 participants were discarded due to either excessive movement artifact or high impedance during the acquisition. After the exclusion, the sixty volunteers (51 males and 9 females; all right-handed; age range 18–29 years; Mean = 21.6 years; Standard deviation = 3.13) were selected for the study. All of them had normal or corrected to normal visual acuity. They all reported no medical history of neurological or psychological disorders. Before starting the experiment, each participant gave informed consent in a format approved by the *Institute Human Ethics Committee* of the institute. The equal number of participants were randomly assigned to each of the four groups — CA_2D, CA_3D, RA_2D, and RA_3D, each for one gaming section. Each group had 15 participants, and they were instructed to play the section of the gaming task assigned to them.

The experiment was conducted in an acoustically treated, isolated, and noise-free environment to avoid any possible distraction and noise to EEG. The participant was seated on a comfortable chair in front of a computer monitor with MR gaming tasks. The monitor size was 24 inches with a screen resolution of 1920x1080, and the distance between the monitor and the participant was approx. ~65 cm. During the experiment, the Tobii TX300 eye-tracking system (Tobii Tech, Sweden) was used for acquiring participants' gaze behavior data at a sampling rate of 300 Hz. A

10-channel MP 150 system (BIOPAC Systems Inc., CA, USA) was used in the unipolar mode to acquire EEG data from 10 scalp positions— FPz, FC1, FC2, C3, Cz, C4, CP3, CP4, Pz and POz. The individual gold-plated electrodes were pasted at the ten pre-marked positions after measuring based on 10–20 international standards using EEG conductive paste. The linked ears were used as a common reference on all the 10 channels. A 14-channel Emotiv Epoc headset with 128 Hz sampling frequency was used to acquire EEG data from 14 scalp positions—AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, and AF4. Electrode placement was according to 10-20 international EEG standards.

3.4. Task Execution

Fig. 3.7 and 3.8 show an overview of the experimental workflow in the study. Before starting the experiment, each participant explained the instructions for the task execution in detail and asked to keep the head movement minimal during the experiment. The eye-tracker calibration with every participant was done at the beginning of the gaming session. The participant was seated on a comfortable chair facing the monitor and ~65 cm apart from the eye-tracker (Fig. 3.7b). The tasks were presented through Tobii Studio (version 3.3.2). The 10-channels MP150^{TM} system was set for a 2 kHz sampling rate, and a 14-channel Emotiv Epoc headset with 128 Hz sampling frequency was used. Before starting the gaming task, baseline EEG data for 5 minutes was recorded, during which the participants were in the resting state. After a training session with four trials (similar but not included in the actual experiment) to get participants familiar with the tasks, the actual gaming task was assigned to the group. The tasks had four increasing levels of angular disparity, and TTL (transistor-transistor logic) triggers were generated for changes in angular disparity during the gameplay using the StimTracker® and a photodiode pasted on the task monitor.

Fig. 3.8 also shows the schematic illustration of the data acquisition during the gaming session. The event triggers were sent to all the systems for synchronizing the data with the ongoing task conditions. The task session for a participant was to complete in a single run. The tasks were not time-limited; however, the elapsed time (in second) was continuously displayed along with the total rewarded points in the monitor's corner. At the end of the gaming session, the datasets were saved along with the triggers for further offline analysis. The gaming scores, response accuracy, and response time were saved as an output log file of the game. After the gaming- task session ended, the workload experienced by the participants during the experimental task was measured using NASA-TLX tests. Fig. 3.7 sketches the experimental workflow, and Fig. 3.8 shows the schematic representation of the experimental set-up and data acquisition used in the study.

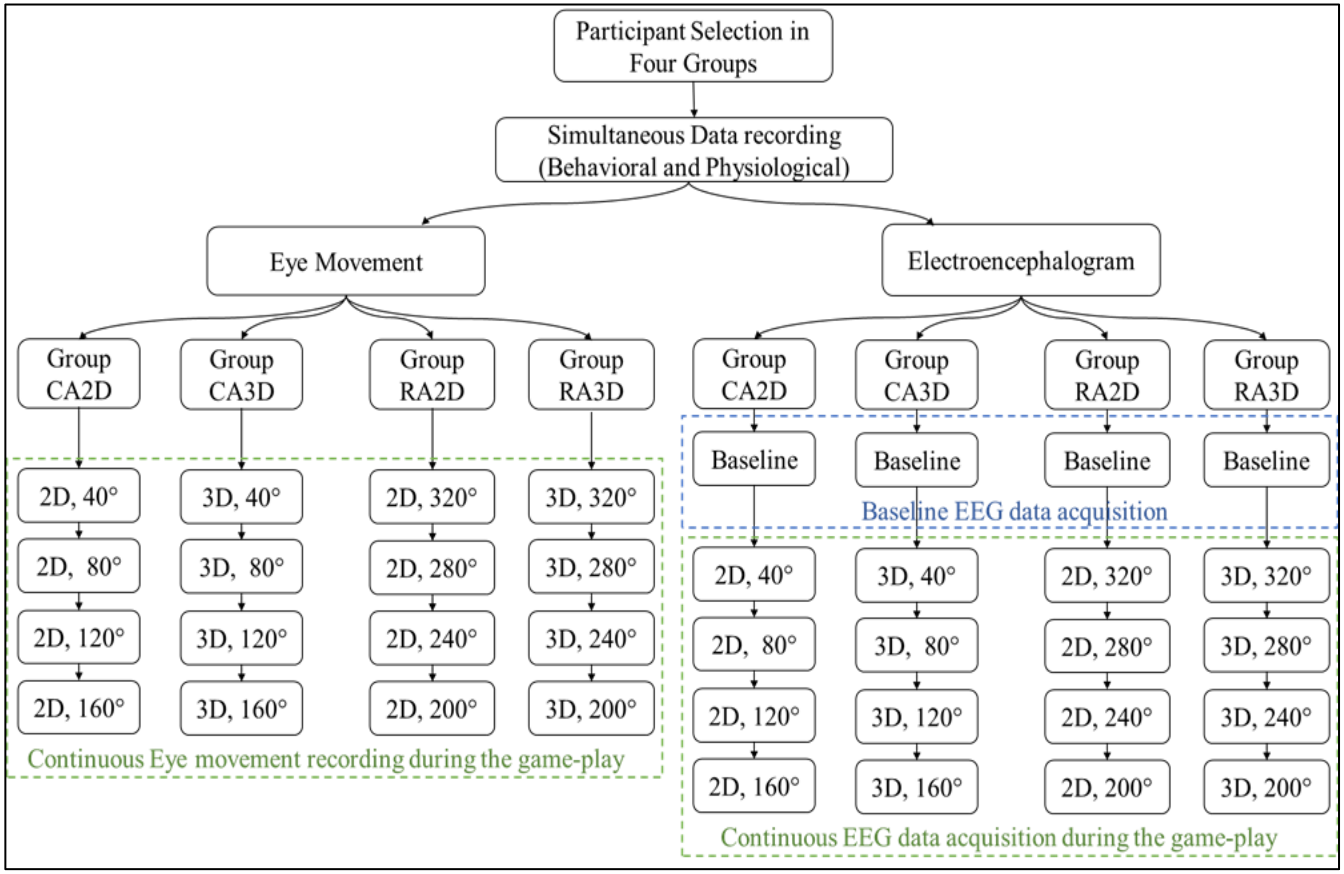


Figure 3.7 The experimental workflow

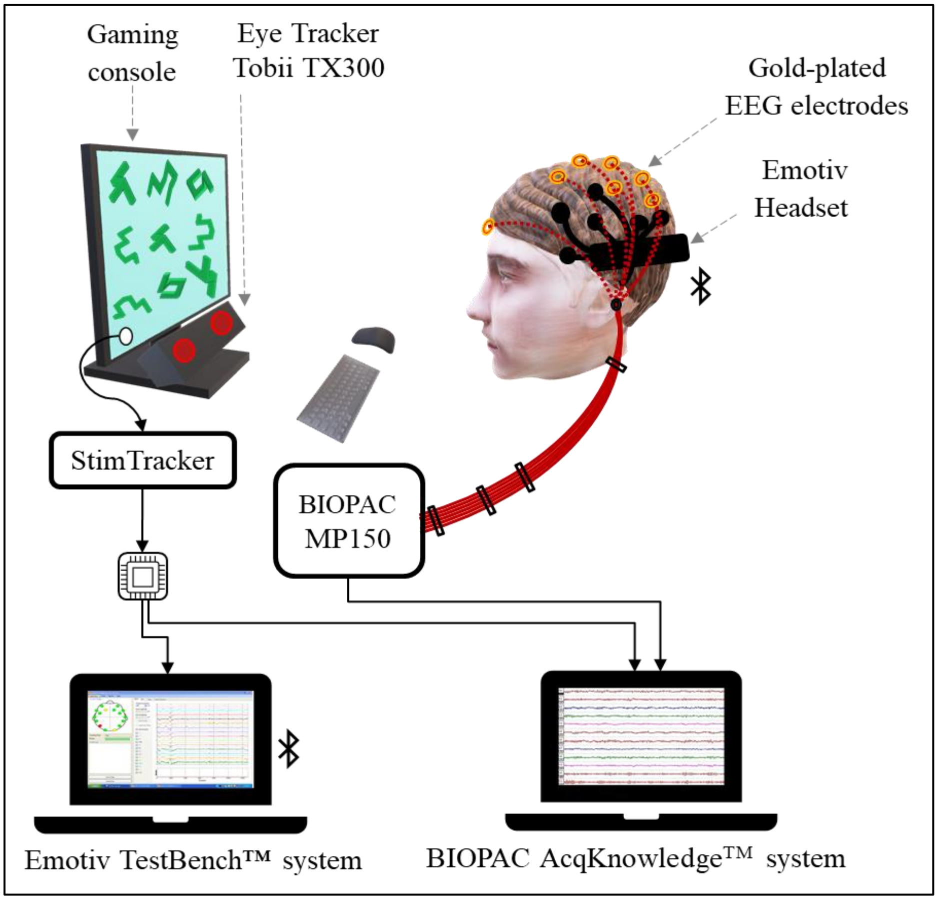


Figure 3.8 Schematic diagram of the data acquisition setup.

3.5. Task Performance Data

Task performance was recorded as a .csv file generated by the game build. In the file, utilized response time for each trial, and the gained score at each step was saved along with the participants' names, group, etc.

3.6. Gaze Behavior Data

Gaze behavior data were recorded and saved in the Tobii studio software library in the video as well as excel format. The excel format data was utilized for the analysis. However, many parameters were provided in the excel data related to eye movement and eye tracker technical specification. Here the saccadic gaze parameters were the focus of interest to study, though, in addition, pupil size was also analyzed.

3.7. NASA TLX Data

NASA TLX data was recorded in text format generated by the test application for each participant. Further, it was saved in .csv format for the analysis. Along with the participants' details, the data file includes a rating of six subscales of cognitive workload, i.e., mental demand, physical demand, temporal demand, performance, effort, and frustration level.

3.8. EEG Data

EEG data were acquired using two independent systems— 1) MP 150 (BIOPAC Systems Inc.) 10-channel system and 2) Emotiv headset (Emotiv EPOC) 14-channel system with software "*AcqKnowledge*" and "*Emotiv TestBench*" respectively. The data sets were saved in *.mat* format for further analysis in MATLAB and other required analysis toolboxes. The EEG rhythms and involved brain regions were explored with hemispheric laterality, channel clustering, and source analysis methods.

3.9. Procedure

The experimental room was properly sanitized before welcoming the participant. Participants were asked to remove all their belongings and keep them safely in a locker shelf, outside the experimental room. Sanitization was done with participants as well as experimenters. Before starting the session, participants were brought to the "*Initiation room*" to brief the pre- and post-experimental instructions.   Participants were asked to fill the log file with required details and sign the '*consent form*' to permit their voluntarily participation in the study. The participants were assigned the group of experimental tasks according to the randomized sequence. The participants were asked to go in the experimental room, and the ongoing experiment '*Indication light'* of the experimental room was switched "ON". The participants were seated on a comfortable chair facing towards the monitor and ~65 cm apart from the eye-tracker. The eye-tracker calibration with every participant was done at the beginning of the gaming session. To ensure the good quality of EEG signal recording, participants were already informed to come with washed heads to participate; the head, forehead, ears were wiped with alcohol wipes before the placement of EEG electrode placement on it. The placement was done as per the 10-20 international electrode placement. After the eye-tracker calibration and EEG electrode set-up, a trial session was done before executing the actual game play. After the training session, the participant started to execute the actual gaming task. All the experimental system belongings from the participant were removed after data recording. Participants were asked to fill the post-experimental questionnaires (NASA TLX) and probing questions. After the session completion, the ongoing experiment '*Indication light'* was switched off. Participants were given a t-shirt as a *token of thanks* for their participation in the study. All the submitted belongings of the participants were returned to them. Before starting the next session with another participant, there were around 40 minutes of a time gap to ensure the sanitization of the experimental room and experimental set-up.

Chapter 4

Object Characteristics and Gaze Behavior in Mental Rotation

4.1. Introduction: Saccade Gaze Parameters and Mental Rotation

Visuospatial information processing involves the transformation and manipulation of information. One of its essential aspects is mental rotation (MR), a process through which the rotation of mental representations of two-dimensional (2D) and three-dimensional (3D) objects/images is achieved (Núñez-Peña & Aznar-Casanova, 2009). In general, it is established that individuals can determine that two 2D images portray objects of the same 3D shape even when objects are depicted in different orientations (Shepard & Metzler, 1971). However, what remains relevant from the perceptive of eye-tracking research is to examine the saccadic activities involving the angular disparity aspect of dimensionality in MR. Considering saccades are rapid eye-movements involved in shifting the foveal orientation to objects of visual interest (Termsarasab et al., 2015), understanding saccadic activities pertaining to the visuospatial relationship among the chunks of stimuli is essential to gain better insight about MR. In this effort, the study experiment reported in this paper was designed to explore saccadic characteristics of gaze behavior by developing an MR gaming task. Such a visually guided task provides an ideal platform to perform a scientific inquiry in a controlled environment (see Fig. 4.1) and the prospect of future remote gaming tasks facilitated by the internet of things (IoT).

Performing an MR task requires moving visual representation of an object to understand what they are (appearance) and where they belong (space). In a typical MR task, the successive processes followed by a participant are— creating a mental image of the presented object, rotating the mental image until it is comparable to imagery or physical target, comparing, and finally making the decision (Johnson, 1990; Xue et al., 2017). Fig. 4.1 illustrates a typical MR process where a participant tries to find the match of the target from the given 3D objects A and B. The participant first selects object A and mentally rotates it via successive rotations to check if it matches with the target object and makes the decision. The same is then repeated for object B.

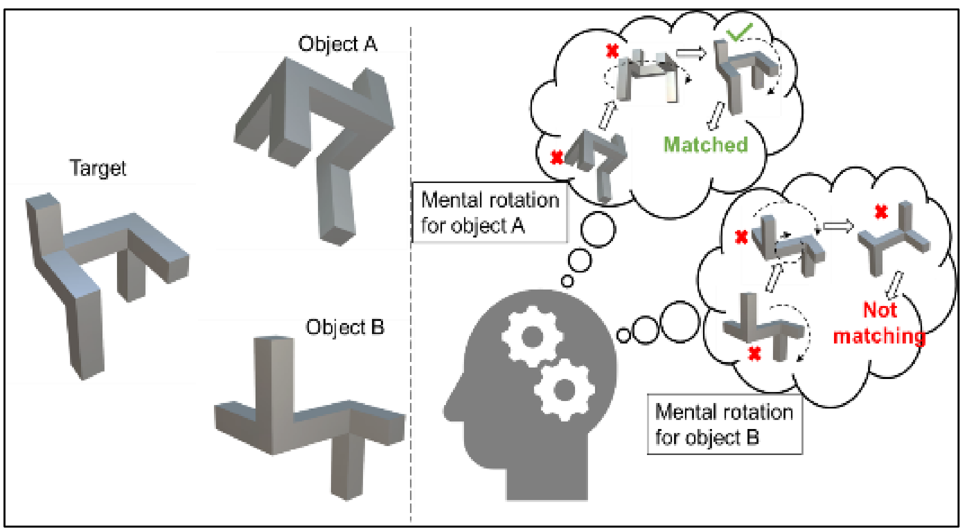


Figure 4.1 MR process of finding a match of the target from objects A and B.

Issues concerning angular disparity and dimensionality in MR have gained the attention of various lines of research. The seminal work of Shepard and Metzler (1971) conducted a study to investigate response time (RT) while the subjects were judging whether the multiple pairs of 3D, cubed, or asymmetrical lined objects were matching with each other. The results revealed that the RT linearly increases from 1 second at 0° to 4–6 seconds at 180° of angular disparity (orientation difference between two objects). When the angular disparity exceeded 180°, it was reported that the response time did not continue to increase monotonically but started decreasing up to 360°. The authors interpreted the result as a process of mental simulation of the physical world. As it takes a shorter amount of time to physically rotate an object 20° than it does 120°, the same applies to the MR process. In 1978, Vandenberg and Kuse also conducted an experiment using similar objects and showed significant sex-based differences in the MR ability, with better performance in the male group. In the last two decades, neuroimaging studies have shown an association between specific brain regions with MR. It has been observed that there is rotation-dependent neural activity in dorsal areas, which indicates the spatial nature of the MR process (Gauthier et al., 2002; Zacks, 2008). Harris et al. (2000), using positron emission tomography (PET) imaging technique, found the right posterior parietal lobe activation during the MR task. Gogos et al. (2010), in a functional magnetic resonance imaging (fMRI) study, investigated differential activation of regions within the parietal region and their functional sub-specialization by examining the effects of varying the angular disparity.

Interestingly, the growing understanding of the mechanisms underlying MR through the diverse approaches driven by the interest the topic of MR has generated. Among several theories of how a cognitive system deals with a visuospatial stimulus, the piecemeal strategy (Khooshabeh et al., 2010) has attracted the attention of various researchers and is widely discussed. The emphasis of the piecemeal strategy lies in the way a person visually perceives the individual segments of the stimuli. The piecemeal approach in the MR process involves segmentation of the mental image into pieces (e.g., the objects' arms shown in Fig. 3.6 (c–d), then mentally rotating one piece in congruence with the target object, and finally applying the same rotation to the other pieces of the objects to see if they match (Khooshabeh et al., 2010; Xue et al., 2017). In the context of the eye-tracking approach of understanding MR, eye fixation sequences are considered to suggest a piecemeal strategy during MR tasks (Just & Carpenter, 1976; 1985). As individuals' fixations maintain the gaze on a single location, MR is closely related to our ability to visually encode spatially distributed information (Shepard & Cooper, 1986; Carpenter, 1988). There are studies (Just & Carpenter, 1985; Irwin & Carlson-Radvansky 1996; Irwin & Brockmole, 2000; Martini et al., 2011; Larsen, 2014; Balaj, 2015; Xue et al., 2017) that have reported the changes in gaze metrics during the MR tasks; saccadic characteristics require the attention of researchers. Irwin and Brockmole (2000) suggested that there is suppression of the MR process during saccadic eye movements. According to Larsen (2014), the initial processing time is roughly constant until the first saccade switched between the stimulus object while the duration of the remaining trial, at the same time, increased linearly as a function of angular disparity. Balaj (2015) showed that the number of fixations increases, and their frequency decreases with the increase in rotation angles of the object in an MR task. It suggested an increase in rotation angle links with increased cognitive engagement and increased task difficulty. Xue et al. (2017), using machine learning, showed that the gaze metrics possess the necessary information for determining the processing strategy during an MR task.

With the increase in accessibility to computers, computer-games have become an everyday engagement for entertainment in society. It is also being facilitated by the rapidly growing accessibility to gaming apps for users through handheld devices. A distinctive feature of the computer-based gaming task is that it comprises complex visuospatial information and requires a speedy response. Therefore, spatial abilities such as MR plays a key role while executing the task efficiently. Computer-games are also gaining popularity as valuable platforms for learning and training, including therapeutic purposes aimed at enhancing cognitive skills, e.g., 2D and 3D computer-based MR tests (Cherney, 2008). Oei and Patterson (2013) suggested that training a specific cognitive ability frequently in a video game improves performance in tasks that share common underlying demands. Meneghetti et al. (2016) also found the transfer effects of MR training in the task requiring spatial skill.

This analysis approach emphasizes the variations of object characteristics, i.e., angular disparity, dimensionality, and saccadic gaze behavior. The investigators consider that in an MR task, angular disparity and dimensionality are crucial for identifying the similarities between two objects (Ganis & Kievit, 2015; Balaj, 2015). The angular disparity is a measure of orientation, and it represents the spatial aspect of an object, whereas dimensionality (whether 2D or 3D) represents its appearance. Since changes in angular disparity and dimensionality will bring variation in the MR processing strategies, which in turn, is expected to affect task performance. With respect to gaze behavior, the point is that the saccades interfere selectively with cognitive processes that rely on the dorsal stream (also known as where-pathway), such as judgments of object orientation (Irwin & Thomas, 2007) and the image or object size shows the correlation with saccadic amplitude during the scene perception (Von Wartburg et al., 2007). In general, while individuals perform MR tasks faster with 3D objects as they hold additional information as compared to the 2D objects, this study tries to examine how the spatial characteristics (angular disparity) of the object and dimensionality (2D/3D) affect the temporal aspect of the saccade and spatial feature of the saccade respectively. The matter of focus is that this study expects — (a) longer saccadic duration involving convex angular disparity as compared to reflex angular disparity and (b) higher saccadic amplitude for 3D objects as compared to 2D objects.

4.2. Data Analysis

4.2.1. Computation of Parameters of Gaze Behavior

Saccadic Duration: It is the time taken to complete a saccade and lies within a few tens of milliseconds. The visual information takes ~75ms to reach the visual cortex, which is usually faster than the saccade duration; therefore, the saccades cannot be modified during the transmission of visual information. The saccade duration has been suggested as a period with no visual intake (Dodge, 1900; Volkmann, 1986) and cognitive processing suppresses (Irwin & Carlson, 1996) during saccades. The investigators computed average saccadic duration (in milliseconds) for each of the four groups.

Saccadic Amplitude: Saccadic amplitude (or saccadic length) is the size of the saccade; it is the visual angle between two consecutive fixations usually measured in degrees or minutes of arc. A higher saccadic amplitude means the eye has traveled a greater distance during the saccade. In this study, average saccadic amplitudes were computed for each group in degree.

Saccadic Velocity: Saccadic velocity is the ratio of saccadic amplitude and duration, and it is usually reported in degree per second. Velocity level can change along with eye movement; therefore, the average of the velocity is usually computed. Saccadic velocity has been used as a measure of cognitive activation level, often called arousal level. Low vigilance decreases saccadic velocity (Galley, 1989), and so does tiredness (McGregor & Stern, 1996). However, McGregor and Stern (1996) suggested that the saccadic velocity change as an index of 'fatigue'. The decrease in saccadic velocity indicates mental fatigue (tiredness) (Schmidt et al. 1979).

Pupil Size: Another important and widely used measure of gaze behavior is pupil size, usually measured as pupil diameter (in mm). The pupil dilates with the increasing complexity of the task (Balaj, 2015; Van der Wel & Van Steenbergen, 2018) and its size instantly responds to the changes in the cognitive workload (Pomplun & Sunkara, 2003).

4.2.2. Computation of Parameters of Game Performance

Response Time (RT): To measure the participant performance during the MR task, the RT is an important parameter. It is the elapsed time between the task/trial presented and the response provided. Mean RT for the four groups was calculated.

Gaming Task Score: The MR task was presented in the form of a computer-based game, and the participants were rewarded with one mark for each correct answer. Accumulated score at any point of time was displayed on the right upper corner of the monitor throughout the session. After completing a task, the total marks scored were used as another measurement of performance in the study. The gaming scores, response accuracy, and time were saved as an output log file of the game.

Cognitive Workload: The workload of each participant was measured using the android-based application of NASA-TLX. The test was done on all participants when they completed the computer-based gaming task. The participants answered the questionnaires of NASA-TLX by rating each of the six subscales (mental demand, physical demand, temporal demand, performance, effort, and frustration level) according to the workload they experienced during the task execution. The rating scale ranged from very low to very high for all dimensions except for the performance, which varies from perfect to failure. After rating, the workload for each subscale and the overall workload were automatically calculated by the application.

4.3. Findings

The data were analyzed offline using MATLAB®, Version 2010b (MathWorks, USA), and SPSS® Version 22 (IBM Corporation, USA). Tobii Studio provided eye-tracking data for each participant. The investigators first extracted the saccadic parameters and pupil size for each of the 60 participants and averaged these metrics within the four groups for further statistical analysis. Using the distribution within each group and their group average, we further conducted the statistical analysis.

To infer the statistical significance, the investigators used alpha level 0.05 throughout this paper. Fig. 4.2 shows the major steps in the study for analyzing the gaze data from the eye-tracker, task performance measures from the MR gaming tasks, and workload scores from the NASA-TLX test.

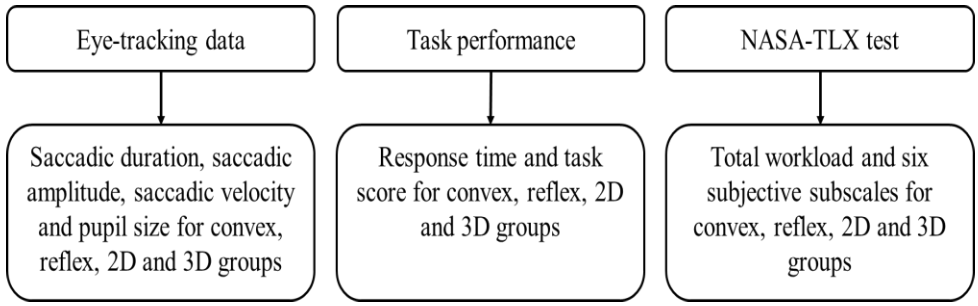


Figure 4.2 Framework of processing the different sets of data.

4.3.1. Gaze Behavior

Analysis revealed a significant main effect of angular disparity on saccade duration, i.e., the convex angular disparity had a longer saccade duration than reflex angular disparity see Fig. 4.3a and Table 4.1. There was no significant main effect of dimensionality on saccade durations; see Table 4.1. There was no significant interaction between angular disparity and dimensionality for their interactive effect on saccade durations; $F(1, 56)=0.496$, $p = .484$. The two-way ANOVA test on saccadic amplitude for 2(AD: Convex Angle vs. Reflex Angle) x 2(D: 2D vs. 3D) between-groups design showed a significant main effect of dimensionality, i.e., there was higher saccadic amplitude for 3D objects as compared to 2D objects. See Fig. 4.3b and Table 4.1. The analysis revealed no significant main effect of angular disparity on saccadic amplitude, although the convex angular disparity range has higher saccadic amplitude than the reflex range; see Table 4.1. There was no significant interaction between angular disparity and dimensionality for their interactive effect on saccadic amplitude, $F(1, 56) = 0.215$, $p = .645$. Further, a two-way ANOVA on saccadic velocity for 2(AD: Convex Angle vs. Reflex Angle) x 2(D: 2D vs. 3D) between-groups design showed a significant main effect of dimensionality. 3D objects had higher saccadic velocity in contrast to 2D; see Fig 4.3c and Table 4.1. There was no significant interaction between angular disparity and dimensionality concerning their interactive effect on saccadic amplitude, $F(1, 56) = 0.005$, $p = .941$; see Fig. 4.3d and Table 4.1. The boldface in Table 4.1 represents a significant *p*-value.

Table 4.1 Saccadic metrics and their significance for different angular disparity and dimensionality groups (M: mean, SD: standard deviation)

	2D	3D	Convex	Reflex
Saccade duration (ms)	*M*=32, *SD*=3.7	*M*=33, *SD*=3.6	*M*=34, *SD*=3.8	*M*=31, *SD*=3.1
	F(1, 56)=0.535, *p*=.468		*F*(1, 56)=6.289, ***p*=.015**	
Saccade amplitude (deg.)	*M*=6.809, *SD*=1.257	*M*=7.637, *SD*=1.103	*M*=7.499, *SD*=1.362	*M*=6.948, *SD*=1.068
	F(1, 56)=7.541, ***p*=.008**		*F*(1, 56)=3.342, *p*=.073	
Saccade velocity (deg./s)	*M*=212.24, *SD*=29.33	M=233.84, *SD*=26.81	*M*=223.53, *SD*=32.14	*M*=222.55, *SD*=28.05
	F(1, 56)=8.562, ***p*=.005**		*F*(1, 56)=0.017, *p*=.895	
Pupil size (mm)	*M*=3.323, *SD*=0.368	*M*=3.528, *SD*=0.445	*M*=3.408, *SD*=0.444	*M*=3.443, *SD*=0.395
	F(1, 56)=3.693, *p*=.060		*F*(1, 56)=0.104, *p*=.748	

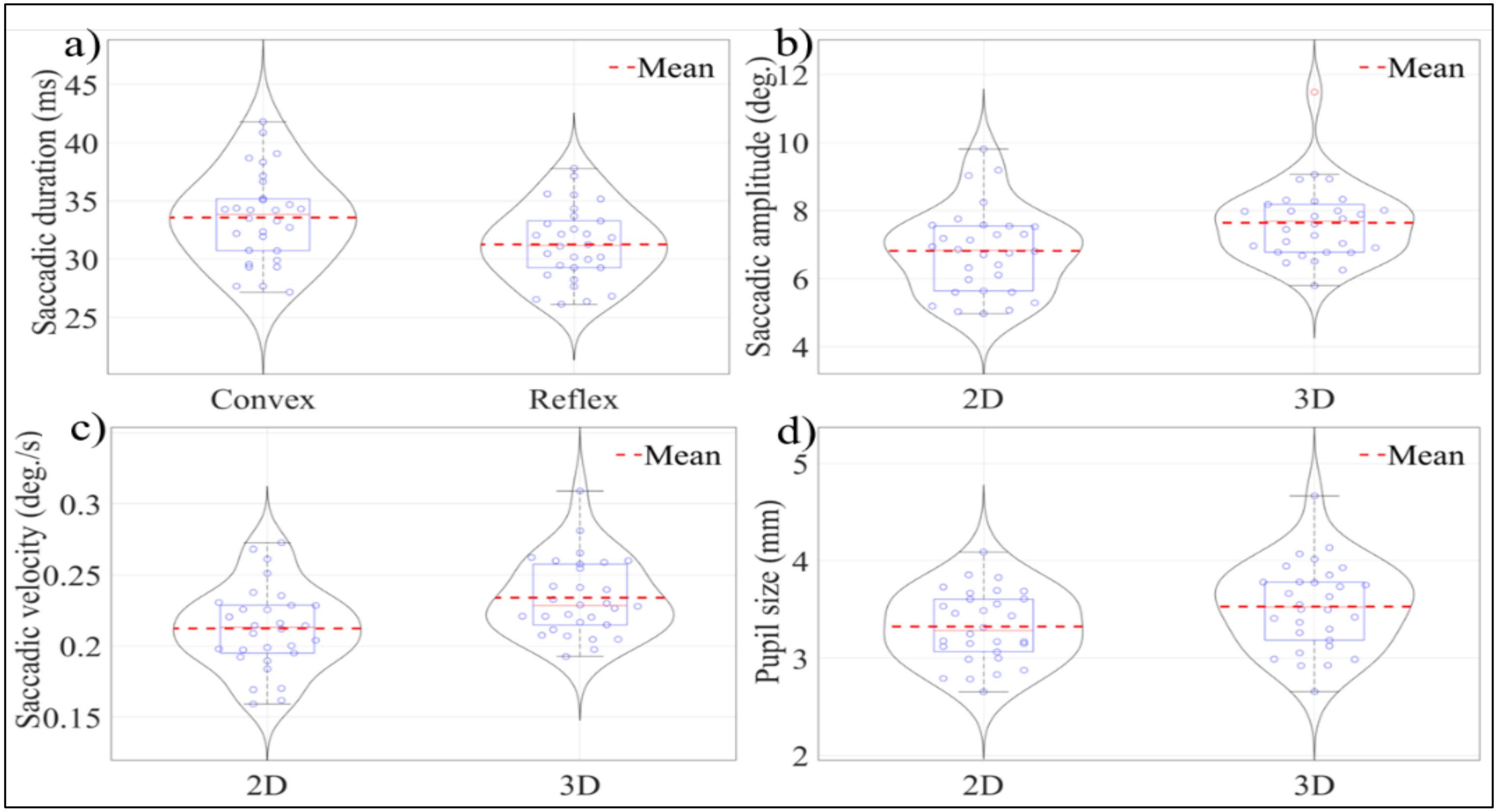


Figure 4.3 Overlapped box-violin plots a) saccade duration for convex and reflex angular disparities, b) saccade amplitude for 2D and 3D object dimensionalities, c) saccade velocity between 2D and 3D object dimensionalities, and d) pupil size between 2D and 3D object dimensionalities.

4.3.2. Game Performance

Response Time

A two-way ANOVA for 2(AD: Convex Angle vs. Reflex Angle) x 2(D: 2D vs. 3D) between-groups design was performed in order to examine variation in RT. Neither AD nor D showed a significant main effect on RT. Although, there was lower RT for 3D as compared to 2D; see Table 4.2 and Fig. 4.4c. There was no significant interaction between angular disparity and dimensionality concerning RT.

The correlation test was performed to investigate the correlation between task response time and gaze behavior. The correlation test was performed to investigate the correlation between task response time and gaze behavior. The result showed a significant negative correlation between response time and saccade duration $r(60) = -.330$, $p<.05$, 2-tailed. A similar trend was observed between response time and saccadic amplitude as well $r(60) = -.376$, $p <. 05$, 2-tailed. Fig. 4.4a shows the negative correlation between response time and saccadic duration, while Fig. 4.4b demonstrates the negative correlation between response time and amplitude of the saccades.

Table 4.2 Gaming-task performance and significance of differences between groups with different angular disparity and dimensionality (M: mean, SD: standard deviation)

<table>
<tr><td></td><td>2D</td><td>3D</td><td>Convex</td><td>Reflex</td></tr>
<tr><td rowspan="2">Averaged response/reaction time (s)</td><td>M=32.631, SD=17.863</td><td>M=26.318, SD=12.973</td><td>M=25.860, SD=16.237</td><td>M=33.090, SD=14.743</td></tr>
<tr><td colspan="2">F(1, 56)=2.508, p=.119</td><td colspan="2">F(1, 56)=3.290, p=.075</td></tr>
<tr><td rowspan="2">Gaming task score</td><td>M=16.43, SD=3.540</td><td>M=21.67, SD=3.546</td><td>M=19.47, SD=4.091</td><td>M=18.63, SD=4.709</td></tr>
<tr><td colspan="2">F(1, 56)=32.119, p=.001</td><td colspan="2">F(1, 56)=0.814, p=.371</td></tr>
</table>

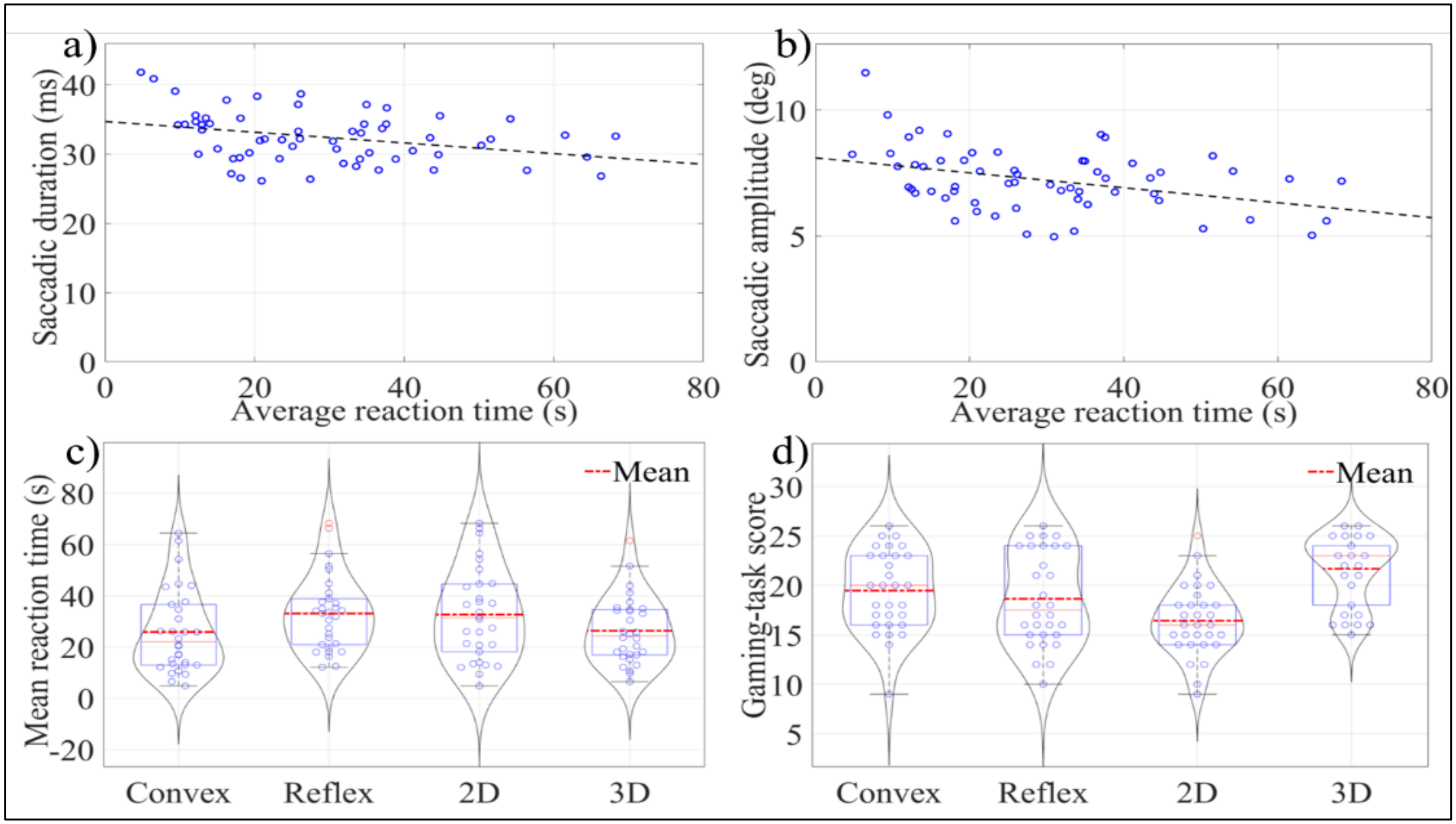


Figure 4.4 Correlation between a) Saccadic duration and average response time, b) Saccadic amplitude and average response time; c) Average response time for two angular disparity and the two dimensionality conditions, and d) Mean gaming scores for two angular disparity and the two dimensionality conditions.

Gaming Task Score

The analysis showed a significant main effect of dimensionality on gaming task scores with a lesser value for 2D than the 3D, but no significant main effect of angular disparity was found for the same; see Fig. 4.4d, and Table 4.2. The test revealed no significant interaction between angular disparity and dimensionality concerning their interactive effect on the task score, $F(1,56) = 0.106$, $p = .746$. A significant positive correlation between the score of the task and the pupil size was found $r(60) = .280$, $p <. 05$). Fig. 4.5a shows the correlation plot between the task score and pupil size.

4.3.3. Cognitive Workload

A two-way ANOVA test for 2x2 between-groups design was performed in order to examine cognitive workload, where the former two groups were convex and reflex angular disparity conditions and the later two were 2D and 3D dimensionalities. The results showed no significant effect of angular disparity, $F(1, 56) = 0.531$, $p = .469$ as well as dimensionality, $F(1, 56) = 0.108$, $p = .744$ on the total workload. We also did not find a significant interaction between the angular disparity and dimensionality, $F(1, 56) = 0.383$, $p = .539$. However, there was a significant interaction between angular disparity and dimensionality for their interactive effect on mental demand subscale, $F(1, 56) = 4.601$, $p = .036$, see Fig. 4.5d. Also, there was a significant negative correlation between mental demand and pupil size $r(60) = -.278$, $p <. 05$); see Fig. 4.5b.

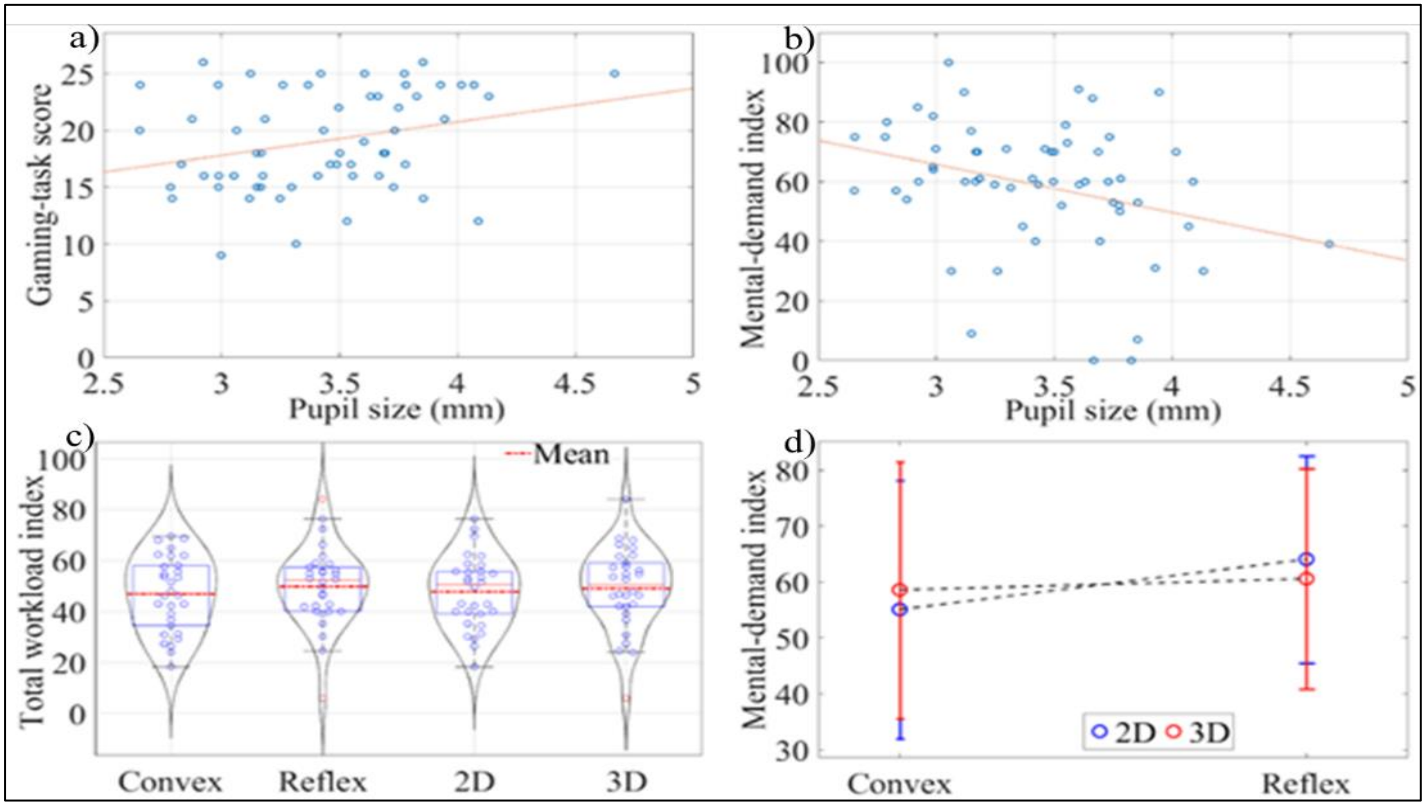


Figure 4.5 a) Correlation between pupil size and task score, b) Correlation between pupil size and mental demand index, d) Total workload index for all the four groups, d) Interactive effect of angular disparity, and dimensionality on mental demand.

Table 4.3 NASA-TLX workload scores and significance of differences between groups with different angular disparity and dimensionality (M: mean, SD: standard deviation)

	2D	3D	Convex	Reflex
Total workload	*M*=47. 7577, *SD*=14.1115	*M*=49.0533, *SD*=16.1126	*M*=46.9666, *SD*=14.71099	*M*=49.8444, *SD*=15.4571
	F(1, 56)=0.108, *p*=.744		*F*(1, 56)=0.531, *p*=.469	
Mental demand	*M*=58.57, *SD*=22.95	*M*=60.57, *SD*=19.748	*M*=55.07, *SD*=23.11	*M*=64.07, *SD*=18.523
	F(1, 56)=0.143, *p*=.706		*F*(1, 56)=2.901, *p*=.094	

4.4. Discussion

Visuospatial information processing in MR gaming tasks relies on perceiving, analyzing, manipulating, and transforming visual patterns. While looking at objects in order to perform the gaming task, human eyes are bombarded with various aspects of visuospatial information and eye-tracking system is a useful tool to analyze the gaze behavior of the users.

This study demonstrates that the spatial characteristic (angular rotation) of an object in the MR task influences the temporal characteristics (saccade duration). The significant effect of angular disparity on saccade duration implies a prolonged suppression of spatial processing (Irwin & Carlson, 1996; Irwin & Brockmole, 2000). As it was expected, results represent the longer saccadic duration involving convex angular disparity as compared to reflex angular disparity. The longer saccade duration indicates an elongated suppression of spatial information processing during the MR tasks when the object's angular disparity was in the convex range. It is important to note that RT increases monotonically from 0° to 180° of angular disparity but decrease from 180° to 360° by identifying a shorter path using structural properties independent from the object's orientation (Takano & Okubo, 2006). Object view similarity often varies in response to the increased angular disparity. Images/objects differing by a large angular disparity might be more similar to those with a smaller rotation difference (Hayward, 1998). When an object rotates with a reflex angular disparity, it starts turning towards the reference object's orientation, which eases object recognition. Thus, with increasing angular disparity, the comparison gets easier, and RT decreases in reflex angular disparity range compared to the increasing RT with rotation in convex angular disparity. Thus, the complexity and time-consuming nature of convex range rotation are higher than the reflex, which leads to a longer saccade duration in convex range (Smit et al., 1987; Vuori et al., 2004). Increasing saccade duration shows the decreasing processing capacity in convex range than reflex range (Bestelmeyer et al., 2006). Interestingly, however, it is possible only if a participant chooses the shortest path to rotate an object from 180° to 360° range in the opposite direction because saccade duration would be higher in terms of the travelled path for rotation in convex range than the reflex. A negative correlation was found between saccade duration and fixation count that means a higher fixation count in reflex angle range than convex. Since the number of saccades between stimuli decreases with experience, participants encode more complete representations, requiring fewer encode–rotate–compare iterations. (Moen et al., 2020; Larsen, 2014). The cognitive emphasis on the angles or major features of the visual stimulus has a significant contribution to the creation of an internal representation of the stimulus, and when an original stimulus is perceived and interpreted by matching, a similar fixation pattern is used on the matched stimuli. Subjects fixated on the same points, edges, or angles of the paired object in the same order as they did when encoding the previous stimulus (Noton & Stark, 1971). In this case, the response time is possibly also affected by object features, e.g., the number of arms and dimensionality, rather than being influenced by angular disparity only. It can provide an external cue to anticipate the object, which might help the participant to make a correct decision. Thus, the RT can also be affected by anticipation and reinforcement learning. The participants might have applied different strategies apart from MR and found this strategy right for finding correct answers. If this strategy succeeds in the coming trials, it gives confidence to the participant to continue the same approach, which worked in each group, and that is why there is no significant difference in terms of response time either in case of angular disparity or dimensionality. Van Duren and Sanders (1995) reported that the target classification and response selection might take place during a saccade, as well. They suggested that the perceptual process, such as those required for stimulus encoding, might be suppressed during saccades, whereas post-perceptual processes such as target classification and response selection might not. Though the previous studies (Shepard & Metzler, 1971; Takano & Okubo, 2006) expected to rotate the object in the same direction for both angular disparity ranges, we are not sure about the path participants followed to rotate and match the objects. Since the statistical test did not show a significant effect of angular disparity on RT, we can assume that the participants matched the arms of the target with the options instead of mentally rotating them.

In the current study, investigators did not find a significant effect of dimensionality on saccadic duration. The saccades interfere selectively with cognitive processes that rely on the dorsal stream (also known as where-pathway), such as judgments of object orientation (Irwin & Thomas, 2007). The spatial characteristics of the object get suppressed during saccade in an MR task. Here, in this study, the angle is the parameter, which is affecting objects' spatial orientation or location, whereas dimensionality reflects objects' physical appearance. This could be the reason that saccade duration was unaffected by dimensionality. It is well known that during saccadic eye movements, exposure to visual stimuli is decreased, a phenomenon known as "saccadic repression" (Matin, 1974; Zuber & Stark, 1966). The suppression of visual sensitivity during saccades is primary because of visual masking (Campbell & Wurtz, 1978). The intake of objects' visuospatial features is masked while planning to make the saccade, during which the brain sends the signal to suppress the visual pathways (Ross et al., 2001). Though the subject focuses on the target during saccades, the suppression in perceiving angular disparity affects an individual's performance in MR. Suppression of cognitive processes during saccades might be expected to occur only when limited processing resources must be shared (Irwin & Carlson, 1996). According to the dual-task theory, cognitive processing can be suppressed during saccades only when shared processing structure are used. While a diverse network of brain structures is involved in the generation of saccadic eye movements, the frontal (and supplementary) eye fields and the posterior parietal cortex tend to be the most important cortical regions (Schall, 1995). Thus, dual-task hypothesis suggests that during saccades, cognitive processes that include these same brain regions will be suppressed. As suggested by several neurophysiological studies, e.g., Alivisatos & Petrides, 1997; Kosslyn et al., 1998; Peronnet & Farah, 1989, MR is one such process that involve parietal region. It was also thought that perceptual memory gets updated during saccades so that information gathered across fixations can be processed.

There was significant effect of dimensionality on saccadic amplitude and velocity. As per our expectation that higher saccadic amplitude for 3D objects as compared to 2D objects, the lower saccadic amplitude and velocity were found for 2D objects, indicating that the tasks were more challenging and attention demanding than the 3D objects. The reason behind the higher amplitude and velocity of saccades in the case of 3D objects can be understood in terms of how the brain anticipates the three-dimensional consequences of eye movements because of the depth perception of the objects (Wexler, 2005). Saccadic amplitude has been found directly proportional to the stimulus (image) size and dimension (Von Wartburg et al., 2007). As the saccadic amplitude increases, it means that a greater portion of the object is being interpreted, and a complete representation of the object is being formed (Moen et al., 2020). Surface depth gradients are followed by saccadic eye movements during random exploration of visual images/objects. Thus, surface orientation has a major impact on eye movements regardless of the task when viewing stimuli in three dimensions (Wexler & Ouarti, 2008). The type of stimuli influences even simple eye movement properties. Furthermore, saccade dynamics vary when viewing 3D images vs. 2D images as the saccade velocity increases with the addition of 3D depth cues. More comprehensive images are explored faster, i.e., the duration of fixations is decreased for images containing more information (Jansen et al., 2009). Angular disparity did not significantly affect the saccadic amplitude and saccadic velocity. The possible reason behind this could be the reflexive nature of these saccades and dealing with the ventral stream, also known as what stream. A surprising and swift route connects visual processing in the ventral pathway (stream) with saccadic eye movement programming (Kirchner & Thorpe, 2006). The saccade velocity is mathematically closely associated with the amplitude, so the effect of dimensionality on saccade velocity was observed similar to the saccade amplitude. Not only the mean but also the maximum velocity increases with the increasing amplitude of the saccade. In the saccadic movement of the eyes, the saccadic amplitude is a controlled quantity on which the clear reception of the necessary visual information depends. The eyes perform each saccadic movement at a maximum velocity, which still provides an opportunity of attaining the required precision. Therefore, when a participant scrutinizes an object, the saccadic amplitude gets shorter than during overview scans, which often happens if the task difficulty and complexity increase.

It is interesting to see a significant effect of dimensionality on the gaming task score. The lower scores under the 2D objects category reflect that the participant faced more challenges while mentally rotating the 2D objects than the 3D (i.e., speed-accuracy trade-off). This trend was present in the case of saccadic amplitude as well. The current study's finding agrees with Neubauer et al. (2010) reports that claimed higher RT and a lower score of tasks for 2D presentation mode in MR. However, few previous studies suggested that 3D objects are more challenging in terms of correct responses and RT. However, those studies compared different non-isomorphic 2D and 3D objects. The 2D objects were isomorphic to the corresponding 3D object obtained by removing the depth (Z-axis) in the current study. 3D objects have comparatively more detailed information, so the brain may start anticipating the consequences of their rotation before the saccadic eye movement starts (Wexler, 2005). This phenomenon makes the MR process faster and reduces response time in an active task. Though there was an insignificant effect of dimensionality on RT, however, the mean RT was found lower for 3D objects than 2D objects. The lower mean RT and high gaming task score collectively support the point that 3D condition can provide an external cue for anticipation, which may help the participant make correct decisions and execute the task more efficiently than 2D condition (Chelnokova & Laeng, 2011).

Angular disparity, as well as dimensionality, did not significantly affect the overall workload. The result showed a significant interaction of angular disparity and dimensionality for the mental demand sub-scale of NASA-TLX. The MR processing with 2D objects in reflex angular disparity was more mentally demanding than that of convex angular disparity; however, this trend was absent in the case of 3D objects. Interestingly, lesser pupil size has been found in the case of the 2D object than in 3D. Here, pupil size is getting affected by the depth perception of the object. The simple act of recollection can dilate the size of the pupil; however, when the brain requires to process at a rate above its maximum capacity, the pupil contracts (Poock, 1973). Depth perception is helping the participant to match the target object with the given option. That is why we have found a negative correlation between pupil size and mental demand. The lesser pupil size in 2D means higher mental demand in 2D compared to 3D.

4.5. Summary

The current analysis investigated gaze behavior and task performance during a computer-based MR gaming task and investigated the effect of the angular disparity and dimensionality on user performance while executing the task. The isomorphic 2D and 3D images were used to minimize the other confounding factors other than the dimension differences. The findings reveal correlations among objects' spatial and appearance characteristics, gaze metrics, and task performances. The study showed that the spatial characteristic of the object, i.e., angular disparity, affects the temporal aspect of the saccade, i.e., saccade duration. In contrast, the spatial aspect of the saccade, i.e., the saccade amplitude and velocity, gets influenced by the objects' dimension. More suppression of MR processing during convex angular disparity makes it more effort seeker than the reflex one. The study also reveals that MR may occur faster and more accurately with 3D objects as they hold additional information, such as depth. As the 2D objects include less object information, a prolonged search for object features may delay the response. The interaction between angular disparity and dimensionality for mental demand in the gaming task indicated that they together could turn the task more challenging, which may increase the response time.

Chapter 5

Object Characteristics and Spatio-spectral Features of EEG in Mental Rotation

5.1. Introduction: EEG and Mental Rotation

When individuals play computer-games, information processed by them is primarily visuospatial in nature. Visuospatial processing involves perceiving, analyzing, manipulating, and transforming visual patterns or images in order to understand them in the task context. Mental rotation (MR) is one of the essential aspects of visuospatial processing, which facilitates transformation, rotation, comparison, judgment, and other spatial manipulation on a mental image to process the object characteristics (e.g., dimensions, angles, directions, reference frame). Even in day-to-day activities in our lives, it plays a crucial role, especially in the tasks requiring fast manipulation of the visual contents, such as learning geometry or navigating a map. Therefore, it significantly impacts visuospatial processing concerning learning, reasoning, decision making, and visual perception tasks (Thompson et al., 2013; Stieff, 2007; Seepanonmwan et al., 2015; Fernandez-Mendez et al., 2018; Critten et al., 2018).

In MR, the characteristics of the visual objects affect task execution. One of these important characteristics is the angular disparity at which an individual has to rotate the mental images (Shepard & Metzler, 1971; Metzler, 1973; Metzler & Shepard, 1974; Cooper, 1975; Balaj, 2015). It is the angular difference between the two objects, whose mental images are compared during an MR task. Shepard and Metzler (1971) suggested an ‘inverted V’ shaped plot between angular disparity and response time during the MR task. Later other studies also reported the same trend of angular disparity on response time in the MR task (Metzler, 1973; Metzler & Shepard, 1974; Cooper, 1975). Another crucial parameter that may affect the performance during an MR task is the dimensionality of the presented images. Studies have explored dimensionality of the object in 2D and 3D categories and reported performance dependency on the dimensionality of the image or object during the MR processes (Metzler & Shepard, 1974; Cooper, 1975; Vandenberg & Kuse, 1978). Also, the differences in mechanism followed by the human brain while processing 2D and 3D objects in MR tasks are discussed earlier. Piecemeal processing is elicited by complex, unfamiliar shapes, such as torus shapes, requiring rotation in-depth, whereas holistic processing is elicited by familiar 2D stimuli, such as alphanumeric characters, requiring rotation in the picture plane (Just & Carpenter, 1976,1985; Bethell-Fox & Shepard, 1988). Studies have suggested that the stimulus category, task environment, and spatial reference frames also play a crucial role in selecting the strategy to process the information during MR.

Previous studies have examined dimensionality in MR. In these experiments, investigators have used different types of objects for 2D vs. 3D, whereby the use of isomorphic stimuli is missing (Shepard & Metzler, 1988; Nikolaev & Anokhin, 1998). This aspect is an important concern because the object category (stimulus type) also could influence the selection of strategy to process MR. The current study has used isomorphic objects, allowing better experimental control in studying the 2D vs. 3D aspects of dimensionality. The point is that if objects are non-isomorphic, there is a concern related to experimental control. In other words, the effect may not be only because of dimensionality, but also the factor concerning non-isomorphic objects itself could play a role. In the context of the current study, the investigators have categorized angular disparity into- convex angular disparity (CA) and reflex angular disparity (RA).

The behavioral and neuroimaging MR studies have used various tasks to measure or train MR abilities. Most of them have utilized paper-pencil-based tasks and visual slides based on parity judgment; however, few studies have also used real-world situations, video games, or computer-based tasks (Redick & Webster, 2014; Van Meertan et al., 2019; Milani et al., 2019). Computer-games composed of complex visuospatial information with patterns requiring rotation usually require fast responses, and the MR ability plays an important role while executing the task efficiently. Though these games have been growing in recent years primarily for entertainment, recent studies have been supporting their usefulness and effectiveness in training cognitive abilities (e.g., Green & Bavelier, 2003, 2006; Feng et al., 2007; Cherney, 2008; Oie & Patterson, 2013; Wu & Spence, 2013; Bejjanki et al., 2014; Trisolini et al., 2018; Petilli et al., 2020). Cherney (2008) investigated the effects of playing video games on MR abilities and suggested improved performance on MR tasks. Recently, Milani et al. (2019) also reported improvements in MR abilities by playing video games. Hence, computer-games requiring MR ability could effectively train the spatial skills, considering their fast-growing access to everyone through smartphones and other multimedia devices. So, to present the MR processing in an interactive and impactful manner, this study has utilized the computer-game environment and presented the MR in the form of a computer-game to the participants.

Previous studies have investigated the neural activities during MR tasks using different neuroimaging techniques (Gardony et al., 2017; Cohen et al., 2001; Just et al., 2001; Kawamichi et al., 2007). Zacks (2008) reviewed several MR studies with neuroimaging methods and suggested the increased activity in the intraparietal sulcus and adjacent regions during MR tasks. The study also suggested neural activities in the medial superior precentral cortex, especially with the stimuli favoring the motor simulation, which indicates the MR dependence sometimes on motor simulation as well. Further, the effects of spatial reference frames in MR tasks have also been discussed by Thomas et al. (Thomas et al., 2013), showing the increased EEG coherence for allocentric reference frames during the MR task.

The frequency bands of EEG rhythms are differently associated with the mental states. The exhibition of stronger alpha-blocking with the use of an allocentric reference frame is suggested by previous studies. Further, the desynchronization (loss in power) in alpha rhythms arises with increasing engagement of the cortical network, which depends on one's attentional demand for the visuospatial tasks (Gardony et al., 2017). Also, due to the task being allocentric, alpha desynchronization is expected in the brain areas associated with the task. Also, as CA and 2D found more challenging than RA and 3D in the previous study, it is expected to reflect higher active areas as no. of clusters for CA and 2D. Further, the object characteristics in the task also affect the strategy selection during the MR process; therefore, the cortical activation may vary depending on whether an individual selects a piecemeal or holistic approach (Milivojevic et al., 2009). The right hemisphere dominates in the holistic approach, whereas the left dominates in the piecemeal approach. The rotation process may approach different strategies with a smaller and larger angle of rotation (Ferdose & Sachdev, 2006). It is suggested in the previous study that rotation through a smaller angle is a holistic process, whereas rotation with a larger angle is a piecemeal process. Further, 2D object processing in MR is found more complex than 3D if the objects are isomorphic. Therefore, the difference in hemispheric laterality is expected between groups, reflecting right-hemispheric laterality for CA and 3D, however left-hemispheric laterality for RA and 2D.

Oei and Patterson (2013) suggested that the frequent training of a specific cognitive skill also reflects in another task if they both share common underlying demands. A similar phenomenon was also reported by Meneghetti et al., suggesting the transfer effects of MR training in the task requiring spatial skill (Meneghetti et al., 2016). Understanding the driving parameters in the MR process would certainly help to improve a computer-game for training the MR abilities. The neural correlates of these parameters may also help to understand its effect on other cognitive skills and design games for brain entrainment. Interestingly, it can provide a covert tool to train a cognitive skill silently behind a computer-game. It motivated us to investigate how the driving components of an MR process in a computer-game impact the human brain.

The parity tasks are the most common among the experiments conducted previously in MR, where an individual had to find the pair of given visual patterns from the given choices by mentally rotating them; see Fig. 5.1. Utilizing the parity-based MR computer-game, continuous scalp EEG data from ten locations of the frontal, central, and parietal regions were recorded while the participant played the computer game. Further, a clustering-based permutation test was applied on the EEG power spectra to find the brain region with significant activation due to changes in the game parameters. Also, the hemispheric laterality was evaluated to show the hemispheric dominance related to angular disparity and dimensionality conditions.

Figure 5.1 An example of MR process in parity task for finding the target-match from image 1 and 2.

5.2. Data Analysis

For the offline preprocessing of the data, we utilized the standard routines in MNE-Python (Gramfort et al., 2016). The further spectral analysis of the preprocessed data at the sensor level was done using the FieldTrip toolbox (Oostenveld et al., 2011) and customized scripts in

MATLAB® (www.mathworks.com). Fig.5.2 shows the study's analysis workflow where the processes written in blue color were completed in MNE-Python and the black one in the FieldTrip toolbox in MATLAB.

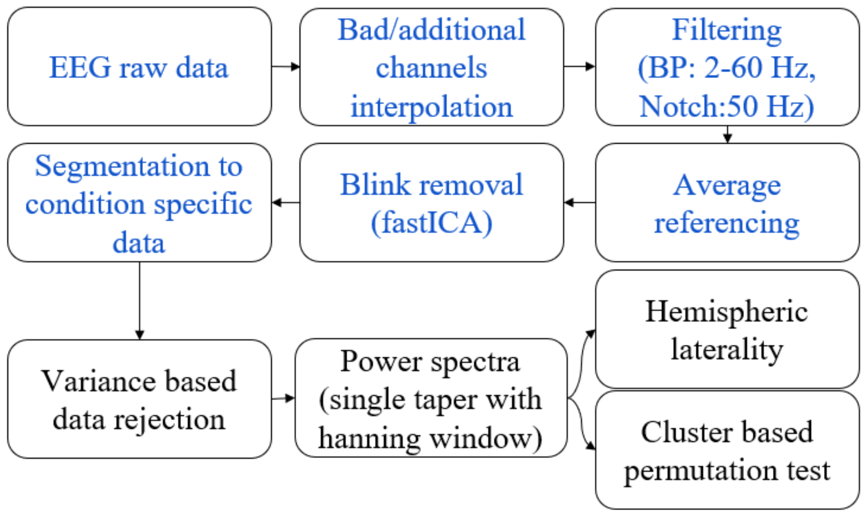


Figure 5.2 The analysis workflow in MNE-Python (blue) and FieldTrip (black**)**

5.2.1 Preprocessing of the EEG Data

First, we manually identified the bad EEG channels utilizing the accelerometer channels' information for the Emotiv system. Since using the MP150^{TM} system, we could acquire data only ten scalp positions with identical EEG channels at the high temporal resolution; therefore, along with the bad channels, if any, we interpolated EEG data also for the four important positions— Fz, CPz, P1, and P2; see channels with blue labels in Fig.5.3. These four positions were in very close vicinity of the recorded channels that minimize the possible interpolation error. The interpolation was done using the spherical spline method (Perrin et al., 1989), which projects the sensor locations onto a unit sphere and interpolates the signals at the bad/missing sensor locations based on good quality signals nearby locations. Thus, the datasets were transformed into a total of fourteen channels. Subsequently, the new sets of fourteen-channel EEG data were filtered through a 2–60 Hz bandpass FIR (finite impulse response) filter followed by a 50 Hz notch filter to remove the power line noise. The filtered data were then re-reference with the average of all the fourteen channels. Then, we applied ICA (independent component analysis) to remove the artifact due to the eye blinks during the experiment, we applied ICA (independent component analysis) (Hyvarinen, 1999). The eyeblink component was rejected based on the components' field map, and the clean signal was reconstructed using the rest of the components, shown in Fig. 5.4. After that, the blink-removed EEG data sets were segmented for baseline, and the four angular disparity categories utilizing the event markers/triggers save with the data. Finally, the preprocessed and segmented (condition-specific) EEG data were saved as individual .*fif* files for group-wise spectral analysis.

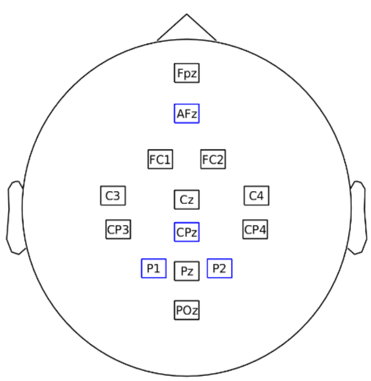


Figure 5.3 The originally recorded (black) and interpolated channels (blue)

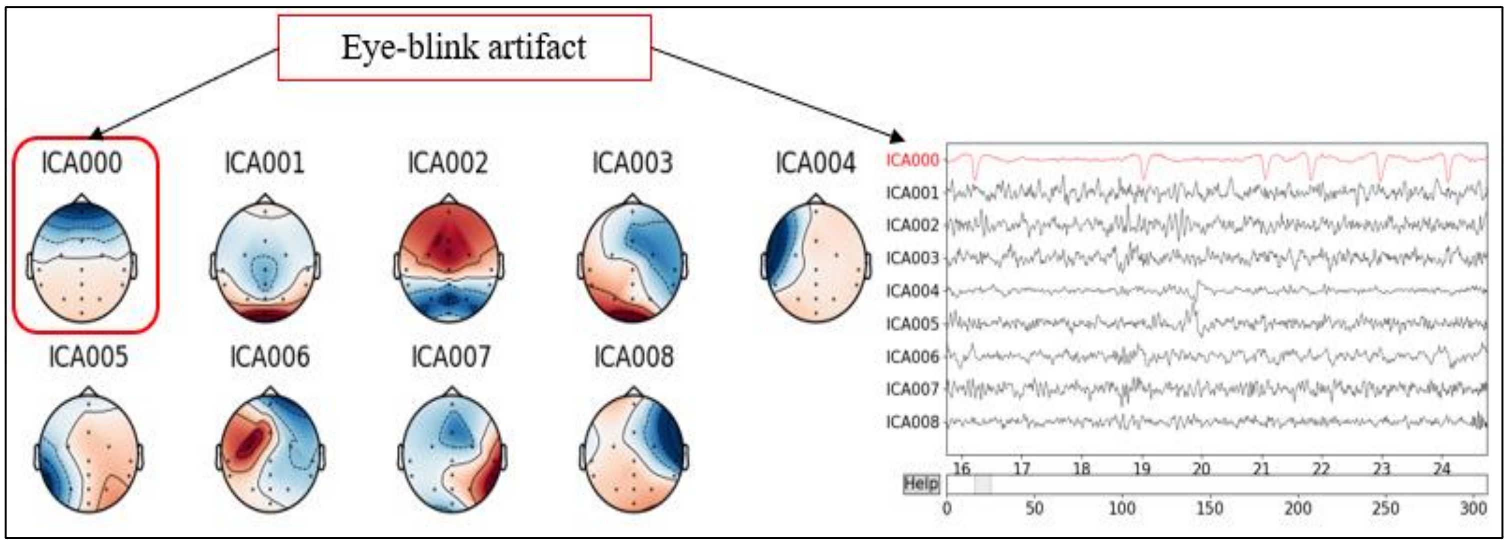


Figure 5.4 Signal's morphology and their potential topoplot-based blink selection from ICs

5.2.2 Spectral Analysis

Oscillatory components contained in continuous EEG signals often show changes in power relative to experimental conditions. Since the EEG data were from resting-state recording, we assume that the power spectrum is stationary over time. Hence, we analyzed the power spectrum averaged for the whole duration in one gaming session, not how it changes over time. We computed the PSD (power spectral density) for the preprocessed continuous datasets from all the participants. The multitaper method (Percival & Walden, 1993; Mitra & Peraran, 1999) for frequency transformation in *ft_freqanalysis* (a function in FieldTrip toolbox for frequency analysis) was utilized with a single hanging taper, a frequency bin of 0.25 Hz, and 4s window length for computing the PSD. A variance-based trial rejection method was used while computing the spectra for discarding the windows with variance higher than the 95th percentile of the maximum variance across all the windows (Jaiswal et al., 2020). It discarded the windows with the data having excessive movement artifacts. Thus, the data were transformed into condition-specific power spectra for each of the fourteen channels. Further, we computed the baseline normalized power spectra within 2–60 Hz for all channels, dividing the power spectra in each MR condition by the baseline power spectra. It gives the relative change in power from the baseline to each experimental condition, usually known as. Relative power. Fig. 5.5 shows the distribution of band-specific relative power across brain regions for all four groups compared with the global baseline (mean of all baselines). The figure also plots the variation in averaged relative power for five regions— frontal (F), central I, left central (CL), right central (CR), and parietal (P). Since the figure indicates that power tends to zero after ~ 30 Hz, we constrained our further analysis below 30 Hz.

Using the computed relative power spectra, we applied cluster-based permutation tests (Maris & Oostenveld, 2007; Maris, 2012) and hemispheric lateralization analysis (Seghier, 2008) to investigate the difference between groups due to changes in angular disparity and dimensionality in the computer-game with MR. To infer the statistical significance, we used the alpha level 0.05 throughout this study.

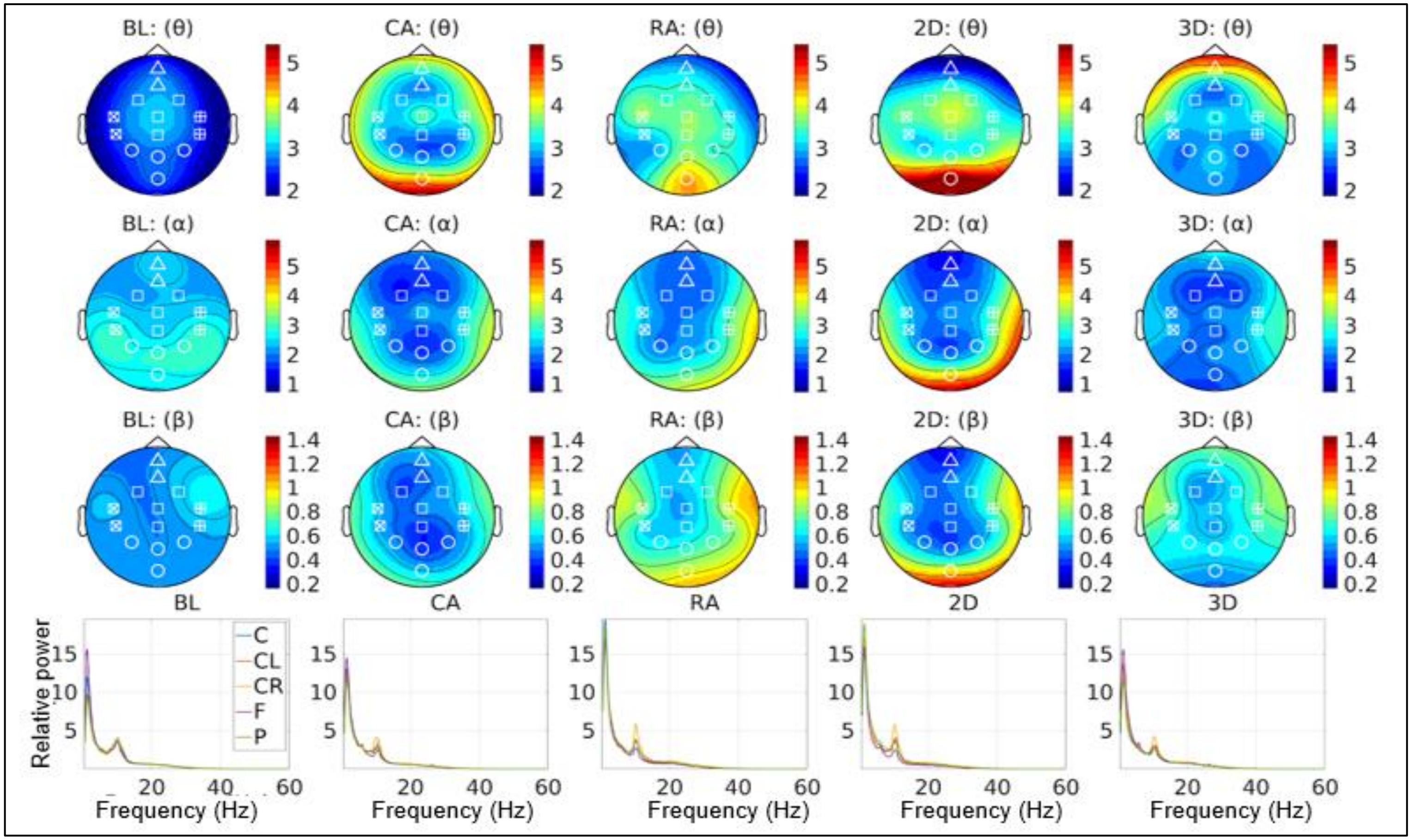


Figure 5.5 Relative power for all the four groups compared with the baseline for the frequency bands θ (3.5 – 7.5 Hz), α (7.5 – 13.0 Hz), and β (13.0 – 30.0 Hz)

Cluster-based Permutation Test

As Fig. 5.5 indicates no changes in power beyond 30 Hz, we constrained our statistical tests within 3.5–30 Hz to improve the test's sensitivity (i.e., the probability of detecting an effect). Differences in the relative power at the frequency range 3.5 – 30 Hz between the baseline and each of the four groups of the computer-game were statistically evaluated by a permutation test utilizing *ft_freqstatistics.m* in the FieldTrip toolbox. The paired sample t-statistic was computed for each of the EEG channels between the baseline and a gaming group. The channels were clustered based on their spatial adjacency using their neighborhood information. We specified the minimum number of neighboring channels equal to two (*cfg.minnbchan = 2*) for considering a cluster sample, i.e., a cluster whose t-statistic is higher than the corresponding $p < 0.05$.

The statistical significance of the spectral power difference between the baseline and a gaming condition was evaluated using a two-tailed t-test where the cluster's observed test statistic was the threshold at the 95th percentile of the null distribution. Subsequently, the cluster level statistic was computed by taking the sum of the t-values in each cluster, which was compared with the null distribution of the cluster statistics computed from the random permutation steps (5000 times) utilizing the Monte Carlo method. The p-values of the clusters were computed by estimating the proportion of draws from the permutation distribution with a maximum cluster-level statistic that is larger than the cluster-level statistic.

Hemispheric Lateralization

For studying the hemispheric lateralization, we analyzed band-wise regional and global hemispheric laterality. The laterality index (*LI*), which is the difference between responses from left (P_L) and right (P_R) hemispheres normalized by the sum of both, was computed as (Seghier, 2008):

$$LI = \frac{P_R - P_L}{P_R + P_L} \quad (1)$$

Here *P* represents the relative spectral power, and the values of *LI* vary between -1 to +1, indicating the complete left hemispheric dominance to the complete right hemispheric dominance. The values corresponding to frontal, parietal, and central regions were computed for each of the four groups. Similarly, the global laterality indices were computed between the entire left and right hemispheres. The subsets of channels selected for the left and light regions are shown in Table 5.1. The channels close to the midline were excluded from either of the regions.

Table 5.1 Region-wise channel selection for computing laterality indices.

Region	**Selected channels**
$\text{Frontal}_{\text{Left}}$	FC1
$\text{Frontal}_{\text{Right}}$	FC2
$\text{Centro-parietal}_{\text{Left}}$	C3, CP3
$\text{Centro-parietal}_{\text{Right}}$	C4, CP4
$\text{Parietal}_{\text{Left}}$	P1
$\text{Parietal}_{\text{Right}}$	P2
$\text{Global}_{\text{Left}}$	FC1, C3, CP3, P1
$\text{Global}_{\text{Right}}$	FC2, C4, CP4, P2

5.3. Findings

5.3.1. Cluster-based Permutation Tests

The condition-specific differences from baseline to each of the four groups were examined using the significance threshold of 0.05. Though we applied the test for each of the θ, α, and β bands, the significant clusters were notable around the α frequency range (5 – 15 Hz) across the four groups. Fig. 5.6 shows the spatio-spectral changes for all the four groups from the grand baseline, where *xlim* represents the frequency range on X-axis and *ylim* represents the relative power on the Y-axis. The vertical gray lines show the frequencies at which the clusters exist with a p-value lower than the significance threshold. For all the four groups, Table 5.2 lists the p-value threshold for the significant clusters, the number of clusters, and the cluster statistics, which is the sum of t-statistics across the clusters with the p-value lower than the threshold mentioned above. The individual clusters for each of the four groups are shown in Fig. 5.7, where '*' represents the clusters with $p < 0.01$ and 'x' for the clusters with $0.01 < p < 0.05$.

A higher number of clusters were notable for the CA group in the frontal and parietal regions within the frequency range of 7.8 – 14.2 Hz. Fig. 5.6 also shows a few clusters involving the left central EEG channels. Fig. 5.7 demonstrates individual clusters at each frequency bin. For the RA group, fewer clusters were notable as compared to the CA group. These clusters were found within a lower alpha range (8.0 – 10.0 Hz). The clusters for the RA group were more visible in the frontal and left centro-parietal regions. In the case of the 2D group, no significant cluster was observed when applying the test for the frequency range 5 – 15 Hz; however, a few clusters were found when testing with the frequency range constrained to alpha (7.0 – 13.0 Hz). These clusters exist within the higher alpha range (11.0 – 11.7 Hz) involving the frontal and parietal regions. For the 3D group, the clusters were found over the frontal and left centro-parietal regions. These clusters laid within a lower alpha range (7.8–10 Hz).

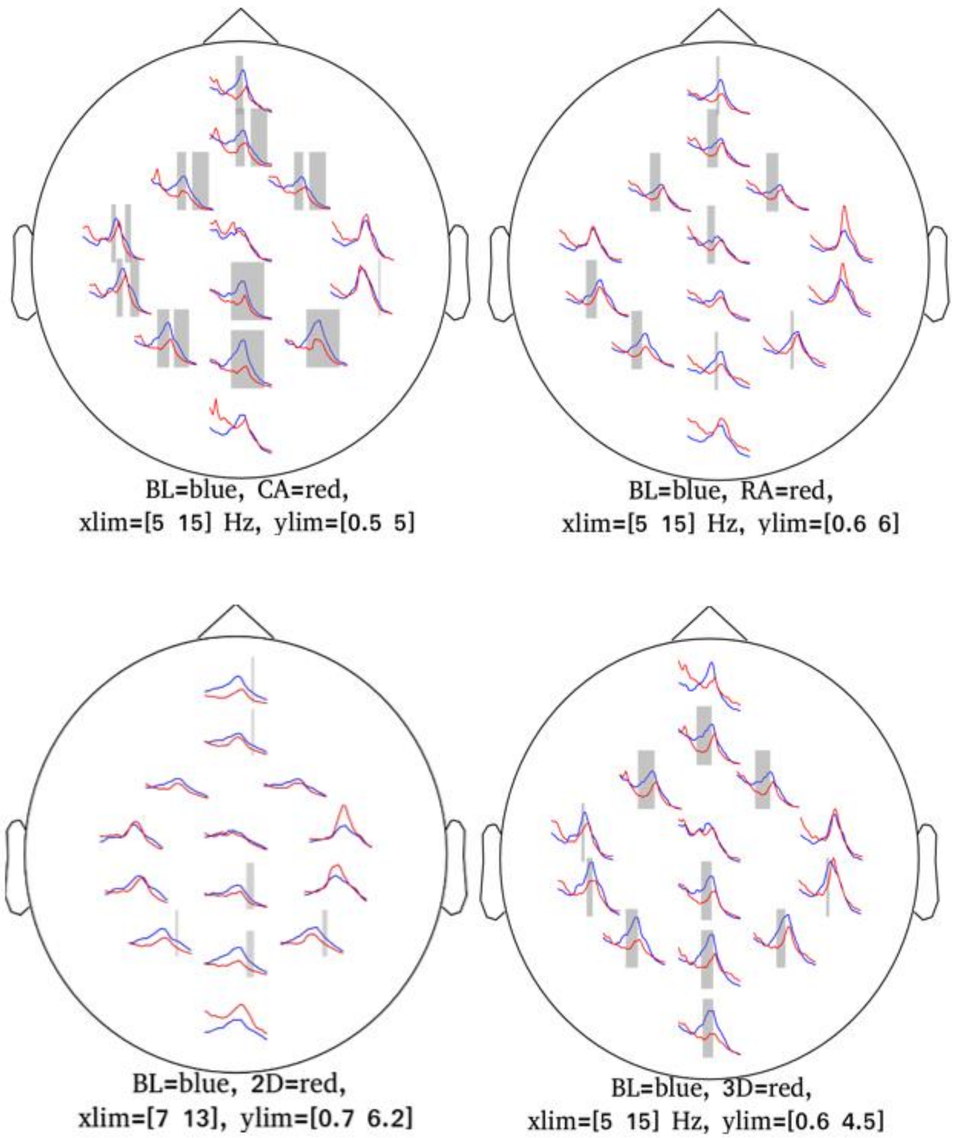


Figure 5.6 The plots corresponding to the frequency range for significance difference from baseline and most significant clusters

Table 5.2 Cluster-statistics (clust.-stat.), p-values (p) and number of clusters (clusts.) for significant clusters for the four groups

	cluster-statistc	p-value	clusts.
CA	187	0.001	27
RA	54	0.020	9
2D	21	0.047	4
3D	93	0.011	12

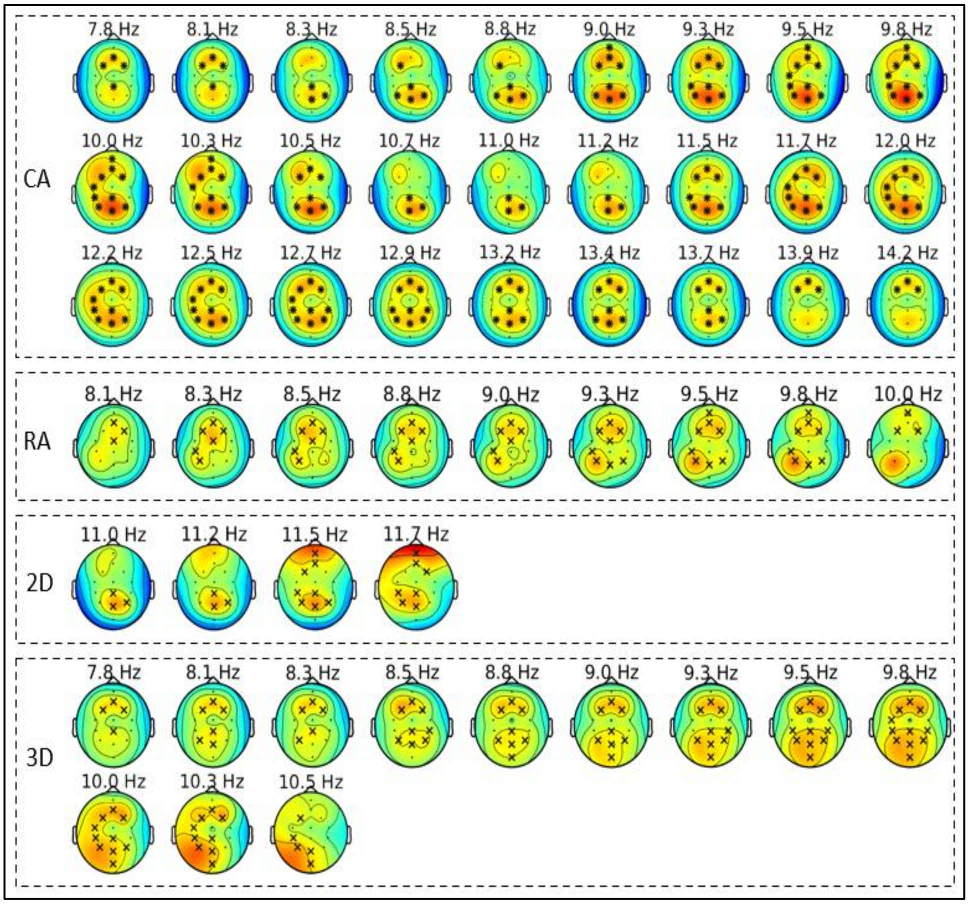


Figure 5.7 Significant clusters for the four analysis groups

5.3.2. Hemispheric Lateralization

LIs were computed for each subject using the relative power for θ, α, and β bands. The distributions of *LIs* for all four groups are shown in Fig. 5.8. Further, to examine the laterality changes from baseline, *T*-statistics was applied separately for the α band and combined θ, α, and β bands, using the significance level 0.05. Table 5.3 lists the *t*-statistics and *p*-values for regional and global laterality changes from baseline in all the four groups. The *italic* entries show the significant changes from baseline. The highly significant changes were found in centro-parietal regions for the alpha band, guiding the variation in global laterality. For the frequency range 3.5 – 30 Hz, similar trends were found.

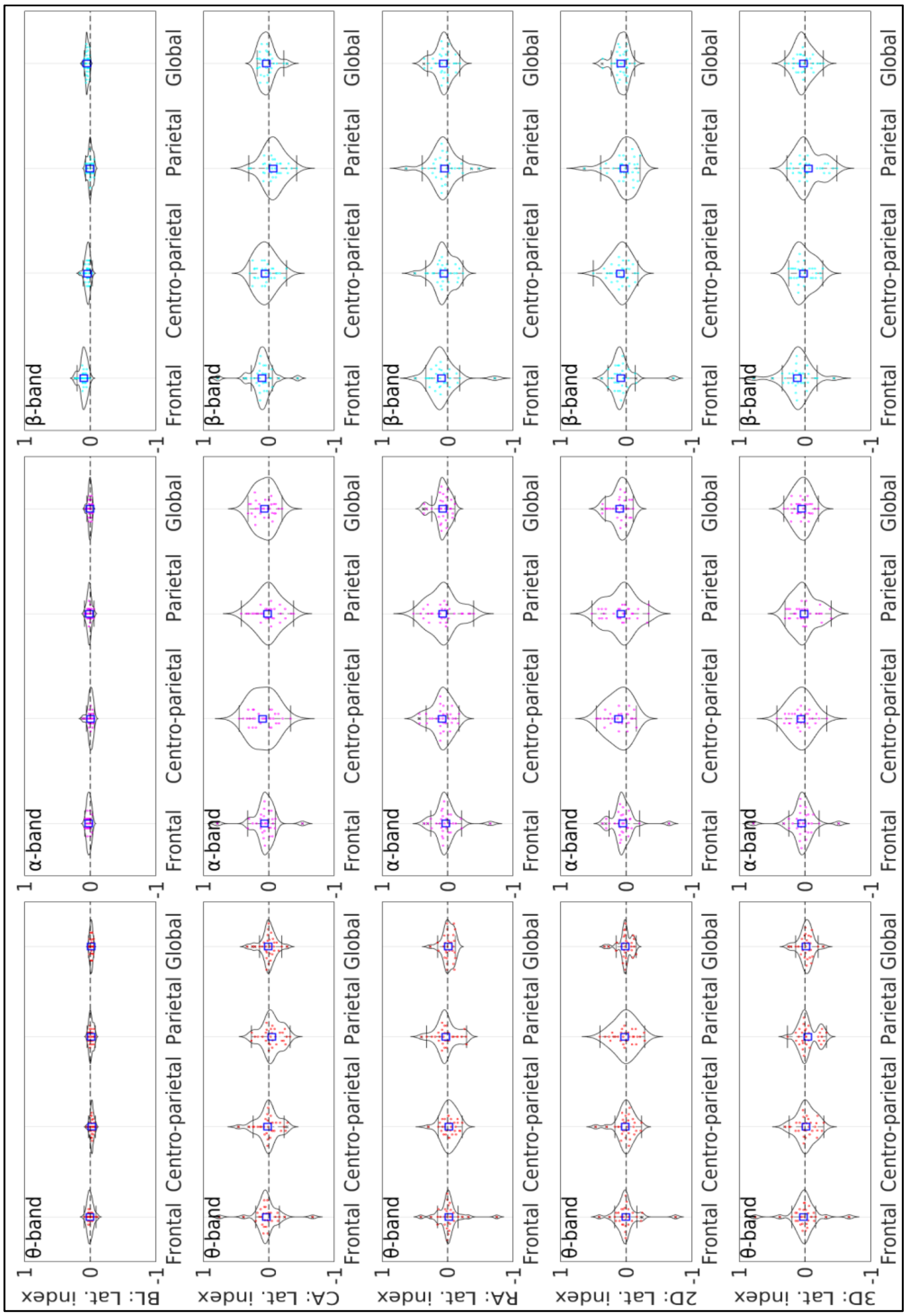


Figure 5.8 Bandwise laterality indices distribution for all participants.

			CA	**RA**	**2D**	**3D**
Only α (7.5 – 13.5 Hz)	**Frontal**	*t-stat.*	-1.20	-0.27	-0.80	-0.74
		p-value	0.23	0.79	0.43	0.46
	Centro-parietal	*t-stat.*	*-2.52*	*-3.00*	*-3.51*	-1.98
		p-value	*0.01*	*0.01*	*0.01*	0.06
	Parietal	*t-stat.*	0.05	-1.42	-1.39	0.09
		p-value	0.96	0.16	0.17	0.93
	Global	*t-stat.*	*-2.21*	*-3.12*	*-3.52*	-1.74
		p-value	*0.03*	*0.01*	*0.01*	0.09
Combined θ, α, and β (3.5 – 30 Hz)	**Frontal**	*t-stat.*	-1.25	0.32	-0.08	-0.84
		p-value	0.21	0.75	0.93	0.40
	Centro-parietal	*t-stat.*	*-2.47*	*-2.15*	*-3.65*	-1.02
		p-value	*0.01*	*0.03*	*0.01*	0.31
	Parietal	*t-stat.*	-1.85	*-2.18*	-1.90	1.45
		p-value	0.07	*0.03*	0.05	0.15
	Global	*t-stat.*	-1.56	*-2.40*	*-3.66*	-0.42
		p-value	0.12	*0.02*	*0.01*	0.68

Table 5. 3 t-statistics (t.stat.) and p-vaue (p) in order to show the significance of the change in laterality from baseline to MR.

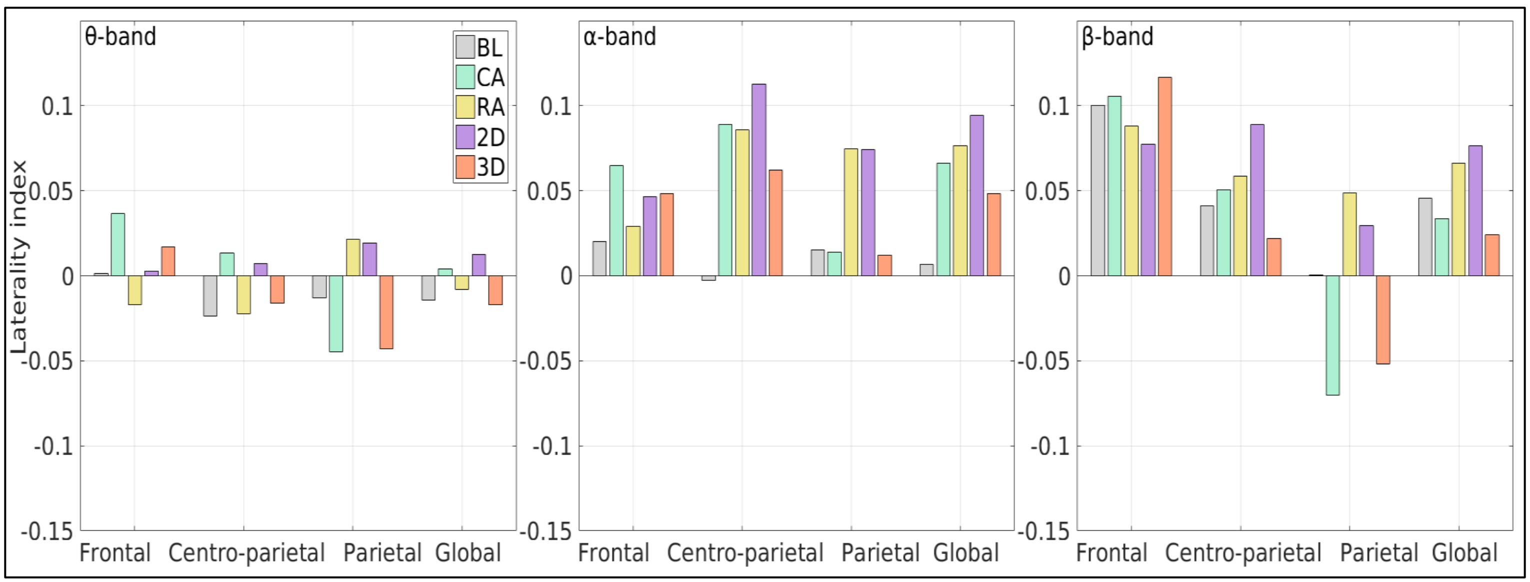


Figure 5.9 Band-wise mean *LIs* for each group, the legends shown in the first subplot are valid for all.

Further, the t-test was applied with a significance level of 0.05 to evaluate the difference between CA vs. RA and 2D vs. 3D groups across the frequency range of 3.5–30 Hz. The mean *LIs* for baseline and each of the groups for θ, α, and β bands are shown in Fig. 5.9. The figure clearly shows the positive *LIs* for most of the groups. The positive *LIs* for α band indicates higher alpha desynchronization in the left hemisphere in all the cases of MR. The CA group showed a significant laterality difference from the RA group only in the parietal region *(t-statistics = -2.91, p = 0.01)*, indicating its right hemispheric dominance; however, the dominant alpha desynchronization in the left hemisphere impacts it, and the synergic effect can be noticed in this band. Similarly, the 3D group showed right-hemispheric dominance in contrast to the left dominating 2D group. The significant differences were found in the centro-parietal *(t-statistics = 1.97, p = 0.04)* and parietal *(t-statistics = 2.43, p = 0.01)* regions as well as globally *(t-stat = 2.32, p = 0.02)*. Though the right frontal region showed higher positive mean *LIs* across all the bands for the CA group compared to the lower *LIs* for RA, a statistically significant difference was not observed *(t-statistics = -0.61, p = 0.23)*. Because of the system limitation, we could not investigate the temporal or other regions.

5.4. Discussion

In the study, the effects of dimensionality and angular disparity in a mental rotation computer-game were investigated, utilizing the power spectra of EEG recorded during the gameplay. The cluster-based permutation tests were applied to find the spatio-spectral changes in EEG for the four groups of the game from the baseline. We also investigated the regional and global hemispheric laterality for θ, α, and β frequency bands.

The permutation tests showed significant clusters in the frontal, centro-parietal, and parietal regions around the alpha frequency range. Increased alpha desynchronization was found in the regions mentioned above (especially in fronto-parietal regions) during the mental rotation games compared to baseline. The fronto-parietal region is frequently referred to in the previous MR studies and related to the visuospatial representation. The posterior parietal cortex is crucial for representing the spatial maps, mental image formation, and uploading the spatial reference frames (Thomas et al., 2013; Tomasino & Gremese, 2016; Jancke & Jordan, 2007; Bhattacharya et al., 2001; Ciaramelli et al., 2010; Mishkin et al., 1983). The decrease in alpha power associates with increased cortical activity in related areas. For instance, reduced alpha power in the parietal region during a cognitive task most likely reflects the cortical activation in the region, indicating the demand for visuospatial representation (Gardony et al., 2017). Since the tasks in the study were allocentric, increased activation in the bilateral parietal cortex was observed due to the object-centered allocation of attention (Wilson et al., 2005).

Significant changes were found across the alpha frequency range and beyond for the group that played the MR game with convex angular disparities (7.8 – 14.2 Hz). On the other hand, the group with reflex angular disparity showed fewer clusters with alpha desynchronization limited to lower alpha frequencies (8.1–10.0 Hz). The former group showed a higher level of alpha desynchronization in frontal, left centro-parietal, and parietal regions, whereas, for the latter group, it was in frontal and left parietal regions; these results match our expectations. A previous study suggested that the rotation process may approach different strategies with a smaller and larger rotation angle. Therefore, rotation through a smaller angle can be holistic, whereas rotation with a larger angle can be a piecemeal process. The analysis approach leads to hemispheric dominance, like the right hemisphere for holistic and left for a piecemeal approach. Further, previous studies have reported the right-hemispheric bias of clockwise rotation and left for the counter-clockwise (Burton et al., 1992). The significant changes in the case of convex angular disparity show right hemispheric lateralization and an extended cortical network, whereas the higher level of left-hemispheric lateralization was found in the case of reflex angular disparity. Since no cluster showed a significant change from baseline beyond 5 – 15 Hz, the cluster-based analysis was limited to this frequency range for better sensitivity.

The statistically significant clusters and the lateralization indices indicate that the MR with reflex angular disparity is globally more left-lateralized than convex angles, which is quite close to our assumption about hemispheric laterality. However, the hemispheric asymmetry in MR processes associates not only the parity judgment but also may reflect visuospatial processing, which utilizes the bilateral fronto-parietal network, rather than regions restricted to the posterior parietal regions (Cohen et al., 2001; Bhattacharya et al., 2001; Koshino et al., 2005; Jordan et al., 2004; Lamm et al., 2001; Harris et al., 2000; Tagaris et al., 1998; Richter et al., 1997). Because of the other high-level processing due to the stimulus type, the MR process may require various levels of planning, reasoning, and other cognitive engagements; the left hemisphere usually gets more involved in the process.

As it is evident that the MR process also depends on the strategy followed by an individual to execute the task (Tomasino & Gremese, 2016), the strategy affects the hemispheric lateralization for the process. The right hemisphere is recruited if the individual uses a holistic strategy (rotating the image as a whole), whereas the left hemisphere when the individual rotates the image in a piecemeal manner using an analytic approach. However, besides the choice of either approach, the type of the objects (stimuli) and the familiarity can also affect the selection of the MR process strategy. An individual may switch to the piecemeal strategy for 'complexed-looking' strange shapes (Bethell-Fox & Shepard, 1988) and holistic for the familiar objects or the objects with information, making the rotation easier (Milivojevic et al., 2003, 2009).

The MR with 3D objects showed significant changes in EEG spectra in the fronto-parietal regions leaned towards the left for the lower-α band (7.8-10.5 Hz). On the other hand, in MR with 2D objects, we found only fewer clusters within a higher alpha range (11.0 – 11.7 Hz), which slightly deviates from our assumptions. The possible reason for the lower number of significant clusters in the case of the 2D group could be the effect of mixed 2D-3D perception of the 2D objects in the experiment. Since the 2D objects in this study were designed by removing the depth information from the isomorphic 3D objects, they still contained some 3D effects, which turned the 2D objects not pure-2D. It made the "less informative" 2D objects more complex, tedious, and extended time and attention-seeking to process. Therefore, the participants possibly followed different strategies, some of them by putting extra effort involving more reasoning and attention, whereas the others just guessed or randomly chose the answer instead of answering after rotating them mentally. Fig. 5.8 also shows that the *IQR (interquartile range)* for 2D is higher than the 3D, indicating higher variance in the former, which further indicates that the participants possibly followed different strategies rather than only piecemeal or holistic approaches.

In laterality analysis, the t-statistics over the variation in laterality indices for each of the four groups from the baseline show the significant changes in centro-parietal regions, which are majorly driven by alpha rhythms; see Table 5.3. Further, the global and regional laterality for each of the four groups over the frequency band (3.5–30 Hz) was evaluated, see Fig. 5.9. The positive values indicate higher right-hemispheric power resulting from the increased desynchronization in the left hemisphere, which indicates a higher level of decision subprocesses and analytical engagement (Gill et al., 1998). In the parietal region, the negative *LI* for CA and positive *LI* for the RA group were observed, indicating right and left dominating activations; however, the overall left-hemispheric alpha desynchronization impacts synergically reduce the right hemispheric dominance of the parietal region for the alpha range.

The t-test indicated significant changes in the central region and global laterality indices (*LIs*) from baseline to 2D group for α band and beyond but not for the 3D group. It indicates the hemispheric asymmetry significantly increases from baseline to the MR tasks with 2D objects. Further, the significant difference between *LIs* for 2D and 3D groups was found for all the regions showing higher positive values for 2D; which show the increased desynchronization in the left hemisphere for 2D. The findings meet with our expectation of hemispheric lateralization. It contradicts some of the previous findings suggesting 2D prone to the right following the holistic approach, whereas 3D to the left utilizing the piecemeal strategy (Bethell-Fox & Shepard, 1988). The possible reasons we find here the complexity and object unfamiliarity. Since the objects were unfamiliar and the 2D without the depth information was more effort seeking, the subjects have possibly followed the more analytical approach to process the 2D than that of the 3D.

Though *permutation-based clustering* is a powerful method to find the sensor level resting-state EEG/MEG (electroencephalogram/ magnetoencephalogram) spectral changes between the experimental conditions, the higher number of channels could undoubtedly be a strong add on to the study. Though the individual gold-plated electrodes facilitated us to reduce the EEG input impedance and acquire high fidelity data, the study could be reproduced with a dense EEG, which would enable researchers to investigate at the source level. For taking the isomorphic 2D and 3D objects, the 2D objects were designed by removing the depth effect from their 3D models; however, they still had some 3D perception, which made them imperfect 2D against the perfect 3D model. The perfect 2D model can be designed for similar studies to distinguish their effect on MR in a better way.

5.5. Summary

The effects of the objects' dimensionality and angular disparity on the ongoing brain activity were investigated using the recorded EEG signal during the gameplay. Increased alpha desynchronization was found in fronto-parietal regions during the mental rotation games. Further, the left hemispheric laterality was observed within 3.5 – 30 Hz for most mental rotation cases; however, the activity during the games with convex angular disparity and 3D objects showed the opposite laterality in the parietal region. The finding suggests possibilities of influencing the mental rotation process by manipulating the parameters in computer-games. Correlation of the parameters with cortical functioning shows the possibilities of their effects on cognitive skills associated with fronto-parietal brain regions.

Chapter 6

Object Characteristics and Dorsal-ventral Visual Streams in Mental Rotation

6.1. Introduction: Visual Pathways and Mental Rotation

The complexity of the human brain and its associated functions has been a great interest of neuroscientists over the years. Visuospatial processing is one of the key functions of the brain, which envelops perception, analysis, manipulation, and transformation of visual patterns/images. The transformation here refers to rotation, translation, zooming, and comparison of the images during the visuospatial processing and is usually encapsulated as *Mental rotation (MR).* Shepard and Metzler (Shepard & Metzler, 1971) first studied the MR using their classic MR parity judgments task with pairs of rotated block stimuli/objects and suggested an 'inverted V' plot between response time and angular differences between the objects. Then after several studies have been conducted to investigate various aspects of MR using behavioral and neuroimaging methods (Zacks, 2008; Milivojevic et al., 2009; Tomasino & Gremsene, 2016; Xue et al., 2017; Moen et al., 2020). MR facilitates fast spatial visualization to our brain in visuospatial processing during various tasks in day-to-day life, such as finding a place, reading a map, navigating, etc.

In an MR process, one utilizes spatial and visual characteristics of the image, which requires both *where* and *what* processing pathways in the brain. Therefore, MR involves both the dorsal and ventral visual processing pathways in the brain (Koshino et al., 2005; Schendan & Stern, 2007). When an individual processes ‘what’ information, usually an allocentric or object-centered approach is involved, whereas an egocentric or viewer-centered approach is utilized for ‘where’ information processing (Norman, 2002). Though in an MR parity task, an individual needs to find a pair of the given object based on its visual features, the spatial information, i.e., the rotation between the objects, also plays a crucial role (Shepard & Metzler, 1971). This rotation is usually known as *angular disparity*, and its effects in MR processing are often investigated (Metzler, 1973; Metzler & Shepard, 1974; Cooper, 1975). Further, the objects' various visual characteristics affect the MR process, such as the object’s complexity, dimensionality (Shepard & Metzler, 1988; Balaj, 2015). The *dimensionality* holds the visual information defining objects’ dimensions in which they are visually perceived. Researchers have investigated the dorsal-ventral pathways using various neuroimaging techniques to study the visuospatial processing during the MR parity tasks (Gauthier et al., 2002; Koshino et al., 2005; Schendan & Stern, 2007). The dorsal pathway starts from the primary visual cortex (V1) and goes to the posterior parietal cortex (PPC) via the secondary visual cortex (V2), dorsomedial area (DM/V6), and middle temporal area (MT/V5). It primarily deals with the object's location, orientation, motion. On the other hand, the ventral pathway starts from V1 and goes to the inferior temporal cortex (IT) via V2 and V4 visual areas. The visual features such as color, size, dimension is processed by the ventral pathway (Bitar et al., 2015). Fig. 6.1 shows the representation of dorsal-ventral processing in associated regions during MR.

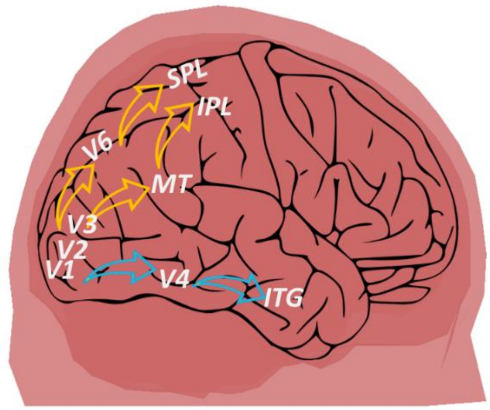


Figure 6.1 Representation of dorsal/where (yellow) and ventral/what (blue) pathways, and the associated regions Visual (V1–V6), MT (middle temporal), ITG (Inferior temporal gyrus), IPL/SPL (inferior/superior parietal lobules).

Cortical activations associated with MR have been investigated using object characteristics, and the association of several brain regions has been identified based on these measures in MR tasks. Although the MR studies have reported active association of PPC and other subregions in dorsal and ventral pathways during MR tasks, the findings are not limited to these areas. Activities in other brain regions have also been often reported during MR depending on the tasks' complexity and nature. Higher cortical activation with increasing angular disparity has been previously reported in the right dominating bilateral superior and inferior parietal lobules, superior temporal gyrus (STG), right medial frontal gyrus, and other higher-order prefrontal regions (Carpenter et al., 1999; Podzebenko et al., 2002; Gogos et al., 2010). The other regions associated with the dorsal pathway, such as precuneus, supramarginal gyrus, calcarine, and precentral gyrus, were also found active in several MR studies (Suchan et al., 2002; Schendan & Stern, 2007; Milivojevic et al., 2009; Tomasino & Gremsene, 2016) Further, the ventral pathway's regions such as an occipital pole, extrastriate region (V2 and V4), lingual, and inferior temporal regions have been primarily reported active during MR tasks while processing objects' features or their subsections (Carpenter et al., 1999; Jordan et al., 2002; Koshino et al., 2005; Tomasino & Gremsene, 2016). The interactive activations across dorsal and ventral pathways and objects' complexity depend on the visuospatial parameters, activation in other brain regions such as higher-order premotor areas, anterior insula, and frontal regions have been often observed active during MR (Milivojevic et al., 2009; Tomasino & Gremsene, 2016; Koshino et al., 2005; Schendan & Stern, 2007). Coactivation in anatomically connected cortical regions has also been reported in few MR studies due to their partial involvement in the task (Rorden & Karnath, 2004).

Besides investigating the effect of rotation angle in MR, studies have evaluated the impact of object dimensionality, e.g., two-dimensional vs. three-dimensional objects. However, these studies have utilized different sets of 2D and 3D objects in the task design, requiring additional processing networks. Also, the stimulus types and task design affect the strategy selection during the task, which further influences the processing network of the brain (Zacks et al., 2003, Zacks & Michelon, 2005; Kessler & Thomson 2010). So far, many MR paradigms have been utilized, such as paper-pencil-based tasks, visual slides, and real-world situations (Voyer, 2011; Quaiser-Pohl et al., 2014; Nakatani & Pollatsek, 2004). Few recent studies have also investigated MR during computer-games (Cherney, 2008; Redick & Webster, 2014; VanMeerten et al., 2019). However, it is still unclear how the game's visuospatial features influence the selection of cortical networks for MR processing. The growing reach of computer-based games through hand-held devices and their effects on several cognitive skills (Green & Bavelier, 2006; Feng et al., 2007; Oie & Patterson, 2013) motivated us to investigate how MR processing varies due to changes in the object's parameters utilized in the games.

In this study, the two categories of angular disparity, i.e., CA and RA, represent the spatial characteristics of the objects. The visual characteristics of these objects are described by their dimensionality, i.e., 2D and 3D. In the light of the above discussion, the current study hypothesizes that spatial information (angular disparity) plays a much influential role than the visual ones (dimensionality) while utilizing the dorsal-ventral pathways in MR, the dorsal pathway is expected to be more engaged than the ventral ones. Also, as CA and 2D are found more challenging than RA and 3D in the previous study, it is expected to reflect higher activation in the dorsal-ventral pathway for CA and 2D in this study. As a result, the dorsal-ventral pathways are likely to be active while playing the MR computer-game, depending on objects' angular disparity and dimensionality. Furthermore, the dorsal pathway should be more active than the ventral. Also, objects with a CA and 2D object are thought to have higher dorsal-ventral pathway activation than RA and 3D appearance. EEG data were recorded for each participant before and during the gameplay using a 14-channel EEG system. We computed the cortical activations for each of the four groups using the DICS (Dynamic Imaging of Coherent Sources) beamforming method and further parcellated the activation maps into sixty-eight functional brain regions. The regions associated with the dorsal-ventral visuospatial processing pathway and the other regions with significant activations were identified and compared to show the parametric changes.

6.2. Data Analysis

The EEG data were analyzed offline using the FieldTrip toolbox (Oostenveld et al., 2011) and customized scripts in MATLAB® (version: 2010b). The data were first preprocessed, and the sensor level Fourier spectra were computed for all the channels. Further, a source analysis using the spectral information was applied to utilize the FieldTrip toolbox. Fig.6.2. shows the analysis workflow used in the study.

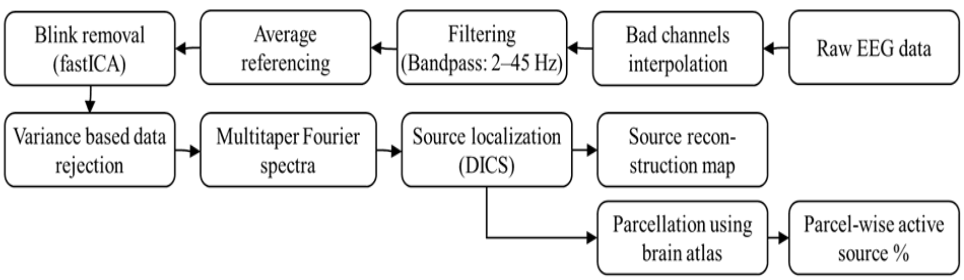


Figure 6.2 Analysis workflow used in the study.

6.2.1. Preprocessing of the EEG Data

After reading the data, we manually checked for any existing bad EEG channels and corrected them. Since the 14-channels Emotiv EPOC system has no electrode in the parietal region, which is essential for MR studies (Cohen et al., 1996; Tagaris et al., 1997; Jordan et al., 2001; Gauthier et al., 2002), we interpolated EEG data for two additional positions in the centro-parietal region— CP3 and CP4; see Fig.6.3. These two positions were in very close vicinity of the recorded channels that minimize the possible interpolation error. The bad channel correction and interpolation were performed utilizing the spherical spline method (Perrin et al., 1989). It projects the sensor locations onto a unit sphere and interpolates the signals at the bad/missing sensor locations based on good quality signals at nearby locations. Thus, the data were transformed into a total of sixteen channels.

The new EEG data sets were further detrended and filtered through a 2–45 Hz second-order bandpass FIR (finite impulse response) filter. The filtered data were then re-reference with the average of all the sixteen channels. We applied ICA (independent component analysis; Hyvarinen, 1999) to remove the artifacts due to the eye blinks during the data acquisition. The data were decomposed into a number of individual components equal to the rank of the data. The eyeblink components were rejected based on coherence higher than 70% with AF3 and AF4 channels, and the clean signal was reconstructed using the rest of the components, shown in Fig.6.4. After that, the clean EEG data were segmented for baseline and gaming durations, utilizing the event markers/triggers saved during the data acquisition. Finally, the preprocessed and segmented (condition-specific) EEG data were saved for group-wise spectral analysis.

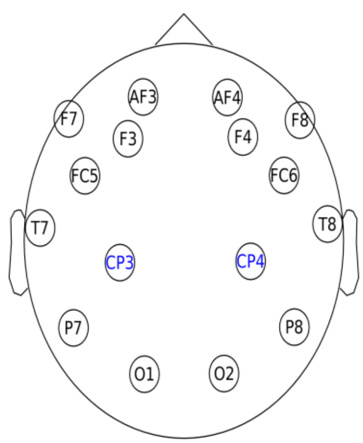


Figure 6.3 EEG channel layout used in the study.

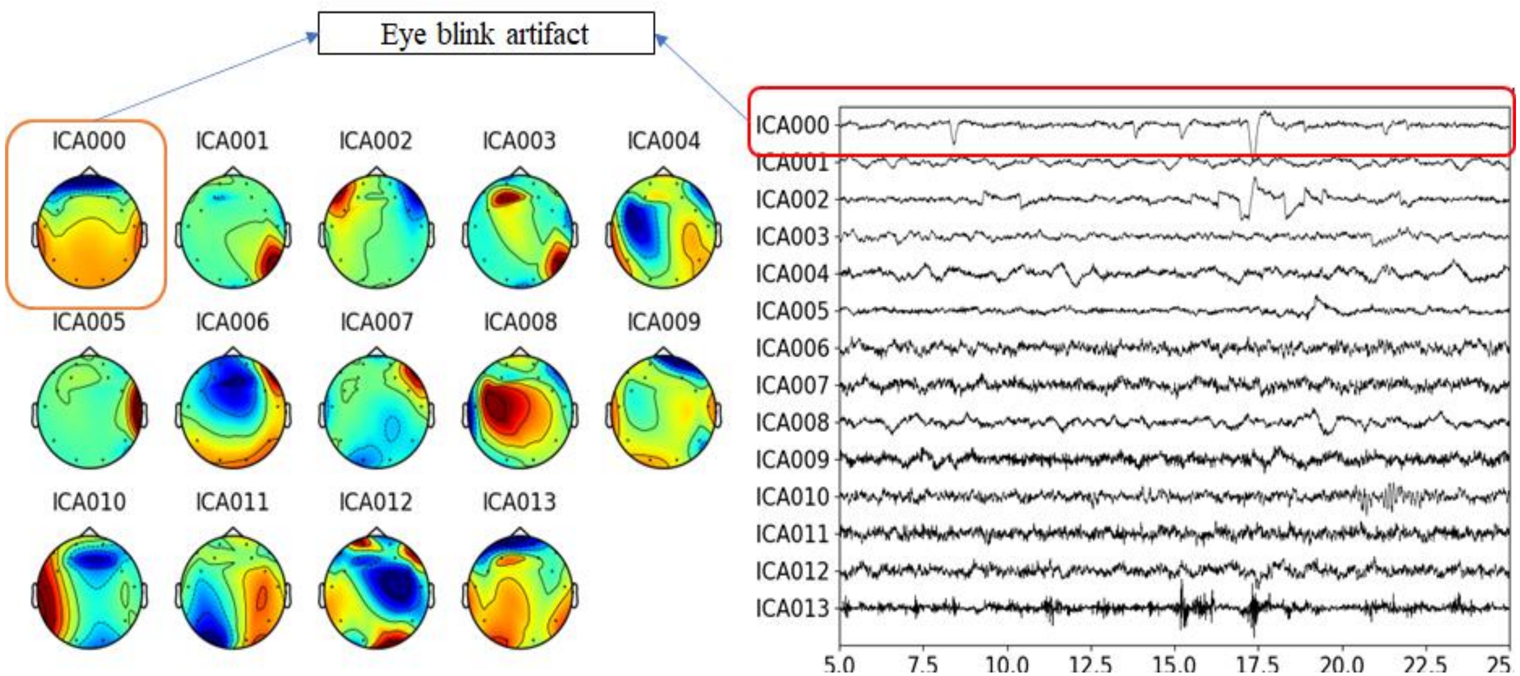


Figure 6.4 Illustration of the independent components and removed blink-artifact for arbitrarily selected data in the study.

6.2.2. Computation of Sensor-level Spectra

The preprocessed EEG data for baseline and gaming sessions were used for spectral computation. Since the gaming session duration was for several minutes, the study is more like a resting-state recording. In such cases, the oscillatory signals are not necessarily phase-locked to the event. Therefore, they would not be represented as event-related fields. In such resting-state studies, we usually assume that the power spectrum is stationary over time (during a gaming session in our case). Hence, we computed the spectral power for the entire duration of the gaming session and the baseline. For all the participants, we computed the spectral power (PSD) over 2–45 Hz with a frequency bin of 0.25 Hz and a sliding window length of 8 seconds. The multitaper method (Percival & Walden, 1993; Mitra & Pesaran, 1999) with a single hanning tapper was utilized for the frequency transformation using *ft_freqanalysis.* A variance-based automatic trial rejection method was used before the spectral computation to discard the windows with variance higher than the 95th percentile of the maximum variance across all the windows (Jaiswal et al., 2020). Thus, condition-specific (baseline and gaming session) PSD was computed for each subject's EEG data. We computed the normalized spectra by dividing the PSD from the gaming session by baseline PSD. It gives the relative change in power from the baseline to the gaming condition, usually known as. *Relative power*. Fig.6.6 shows the distribution of band-specific relative power across brain regions for all four groups compared with the corresponding baseline.

6.2.3. Source Reconstruction

To localize the sources underneath the oscillatory activity, we applied the DICS (Dynamical Imaging of Coherent Sources; Gross et al., 2001) beamformer techniques and represented the source reconstructed using the PCC method (Partial & Canonical Correlation; Schoffelen & Gross, 2009). We utilized a standardized template head-model to define the volume conduction model using the boundary element method (BEM). Using the conductor model and source-model with a regular volumetric grid of approx. 3000 points fitting inside the inner skull, we further defined the forward solution (Fuchs et al., 2002). The source-model and the EEG electrodes positions were aligned with the standardized *colin27* template MRI (Holmes et al., 1998) and further transformed to MNI (Montreal Neurological Institute) coordinate system before the forward model computation (Fig. 6.5). The forward model was further utilized for preparing the spatial filter in the source reconstruction.

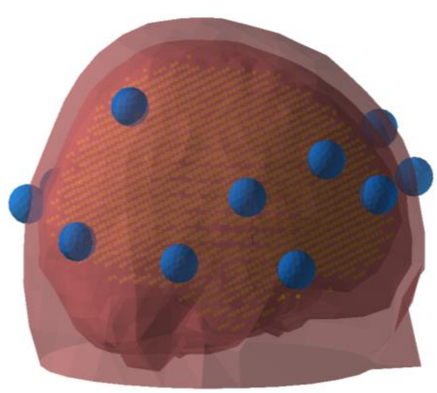


Figure 6.5 The volumetric source model (yellow-colored grid) and the head model (red surface) aligned with the sensor position (blue).

In contrast to time-domain beamforming such as LCMV (Linearly Constrained Minimum Variance: (Van Veen et al., 1997; Sekihara et al., 2006), DICS is a frequency domain beamforming method, which allows reconstruction of source activity using cross-spectral density matrix at a given frequency. The filter is based on minimizing the source power at a given location in source space, subject to 'unit-gain constraint'. The beamforming methods generally assume that sources in different parts of the brain are temporally uncorrelated. For applying the DICS method, we first computed the Fourier spectra of 16-channels EEG for baseline and gaming session using the multitaper method with the DPSS (Discrete Prolate Spheroidal Sequences) tapper. The spectra were computed over 8 seconds sliding window. Further, the spectra for all the subjects within a group were concatenated separately for baseline and gaming sessions. The cross-spectral density $\boldsymbol{C(f)}$ was then computed using the complex Fourier spectra. Here, elements $\boldsymbol{C}_{i,j}(f)$ of the matrix $\boldsymbol{C(f)}$ represent the cross-spectral densities between the i^{th} and j^{th} channels. The spatial filter of DICS for frequency f is defined as:

$$W_s^T(f) = (L_s^T C(f)^{-1} L_s)^{-1} L_s^T C(f)^{-1} \quad (1)$$

Here L_s represents the forward solution for any source s describing it is sensed by the EEG electrodes. Since the spectral topography showed minimal change in the frequency range of β2 and onward (Fig. 6.5), we limited the source analysis to 5 – 17 Hz. Using the spatial filter in equation (1), the neural activities for each source s in the source-model were computed at θ1(4–5.75), θ2(5.75–7.5), α1(7.5–9), α2(9–11), α3(11–13), β1(13–17.25), and β2(17.25–21.5) frequency sub-bands. Thus, we produced the spatial distribution of the activations in the brain. This distribution is then interpolated with an inflated brain surface derived from *colin27* template MRI and visualized. We further interpolated (mapped) the reconstructed sources over the Desikan-Kiliani atlas (Desikan et al., 2006) into 68 brain regions (Senden et al., 2018). Since the EEG data were recorded during the gaming session, which is like a resting-state, we expect quite a distributed source across the cortex rather than localized as in time-locked studies. Therefore, we fixed a threshold of 75th quantile of activities for each parcel and computed the number of sources with activity higher than this threshold for each parcel. The percentage of active sources (voxels) in each parcel was further computed and compared for CA vs. RA and 2D vs. 3D groups.

6.3. Findings

6.3.1. Spectral Topographies for MR Groups

The condition-specific spectral changes from the corresponding baselines for each of the four groups were evaluated using the multitaper method. Since the DICS pipeline reconstructs the source at a single frequency (takes mean if a band is given), we first examined the power contained in the data at different frequencies. We separately plotted the PSDs for $\theta 1$(4–5.75), $\theta 2$(5.75–7.5), $\alpha 1$(7.5–9), $\alpha 2$(9–11), $\alpha 3$(11–13), $\beta 1$(13–17.25), $\beta 2$(17.25–21.5), $\beta 3$(21.5–25.75), $\beta 4$(25.75–30), $\gamma 1$(30–35), $\gamma 2$(35–40), and $\gamma 3$(40–45). The figure shows significant changes only before 17 Hz; therefore, we constrained our analysis between 4–17 Hz. Fig.6.6 shows the spectral changes over successive frequency bands.

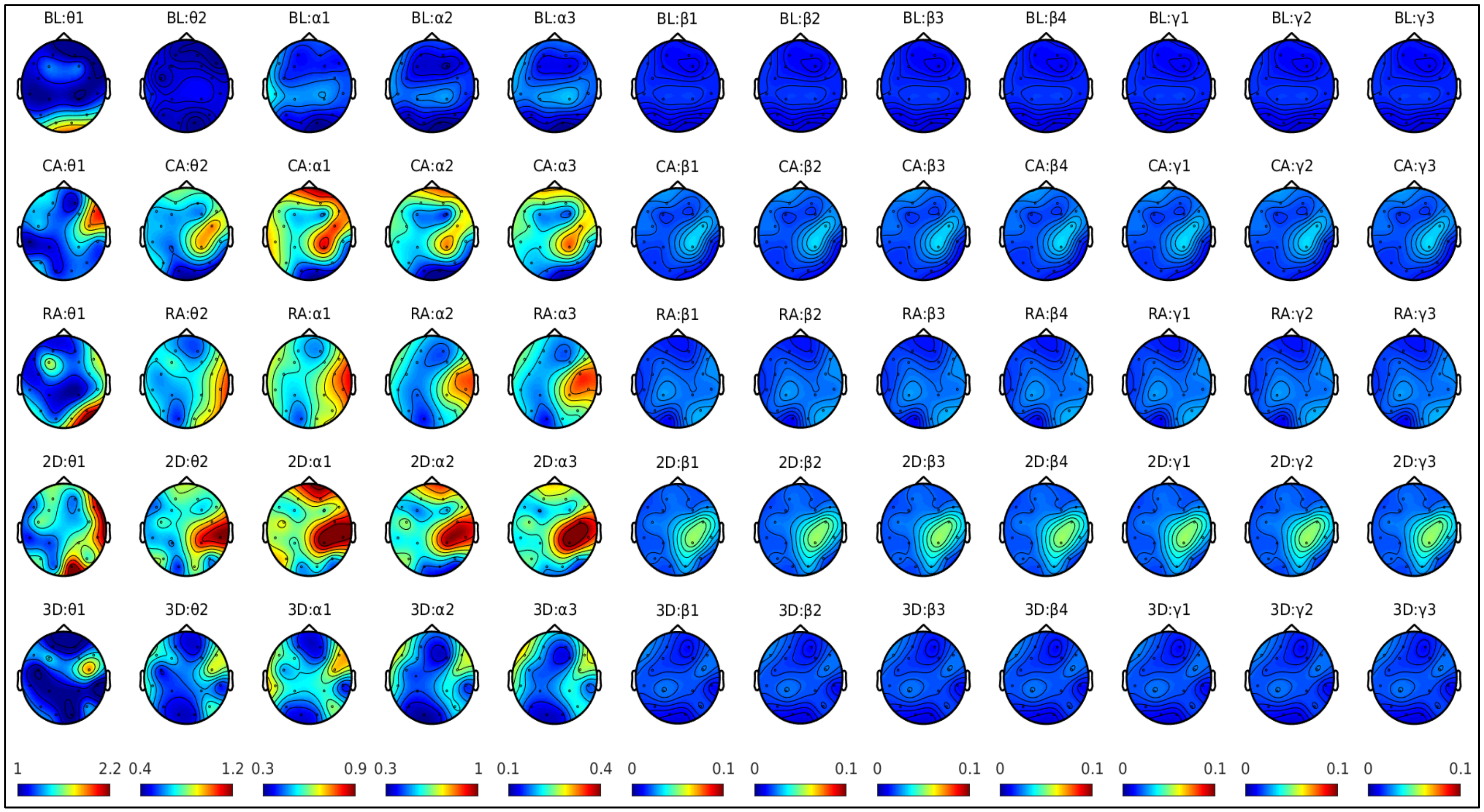


Figure 6.6 Condition-specific power Spectra plot for theta, alpha, beta, and gamma frequency bands.

6.3.2. Reconstructed Sources

Since the DICS method estimates the source activity at a single frequency, we applied it for narrower frequency bands. Fig.6.7 shows the locations of reconstructed sources for different frequency sub-bands for all four groups. The reconstructed sources were plotted over the inflated cortical surface derived from the *colin27* averaged brain. The figure shows only the sources with power higher than the 75th percentile. The figure shows both the left and right views for each set of the reconstructed sources to illustrate the activation better. We further mapped the estimated sources with Desikan-Kiliani atlas and investigated each of the 68 parcels' activities. Here we set the 75th percentile (Q3) of power as the threshold and evaluated the percentage of active sources above this threshold for each parcel. Fig. 6.8 shows the percentage of active sources for each of the parcels for all four study groups.

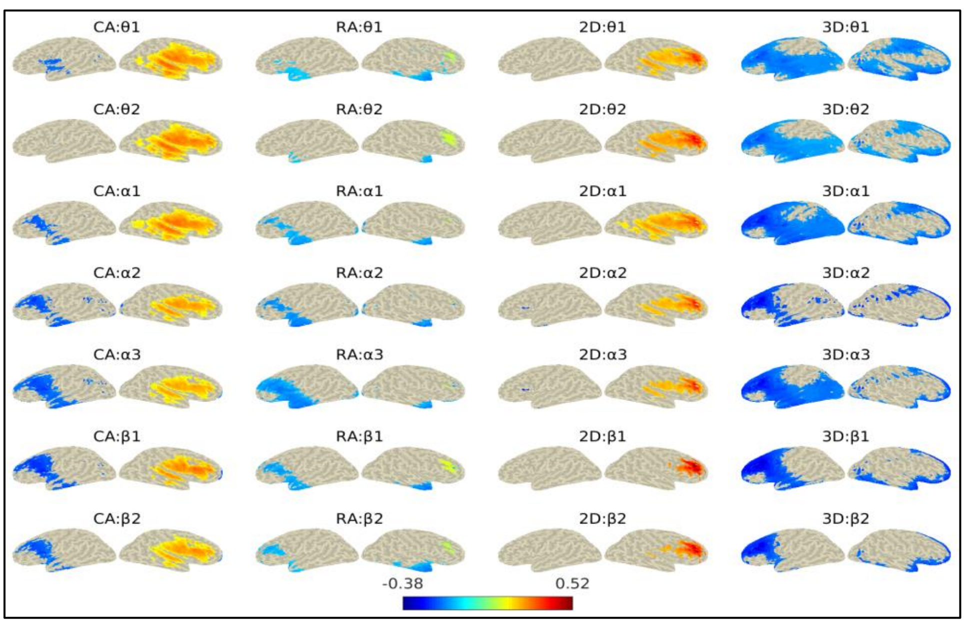


Figure 6.7 Neural activities for the four gaming groups during the computer games for alpha and beta frequency sub-bands.

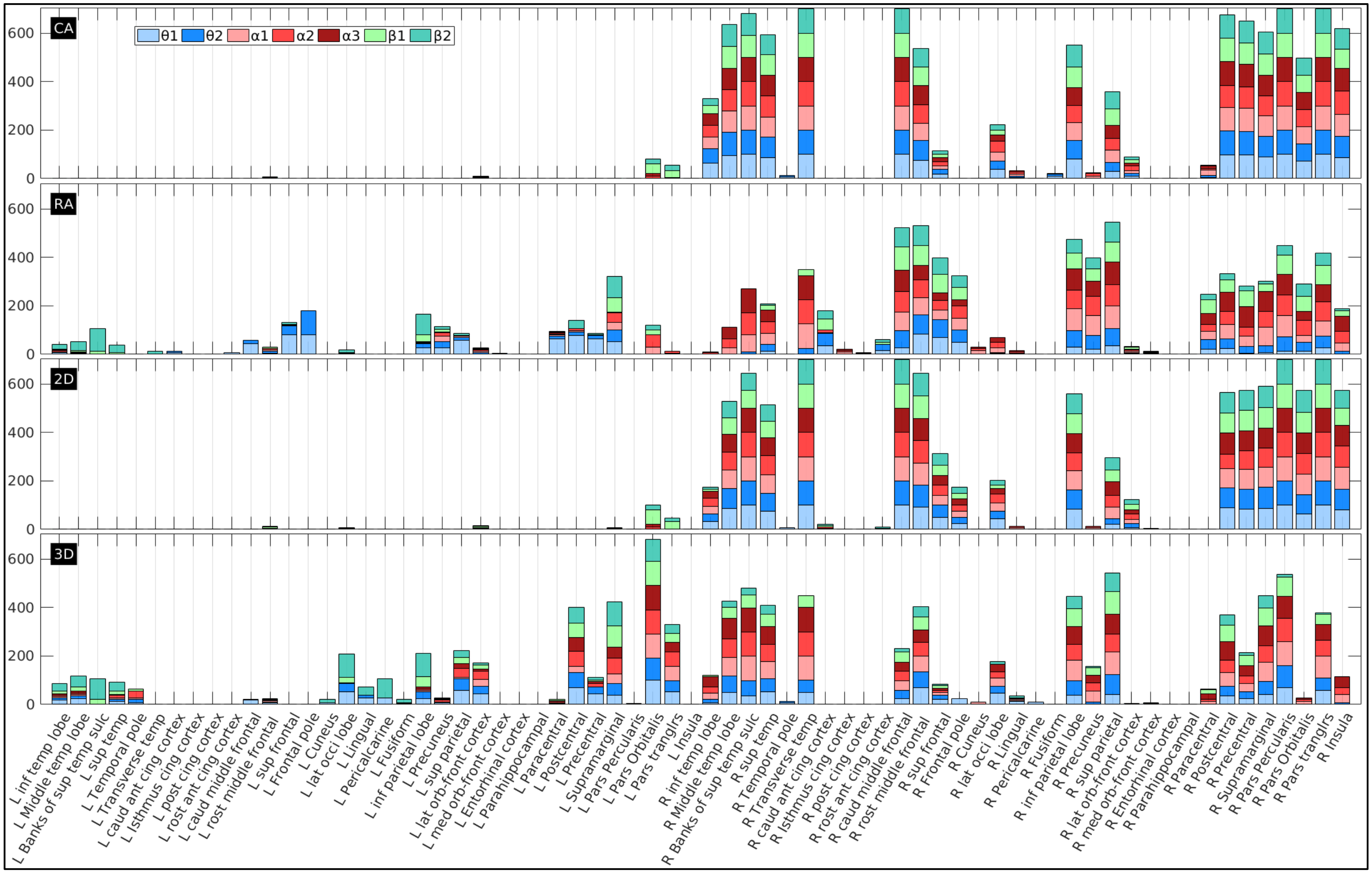


Figure 6.8 The labels/parcels with active sources at different frequency bands for the four groups of the MR computer-game. The labels/regions and the percentage of active sources for each parcel are shown at the X and Y-axis.

6.4. Discussion

In the study, we investigated the effects of angular disparity and dimensionality by utilizing the spatio-spectral source reconstruction from the EEG data recorded during the MR gameplay. The DICS method was used for the source reconstruction at θ, α, and β sub-bands for all the four analysis groups to evaluate the parametric effects on MR. Fig 6.8 shows the percentage of the active number of sources/voxels in each of the sixty-eight brain regions at seven frequency sub-bands among the four groups. The figure shows a higher percentage of significantly active sources in the regions associated with dorsal and ventral visuospatial processing pathways. Along with the parietal region, which has been often referred to in MR studies, several temporal and occipital regions associated with the dorsal-ventral pathway were also found significantly active. We also found significant activities in the frontal, central and other regions associated with higher-order motor functions, planning, etc., which supports the previous findings (Carpenter et al., 1999; Zacks, 2008; Bhattacharya et al., 2001; Leek et al., 2016). The activations in these brain regions varied over frequency sub-bands.

In the dorsal pathway, activities were notable in occipital (lateral occipital cortex, cuneus), MT/V5, and parietal (precuneus, inferior and posterior parietal cortex) regions. In the occipital region, we found activations in the right lateral occipital lobule across the sub-bands, which indicates the response to encoding object parts and the spatial relationships among them (Erdogan et al., 2016; Moen et al., 2020). These activations were higher in the case of CA and 2D groups compared to RA and 3D. The possible reasons could be a higher demand for encoding as 2D objects possess less spatial information to facilitate MR processing anticipation. We also observed less percentage of active sources in the left lateral occipital region at lower frequency sub-bands. The cuneus also showed a significant but smaller number of sources active for RA and 3D groups. The middle temporal (MT/V5) region, commonly known as a higher-order visual area associated with motion-processing during visual stimuli (Gao et al., 2020), was found active for CA and 2D groups comparatively higher than that of the RA and 3D. The right posterior parietal cortex was found active across all the four groups with comparatively higher activations in superior lobule for the RA and 3D, and inferior lobule for the CA and 2D groups, at all the frequency sub-bands. A comparatively lesser number of sources in the left parietal region were also found active for RA and 3D groups. While the activation in the right superior parietal lobule is associated with angular disparity (Zacks, 2008; Zacks et al., 2003), the inferior parietal activity is associated with the parity judgments in MR tasks (Alivisatos & Petrides, 1997). Besides, we also observed activation in the right precuneus for RA and 3D compared to their respective counterparts, primarily responsible for intuitive imagery representation during MR processing (Suchan et al., 2002). Further, the bilateral supramarginal gyrus (SMG) showed significant RA and 3D activation while the right lateral higher activation for CA and 2D groups. Here, the higher activities in SMG indicate the interaction with objects' orientation in MR tasks. The pre and postcentral regions, previously referred to for motor imagery (Tomasino & Gremsene, 2016; Cona & Scarpazza, 2019), were observed bilaterally but right dominating active for RA and 3D whereas right laterally active for CA and 2D groups.

The lingual (occipital region) activities and inferior temporal gyrus (temporal region), and the primary visual area indicate the engagement of the ventral pathway in the study. The lingual, also known as medial occipitotemporal gyrus, was found right laterally active for all groups with fewer active sources; the left hemispheric lingual activity was also found for the 3D group. The lingual activity usually refers to the encoding of complex images. Significant activities in the right inferior temporal region reflect the participation of the *what system.* The right laterality of this region has also been previously suggested by Carpenter and colleagues (Carpenter et al., 1999). The results indicate a higher engagement in objects' identification and processing of salient features for CA and 2D groups. Overall, the ventral pathway areas showed a lower number of active sources above the threshold than that of the dorsal pathway, reflecting comparatively higher engagement in spatial processing than the visual. It indicates that the participants put more effort into rotating the mental image during the MR than the object identification. The possible reason could be the images' complexity, which required more effort to rotate their mental images.

Besides the dorsal-ventral pathway in processing the visuospatial information during MR parity judgment tasks, several other brain regions were also notably active due to higher-level brain functions such as strategy selection and motor planning, decision-making. As MR utilizes different processing strategies (Egocentric vs. allocentric approach or holistic vs. piecemeal approach) depending on the stimulus and task design, the active participation of the frontal region and associated motor areas has been reported in previous studies. In this study, the frontal region activations were found dominantly in the right hemisphere for all the four groups, with minimal activation in the left hemisphere for RA and 3D groups. The right hemispheric middle frontal, superior frontal, and frontal pole were primarily found active among the four groups; the middle frontal activation shows the motor area's involvement during MR (Cohen et al., 1996). The rostral and caudal middle frontal gyri associated with the process of rotation and encoding the objects' representation were also found active comparatively higher for CA and 2D than their counterparts. It shows that CA and 2D demand more motor processing during MR. The higher demand for spatial processing in 2D is due to a lack of anticipation in identification because of fewer visual features (depth). The right orbitofrontal cortices known to be involved in decision-making (Kringelbach, 2005) showed significant sources comparatively higher CA and 2D groups, indicating more effort in decision-making. The right pars (percularis, orbitalis, and triangularis) suggested for non-bodily stimuli were also highly active for all the groups. The pars regions in the left hemisphere were found notably active for the 3D group. The insula known to be a part of spatial processing networks in the MR tasks (Carpenter et al., 1999) was observed right lateral activity with higher values for CA and 2D groups. The increased anterior insula activation was also observed previously in parity judgment tasks (Milivojevic et al., 2009). The superior temporal gyrus (STG) connected with the insula also showed higher activation for CA and 2D groups.

The study showed the activities in the brain areas associated with dorsal and ventral pathways for visuospatial processing during the MR computer-game. However, we found that the active sources in the regions associated with the dorsal pathway were higher than that of the ventral pathway. It indicates higher involvement of the dorsal pathway than the ventral; however, it is highly dependent on the objects/stimuli utilized. We observed that the difference in brain regions' activities is quite notable among the four groups with unique visuospatial parameters. In most active sources, the activation was higher for the groups with either convex angular disparity or 2D objects. However, the recruitment of brain regions and the associated function is moreover influenced by the strategy selected and visuospatial skill. The study showed right hemispheric dominance over θ, α, and β sub-bands; and the overall α-band activities were found more prominent among all groups. Though the study supports the previous MR studies' findings, a higher number of EEG channels could undoubtedly reveal the findings with better spatial resolution.

6.5. Summary

This investigation was focused on the effects of object characteristics on cortical activities in the MR process during a computer-game. The activation differences in dorsal-ventral pathways for visuospatial processing were primarily investigated along with few other higher-level processing regions. The reconstructed source activities for EEG sub-bands showed differences in several brain regions. The dorsal and ventral pathways were found active across the four groups with individual characteristics; however, the dorsal pathway was found notably more active than the ventral, indicating more influence of spatial information than the visual ones. Higher activation was found for CA than RA, reflecting the complexity of information processing under CA. Similarly, as compared to 3D objects, higher activation was seen for 2D objects, indicating difficulty in information processing due to deficient visual features. The activations were observed right dominating bilateral in RA and 3D whereas almost entirely right lateral for the CA and 2D groups. Overall, a sizeable cortical network was observed involving the dorsal-ventral pathways and other regions associated with higher-order motor activities, planning, and decision-making. The findings suggest that angular disparity and dimensionality can influence the MR process in the computer-games, and the effects are also visible at the cortical level. The connection among MR object characteristics with the cortical activities also indicates their effects on cognitive skills associated with the respective brain regions.

Chapter 7

General Discussion

The present dissertation (on the whole) addresses the role of cognitive processes underlying the visuospatial information (angular disparity and dimensionality) processing during MR computer-game, using saccadic gaze behavior and EEG spatio-spectral characteristics. As shown in previous chapters, a growing study has added to our awareness of different facets of mental rotation processing; the current research attempts to follow this direction to further scientific advancement by taking into account the various visuospatial information processes. In particular, this research emphasizes how the spatial (angular disparity: convex and reflex) and appearance (dimensionality: 2D and 3D) characteristics of an object can influence saccadic gaze parameters (i.e., saccade duration and saccadic amplitude) and EEG spatio-spectral characteristics along with the involvement of the brain regions associated with dorsal-ventral pathways during a mental rotation computer-game. The current chapter unifies and reflects on the findings of the present research in the light of the available literature and relevant insights. When we see the saccadic gaze parameters and EEG rhythms along with the brain region activations together, the effect of object characteristics, i.e., *angular disparity* and *dimensionality* on mental rotation processing, can be seen to follow a similar pattern to some extent.

7.1. Saccadic Eye Movement

The essential feature of human cognition is visuospatial processing, which is part of a complex and intricate network. In other words, it is one of the foundations of an individual's identity and behavior. The piecemeal strategy is the most widely recognized hypothesis for how the cognitive system develops a mental representation of visual input. This theory states that representations form through a step-by-step process in which people visually observe discrete parts of a stimulus and internalize the parts to represent the entire stimulus. This strategy breaks down the stimulus figure into numerous pieces, mentally rotating one piece to match the comparison figure and repeating the process with the remaining segments to ensure parity. Just and Carpenter (1976; 1985) proposed that participants rotated one section of the stimulus first, then determined if the remaining portions were rotated into congruence. Some piecemeal mental rotation models have been developed to describe the mental rotation of complex stimuli, such as irregular checkerboard patterns (Bethell-Fox & Shepard, 1988; Folk & Luce, 1987). Because these models assume that individual elements of the complex stimulus are aligned, the rotation rate slows as the number of pieces increases. During mental rotation processing, the effect of the stimulus or object characteristics like angular disparity and dimensionality can be understood by eye movements. The eye movements include specific gaze parameters, e.g., fixation, saccade, pupil size/diameter, blink rate, etc. The current research has utilized saccadic gaze parameter- saccade duration and saccadic amplitude to explore the variation of angular disparity and dimensionality during mental rotation computer-game.

When reading, seeing objects, or exploring the world around them, people make quick saccadic eye motions about three or four times per second. During the fixations that distinguish successive saccades, the eyes are comparatively still. The typical fixation lasts 250–300 milliseconds, whereas saccade duration depends on saccade distance. Saccade duration increases as saccade distance increases, but during reading and picture viewing, the average saccade duration is 30–50 msec (Rayner,1978; 1998).

This research examines how the object's spatial characteristics (angular disparity) and dimensionality (2D/3D) influence the saccade's temporal component and spatial feature, respectively. Here, it was expected that longer saccadic length for convex angular disparity than for reflex angular disparity, and higher saccadic amplitude for 3D objects than for 2D objects. The results showed a significant effect of angular disparity on saccade duration. It implies that the saccade’s temporal characteristics (saccade duration) are influenced by an object's spatial characteristic (angular rotation) in the MR task. Our results indicate a higher suppression of spatial information processing during the MR tasks when the object's angular disparity was in the convex range. The longer saccade duration represents a sustained suppression of spatial processing (Irwin & Carlson, 1996; Irwin & Brockmole, 2000). It was described by Takano and Okubo (2006) that the response time increases monotonically from 0° to 180° of angular disparity but decreases from 180° to 360° by finding a shorter path using structural properties that are independent of the object's orientation. It represented that convex range rotation is more effort-seeking and time-consuming than the reflex. However, it is only feasible if a participant takes the shortest way to rotate an object from 180° to 360° in the opposite direction since the saccade duration for rotation in the convex range will be longer in terms of path length than the reflex.

During an MR task, the spatial characteristics of the object are suppressed as saccades disrupt neural functions that depend on the where-pathway, i.e., dorsal stream, such as object orientation decisions (Irwin & Thomas, 2007). So, the main effect of angular disparity was found on saccade duration but not for the object's dimensionality as it holds the appearance information. It is well recognized that sensitivity to visual stimuli is reduced; this effect is often referred to as "saccadic suppression" (Matin, 1974; Zuber & Stark, 1966). Visual masking tends to be the primary source of reduced visual sensitivity during saccades (Campbell & Wurtz, 1978). Suppression of cognitive functions during saccades is likely to happen only when memory capacities are reduced (Irwin & Carlson, 1996). According to the dual-task theory, cognitive processing can be suppressed during saccades only where shared processing mechanisms are used. While a diverse network of brain structures is involved in the generation of saccadic eye movements, the frontal (and supplementary) eye fields and the posterior parietal cortex tend to be the most important cortical regions (Schall, 1995). As a result, the dual-task hypothesis suggests that during saccades, cognitive processes that include these same brain regions will be suppressed. MR is one of these tasks, although many neurophysiological studies have shown that it is performed in the parietal cortex (e.g., Alivisatos & Petrides, 1997; Kosslyn et al., 1998; Peronnet & Farah, 1989). While along with the parietal regions, other areas associated with the visual cortex in dorsal-ventral pathways, i.e., occipital and temporal regions, are also involved during MR processing. And due to higher-order function processing, frontal and motor areas also take part in MR.

Saccadic eye movement is commonly used to study sensorimotor integration and information processing in various cortical areas (Squire et al., 2012). The programming and orientation of the saccadic eye movement during the search for the target stimulus reveal the engagement of cognitive processes, including attention. The saccadic eye movement is associated with the first stages of information processing, namely stimulus identification. As a result, a robust link between the activation of cortical regions involved in saccadic movement programming and attention regulation has been discovered (Shipp, 2004). The results of Diniz et al. (2012) revealed that saccadic eye movement execution modulates the left parietal cortex. In other words, this region is more active after stimulus presentation (and throughout the performance), validating prior findings that this area is involved in sensorimotor integration processes (Neuper & Pfurtscheller, 2001).

The distance traveled by the eye between two fixation locations is referred to as saccadic amplitude: The amplitude of a saccade toward an intended target is generally such that the eyes land near the target. Saccade amplitude is highly dependent on the spacing of the objects that are important for the task to be solved, and as a result, if an image is scaled to different sizes, saccade amplitudes should vary proportionately. Our findings further showed a significant effect of dimensionality with the lower value of saccadic amplitude and saccadic velocity for 2D objects. The researchers discovered an almost perfect positive association between mean and median saccade amplitude and image size in their study (Von Wartburg et al., 2007). The size of the stimulus images, according to the authors, is the most important element determining mean and median saccade amplitude during scene image viewing. It suggests that tasks involving 2D objects are more complicated and attention-seeking than those involving 3D objects. The reason behind the higher amplitude and velocity of saccades in the case of 3D objects can be understood by the study Wexler M (2005), where it showed how the brain anticipates the three-dimensional consequences of eye movements because of the depth perception of the objects. The saccadic amplitude and velocity were not significantly affected by angular disparity. The reflexive aspect of these saccades and dealing with the ventral stream (also known as what stream) may explain this, as visual processing in the ventral stream connects with saccadic eye movement programming through a surprising and swift route (Kirchner & Thorpe, 2006). The shape (dimensionality) of the object impacts the effects of the spatial properties in this situation (angular disparity). Since the saccade velocity and amplitude are mathematically related, the impact of dimensionality on saccade velocity was observed similarly to the saccade amplitude. For rising saccade amplitude, not just the mean but also the maximum velocity increases. The amplitude of the saccade is a controlled quantity in the saccadic movement of the eyes, on which the clear reception of the requisite visual information is dependent. Each saccadic movement is performed at maximum velocity by the eyes, allowing for the necessary precision. As a result, the saccadic amplitude gets shorter when a participant scrutinizes an object than during overview scans, which often happens if the task difficulty and complexity increase.

7.2. Spatio-spectral Characteristics of EEG

Neuroimaging investigations are a useful way to evaluate the concept that mental rotation, in particular, is based on analog spatial representations. For such representations, imaging evidence must meet two conditions. To begin, activation should be seen in locations that have already been spatially mapped. Second, the amount of mental rotation performed in a specific trial or block of trials should be regulated by factors such as the angular distance of the rotation or the participants' reaction time. Mental rotation is accompanied by increased activity in the intraparietal sulcus and adjacent regions. These regions are regulated by manipulations of object characteristics in mental rotation tasks, indicating that mental rotation is based on analog representations (zacks, 2008).

Using the power spectra of EEG recorded during the gameplay, the effects of dimensionality and angular disparity in a mental rotation computer game were studied. To find the spatio-spectral variation in EEG for the four groups of the game from the baseline, cluster-based permutation tests were used. We have also looked at regional and global hemispheric laterality for the θ, α, and β frequency bands. In the current context of the study, the heterogeneity in alpha desynchronization was expected in the associated brain regions due to the use of stimuli with distinct categories of angular disparity and dimensionality in allocentric reference. Since the task's parameter manipulation influences the strategy selection during the MR process, cortical activation difference as hemispheric laterality was also expected between groups which will be based on whether a person chooses a piecemeal or holistic method. Significant clusters were found for the alpha frequency band, especially in frontal, centro-parietal regions of the brain during MR computer games with 2D and 3D objects in convex and reflex angular disparity. The decrease in alpha power associates with increased cortical activity in related areas. Increased involvement of the cortical network, which in the case of visuospatial processing is contingent on one's attentional demand to the visuospatial activities, induces desynchronization (loss of power) in alpha rhythms (Gardony et al., 2017). The manipulation of task parameters such as dimensionality and angular disparity affects the degree of interaction with the task in the MR process, and thus alpha desynchronization has been recorded predominantly in the fronto-parietal brain regions (Zacks, 2008). Relevant variations were observed in the alpha frequency band and beyond (7.8 – 14.2 Hz) for the category that played the MR game with convex angular disparity. The community with reflex angular disparity, on the other hand, had fewer clusters of alpha desynchronizations restricted to lower alpha frequencies (8.1–10.0 Hz). Alpha desynchronization was seen in the frontal, left centro-parietal, and parietal regions in the former category, but only in the frontal and left parietal regions in the latter. The strategy followed in MR processing significantly affects the role of brain regions recruitments and involvements (Bethell-Fox & Shepard, 1988; Milivojevic et al., 2003; Milivojevic et al., 2009; Tomasino & Gremese, 2016). Feredoes & Sachdev (2006) studied a parity judgment task with 3-D torus shapes by utilizing TMS (transcranial magnetic stimulation), and they reported different hemisphere involvement for varying angles of rotation of the visual stimuli. There was a reduction in performance accuracy with both right and left posterior parietal cortex

(PPC) stimulation. They further suggested that rotation through smaller angles associates with a holistic approach, whereas rotations through larger angles with piecemeal. The EEG spectra in the fronto-parietal regions leaned left for the lower α band (7.8-10.5 Hz) MR with 3D objects revealed significant changes. In MR with 2D objects, on the other hand, we find fewer clusters in the higher alpha spectrum (11.0 – 11.7 Hz). The effect of mixed 2D-3D perception of the 2D objects in the experiment may explain the lower number of significant clusters in the 2D group. The mechanisms used by the human brain to process 2D and 3D structures in MR tasks have been reported by previous studies suggesting that piecemeal processing is elicited by complex, unfamiliar shapes that require rotation in space, such as torus shapes, while holistic processing is elicited by common stimuli that require rotation in the picture plane, such as alphanumeric characters (Just & Carpenter, 1976, 1985; Bethell-Fox & Shepard, 1988). So, brain region activation is also influenced by the object's dimensionality. Mental rotation with 3D shapes was shown activation in both parietal regions in studies (Cohen et al., 1996; Tagaris et al., 1997; Jordan et al., 2001; Gauthier et al., 2002), whereas activation was reported in any one side of the parietal region during mental rotation with 2D shapes (Harris et al., 2000; Yoshino et al., 2000; Podzebenko et al., 2002).

The lateralization indices and statistically significant clusters show that the MR with reflex angular disparity is more left-lateralized than convex angles. The variance in laterality indices for each of the four groups from the baseline shows substantial differences in centro-parietal areas. The majority of brain imaging research exploring mental rotation mechanisms has observed bilateral activity in parietal and frontal regions, suggesting that mental rotation is controlled by both hemispheres of the brain. On the other hand, evidence is mounting that both hemispheres are involved differently depending on the stimuli, applied strategies, and reference frames used for mental rotation. It is suggested that the rotation of simple objects utilized holistic strategy, favoring the engagement of the right hemisphere, whereas rotation of complex stimuli may utilize piecemeal strategy, favoring the involvement of the left hemisphere during MR (Just & Carpenter, 1985; Bethell-Fox & Shepard, 1988), this may depend on the degree of rotation as well as dimensionality in MR. Negative *LI* for CA and positive *LI* for RA were observed in the parietal region, suggesting right and left dominant activations; however, overall left-hemispheric alpha desynchronization impacts synergistically decrease right-hemispheric domination of the parietal region for alpha range. The central region and global laterality indices (*LI*s) demonstrated substantial improvements from baseline to the 2D group for α band and beyond, but not for the 3D group. It shows that hemispheric asymmetry increases significantly from baseline to MR tasks with 2D objects. Further, the significant difference between *LI*s for 2D and 3D groups was found for all the regions showing higher positive values for 2D.

Further, we used the spatio-spectral source reconstruction from the EEG data collected during the MR gameplay to investigate the effects of object characteristics in a mental rotation-based computer-game on the cortical activities in dorsal-ventral pathways and other associated brain regions. DICS approach was used for source reconstruction at θ, α, and β and sub-bands for all four analysis groups. The regions associated with dorsal and ventral visuospatial processing pathways had a higher proportion of substantially active sources. Several temporal and occipital regions associated with the dorsal-ventral pathway were also found to be substantially involved, in addition to the parietal region, which has been often referred to in MR studies. We also discovered major movements in the frontal, central, and other regions linked to higher-order motor processes, planning, and other tasks, previous corroborating results. These brain regions' activations differed across frequency sub-bands. The variance in visuospatial parameters in a computer-game was expected to influence the MR during gameplay, indicating variations in the engagement of the dorsal-ventral pathway and other cortical regions associated with MR processing.

According to neuroanatomical, electrophysiological, and lesion research, dorsal (where) and ventral (what) pathways lead to a proposed organization of the visual system. It refers to the occipital cortex's two information processing streams: dorsal and ventral, responsible for object perception (what) and spatial vision (where). Both the dorsal and the ventral pathways represent the interactive effects of the object and spatial processing, indicating that multiple brain regions interact with each other to achieve mental rotation (Koshino et al., 2005). By utilizing the source reconstruction analysis, the notable activations were found in occipital (lateral occipital cortex, cuneus), MT/V5, and parietal (precuneus, inferior and posterior parietal cortex) regions, in dorsal pathways. However, the activities in the lingual (occipital region), inferior temporal gyrus (temporal region), and primary visual field show the involvement of ventral pathways. When compared to reflex angular disparity and 3D, these activations were higher in the convex angular disparity range and 2D objects. One potential explanation is that there is a greater need for encoding because 2D objects have less spatial information to aid MR processing anticipation.

Neuroimaging studies with a parametric design reveal that with increasing angular disparity, there is a linear increase in activation of the parietal and adjacent dorsal occipital cortex, especially in the right hemisphere, reflecting the involvement of this dorsal stream region specifically in the scaling of mental rotation task performance with angular disparity (Carpenter et al., 1999; Harris et al., 2000; Podzebenko et al., 2002). Prior research on mental rotation has revealed that figural complexity and rotation influence both the dorsal and ventral posterior systems, with inferior parietal and inferior temporal regions cooperating as part of a top-down prefrontal–posterior network to analyze, compare, and match two shapes during mental rotation tasks (Cohen et al., 1996; Koshino et al., 2005). The inferior prefrontal cortex has previously been found to play a role in spatial and object working memory during mental rotation and object-decision tasks (Owen et al., 1998; Stern et al., 2000). The premotor regions, such as the occipitoparietal region, are also important for mental rotation (Richter et al., 2000; Vanrie et al., 2002). Because of the relative specialization of cortical regions, certain areas are more engaged in certain processes than others. Koshino et al. (2005) found that the amount of rotation affected the frontal, temporal, and occipital areas only for complex stimuli but not for simple stimuli. However, even for simple stimuli, activity increased from 0^{o} to 90^{o} of rotation in the parietal areas, but considerably more so for complex stimuli.

In addition, we found activation in the right precuneus for RA and 3D as opposed to their counterparts, which is primarily responsible for intuitive imagery representation during MR processing (Suchan et al., 2002). Furthermore, RA and 3D groups displayed greater activation in the bilateral supramarginal gyrus (SMG), while CA and 2D groups showed higher activation in the right lateral SMG. The higher SMG behaviors show the association with object orientation in MR tasks. The pre- and postcentral regions, previously linked to motor imagery (Tomasino & Gremese, 2016; Cona & Scarpazza, 2019), were observed bilaterally, with the right dominating but bilaterally active for the RA and 3D groups and the highly right laterally active for the CA and 2D groups. Besides the dorsal-ventral pathway in processing the visuospatial information during MR parity judgment tasks, several other brain regions were also notably active due to higher-level brain functions such as strategy selection and motor planning, decision-making. The right hemispheric middle frontal, superior frontal, and the frontal pole, the rostral and caudal middle frontal gyri, right orbitofrontal cortices, the right pars (percularis, orbitalis, and triangularis), and insula were found activated highly in the case of CA and 2D compared to RA and 3D during the mental rotation processing. It is well known that MR processing is influenced by the reference frame (egocentric or allocentric). When comparing the strategy account to the reference frame variable, Tomasino and Gremese (2016) observed motor-imagery-based MR (vs. Egocentric MR) stimulated the left superior parietal lobule, right postcentral gyrus, precentral gyrus/middle and superior frontal gyrus bilaterally, and the left inferior occipital gyrus. On the other hand, the left cuneus left middle temporal gyrus, left lingual gyrus, calcarine sulcus, and right cerebellum were activated by egocentric MR (vs. Motor-imagery-based MR). These findings suggest that these two processes are distinct. The egocentric-based MR includes a (primarily spatial) evaluation from another point of view (different from the perspective of the physical body), whereas motor strategies engage motor actions covertly. Mental rotation of different stimulus types has also shown the recruitment of different brain regions. MR of body stimuli showed the left lingual gyrus activation, including the cerebellum, middle and inferior occipital and calcarine gyrus, superior parietal lobule, postcentral gyrus bilaterally, and left postcentral gyrus, left inferior parietal lobe and right supramarginal gyrus. Further, some other regions also showed association with MR, e.g., left precentral gyrus and inferior frontal gyrus (pars opercularis) bilaterally, left superior frontal gyrus, right middle frontal gyrus, and posterior frontal gyrus medially, in addition to the right insula. The comparison between hand and body stimuli reported the activation in the left precentral gyrus that MR of hands. On the other hand, activations in the middle occipital gyrus bilaterally left inferior occipital gyrus, left cerebellum, and left inferior temporal gyrus, right superior and inferior parietal lobe, and inferior frontal gyrus (pars opercularis and triangularis) bilaterally, in the insula and the middle frontal gyrus in addition to the right precentral gyrus and the posterior frontal gyrus medially has found for MR of non-bodily related stimuli (Tomasino & Gremese, 2016).

Overall, the study showed recruitment of brain regions with higher activation in dorsal and ventral pathways along with other associated regions for visuospatial processing during the MR computer-game. The active sources in the regions aligned with the dorsal pathway, on the other hand, were greater than those in the ventral pathway. It suggests that the dorsal pathway is more involved than the ventral; however, this is strongly dependent on the characteristics of objects/stimuli used. We noticed a significant difference in brain activity within the four groups with different visuospatial parameters. The activation with either convex angular disparity or 2D objects was higher in most active sources. However, the approach or strategy is chosen, and visuospatial abilities affect the recruiting of brain regions and the related function.

7.3. Game Performance

The analysis revealed a significant effect of the object's dimensionality on the task score. The lower scores for 2D objects indicate that the subject had more difficulty in visually spinning the 2D objects than the 3D objects. The object dimensionality has the same effect on saccadic amplitude. EEG alpha wave desynchronization and higher brain region involvement followed by dorsal-ventral visual pathways for 2D objects in comparison to 3D objects are also represent the same pattern. The 2D objects in the current study are isomorphic to the 3D object obtained by extracting the depth (Z-axis). Since 3D objects provide more accurate details than 2D objects, the brain can begin anticipating the effects of their rotation before the saccadic eye movement begins (Wexler, 2005). In an active process, this phenomenon speeds up the MR process and decreases response time. The results revealed that dimensionality had little effect on response time; however, the mean response time for 3D objects was lower. The lower mean response time and high task score affirm the findings of Chelnokova and Laeng (2011), who claim that the 3D condition will offer an external cue for anticipation, potentially assisting the individual in making better decisions. We did not find a significant effect of angular disparity on response time. Rather than being influenced by angular disparity only, other object characteristics such as the number of arms and dimensionality can also affect response time in this situation as well. It may act as an external cue to help the user anticipate the entity and make the best decision. As a result, anticipation and reinforcement learning can affect response time. According to Van Duren and Sanders (1995), target classification and response selection may occur during a saccade. They speculated that perceptual processes like stimuli decoding could be silenced during saccades, but post-perceptual processes like target classification and response selection may not.

On the overall workload, neither angular disparity nor dimensionality had a noticeable impact (NASA-TLX). Furthermore, no significant interaction between angular disparity and dimensionality was discovered. However, for the mental demand index, we discovered a significant interactive influence of angular disparity and dimensionality, representing that the combination of the angle of rotation and dimension may turn the MR processing more mentally challenging. The category with dimensionality 2D and convex angular disparity had a greater mental demand for cognitive interaction than the other three groups in the study. The spatio-spectral characteristics of EEG signal and the localized active sources out of 68 brain regions also support this scenario in convex angular disparity and 2D objects. In addition, we discovered a partial influence of dimensionality on pupil size. In the case of a 2D object, the pupil size is less than in a 3D object. The depth perception of the object has an impact on pupil size in this case. The act of recollection can dilate the pupil size; but when the brain is required to process the information at a faster rate than it can handle, the pupils constrict (Poock, 1973). Depth perception is helping the participant to match the target object with the given option. So, here in this study, this could be one possible reason to get a negative correlation between pupil size and mental demand, and it can be interpreted as higher mental demand in 2D compared to 3D with lesser pupil size in 2D.

Chapter 8

Conclusions

This chapter summarizes the major findings of the current research. It also discusses the implications of the results, limitations of the present research, and along with the application, it provides insights for future research.

8.1. Highlights of the Findings

- This dissertation provides an understanding of visuospatial information processing as an object characteristic (angular disparity and dimensionality) in mental rotation during a computer-game environment. The study analyzed gaze behavior, EEG spatio-spectral characteristics, and task performance during a computer-based MR gaming task and investigated the effect of the angular disparity and dimensionality on user performance while executing the task. The computer-game involving the MR tasks in four different categories in a single game was designed, and the isomorphic 2D and 3D multi-arms objects were utilized with convex and reflex angular disparities. In addition, the dimensionality of objects and the angular disparity between two objects were considered individual parameters in the game design with parity-judgment MR tasks.
- The research results represent the relationship among objects' spatial and appearance characteristics, gaze metrics, EEG spatio-spectral aspects, and associated source brain regions and task performances. The study found that the temporal component of the saccade, i.e., saccade duration, is influenced by the object's spatial characteristic, i.e., angular disparity. The spatial component of the saccade, i.e., the amplitude and velocity of the saccade, is, on the other hand, influenced by the objects' dimensions.

- The study also found that since 3D objects contain more detail, such as depth, MR can occur faster and more accurately. Since 2D objects contain less object information, a prolonged search for object features can cause the response to be delayed. More MR processing is suppressed during convex angular disparity, making it more effort seeker than reflex. The interaction between angular disparity and dimensionality for mental demand revealed that they could make the task more difficult, and potentially increase the response time.
- By utilizing the spatio-spectral properties of the EEG signal recorded during gaming, the effects of the objects' dimensionality and angular disparity on the ongoing brain activities were examined. The results indicate that object characteristics can influence the mental rotation mechanism in computer-game. Increased alpha desynchronization was found in frontal, centro-parietal, and parietal regions and especially in fronto-parietal region during the mental rotation games compared to baseline. Furthermore, convex angular disparity and 3D objects displayed right-hemispheric laterality between 3.5 and 30 Hz of the frequency range; however, activities during reflex angular disparity and 2D objects showed the opposite laterality. Higher active areas as no. of channel-clusters for convex angular disparity and 3D objects were found. The connection between object characteristics and cortical activations reveals the potential for their impact on cognitive skills associated with fronto-parietal brain region
- Further, the activation variations in dorsal-ventral pathways for visuospatial processing, as well as a few other higher-level processing areas, were primarily examined. Several brain regions showed variations in the reconstructed source activities for EEG sub-bands. With individual parameters, the dorsal and ventral pathways were found to be involved in all four groups; and the dorsal pathway was significantly more active than the ventral, suggesting that spatial information processing takes precedence over visual information processing. Higher activation in the dorsal-ventral

pathway for convex angular disparity and 2D objects was found compared to reflex angular disparity and 3D objects. For RA and 3D, the right dominating bilateral activations were observed, whereas almost right unilateral activations were found for the CA and 2D groups. Collectively, activation in a substantial cortical network was observed involving the dorsal-ventral pathways and other regions associated with higher-order motor activities, planning, and decision-making.

8.2. Limitations and Implications of the Study

While the study adds to the existing literature on the issue of MR-computer-games and information processing of object characteristics, it also has some limitations. Encountering those limitations in future studies would undoubtedly provide more confidence and possibly other significant outcomes.

- Though the sample size in the study is in line with other studies in the domain, a larger sample size would reveal much deeper insights and with greater confidence level.
- To avoid perception-specific differences between 2D and 3D conditions, we modeled the 2D objects by removing the depth dimension from the 3D objects. However, due to the modeling constraints of objects used in the experiment, the 2D objects still had a bit of depth perception, possibly requiring a 3D-like strategy for mental rotation. On the other hand, it might have made the 2D vs 3D differences slightly unambiguous therefore a more significant reduction of depth perception from isomorphic 2D objects would be better.
- Though this research involved both male and female participants, the higher number of male participants leads to the male population. An equal number of both genders would reduce gender biasing in future studies.

- Due to the resource limitation, the lower number of EEG channels has been a major limitation in the study. Also, one of the EEG systems has a lower sampling rate. Therefore, a dense EEG system, or other modalities with higher spatiotemporal resolution such as MEG, would enable researchers to precisely investigate the source-level activities and spatially resolved networks associated with MR processing during computer-games.
- The current study explores the psycho-physiological variations only during the gameplay. Further, longitudinal studies may reveal the long-term effects of such computer-games. It would also be helpful in quantifying the training effects of computer games with specific cognitive metrics.

8.3. Application of Current Study and Future Scope

Though the study has a few limitations, the findings enlighten the association of dependent and independent parameters in the mental rotation task, which can be considered for making the strategies for improving the performance in a task involving spatial manipulation. The findings may help to plan the structure of a computer-based game (or videogame) to train MR abilities for training or rehabilitation and brain entrainment purposes. Since computer games are increasingly being part of our day-to-day lives, they can also be utilized as a covert tool to entrain our cognitive skills behind the entertainment silently. This study also has potential applicability in modeling human cognitive processes, primarily visual and spatial features. It also suggests that such computer-games with individual controlled parameters may help as a therapeutic intervention for those with visuospatial deficits. Such a guided computer-game has potential for future remote gaming framework for cognitive enhancement assisted by the internet of medical things (IoMT). Furthermore, real-time physiological and performance feedback could be used to direct artificial intelligence-assisted training.

From the perspective of visuospatial abilities and computer/video-gaming research interest, there are a few fields on which modern human factors researchers and clinicians could focus their efforts. As mental rotation and other spatial abilities have great importance and application not only in science and the academic world (human anatomy, human dentistry, veterinary medicine, etc.) but are also required in certain professions in working life., e.g., architects, engineers including pilots, mechanics, machine operators, and draftsmen. Mental rotation is needed for success in various courses and lucrative professions (Brownlow et al., 2003). The air traffic controller is an example of an occupation where spatial ability is "particularly germane for efficient efficiency" and where spatial ability assessment is critical in selecting applicants (Contreras et al., 2003). Also, in luggage scanning at security points, mental rotation enables the monitors to mentally rotate objects images and identify a prohibited item in the baggage. Mental rotation and other spatial abilities help soldiers in the military environment to make the mission-critical judgments more resource-efficient. Furthermore, it appears that these abilities are widely used in the engineering, architectural, and construction trades (Halpern, 1986). Keeping in view the potential application and importance of the visuospatial skills, the presence of gaming context to train or improve the spatial abilities can aid the learning process faster and accurately. Further studies in the current context could offer a better connection between learning and playing computer/video games. In future work, the idea of rotation axes and directions of the rotation can be considered along with isomorphic characteristics of objects.

Appendices

Informed Consent Form

You are invited to participate in a scientific study, which the Institutional Human Ethics Committee (IHEC), Department of Biosciences and Biomedical Engineering, Indian Institute of Technology Indore has reviewed and approved**.**

Thank you for agreeing to participate in this study. This study involves investigating **"*Mental Rotation in Computer-gaming*"**. Participation in this study will take approximately 25-30 minutes of your time. The risk involved in this study is not greater than day-to-day interaction with a computer. Your details will not be revealed when the data are presented or reported. All the data collected will be the property of Human Factors and Applied Cognition Lab, Indian Institute of Technology Indore, stored securely with protected confidentiality.

Your participation in this study is completely voluntary. Should you decide to discontinue participation at any point during the study, you may do so. You will receive a T-Shirt as compensation in exchange for your participation. Should you have any further questions, please feel free to communicate with the experimenter.

CONSENT STATEMENT

I, ___________________________________, hereby give my consent to participate in this study. I have read the above information provided by the experimenter and I agree to voluntarily participate in the study.

Participant's signature: ______________________ Date: ____________

I hereby certify that I have given an explanation to the above individual about the study.

Experimenter's signature: ___________________ Date: ____________

Instruction

You are most welcome to our HFAC lab for MR computer-game study. The game is designed in the HFAC lab. For this study, you are required to play a video game usually.

(A) General instructions:

- You are not supposed to discuss the details of the computer-game with the other participants to avoid the presumption.
- You are not allowed to do anything else except whatever asked you to do by the experimenter.
- You have to play the game by following the instructions of the game as mentioned below in section (B).
- You'll get a score for the game, which will be shown in real-time on the monitor. You have to try to get more scores with maximum correct answers.
- During the game play, we'll also record scalp EEG (Electroencephalogram, which is a non-invasive neuroimaging method without any pain or discomfort). We'll put EEG electrodes on your head using some electrolyte easy to wash gel; it may take 20-30 minutes. Once it is set, you don't have to disturb its arrangement by touching it.
- We'll also record eye movement simultaneously over the computer-game using an eye-tracking device that needs calibration, which may take 2-5 minutes. For calibration, you need to sit in front of the monitor and follow the instruction given by the experimenter at the time of calibration.
- When you start to play the game, you need to follow the game rules and instructions given on the screen at different stages.
- If you need help or feel discomfort at any point between the experiment/ game play, you can raise your hand.

- If you want to escape from the experiment because of any discomfort with the game or any imaging modality, you can withdraw from the study at any time.
- You have to place your cellphone, other magnetic/electronic devices, metallic objects out of the recording room in a locker, and you can have the key with you.
- Thank you for your acceptance to participate in our experiment.

(B) Instructions for game play:

- Basically, in the game, you will see an object separately left side of the screen, and on the right side of the screen, that same object will present with a different angle of rotation and distracters.
- You have to match the left side shown object with the right side shown objects mentally rotate its position and arms.
- You have to respond to the correct option as quickly as possible.
- You will get the fixed mark for a correct answer only. So, you need to play carefully to get the maximum score.
- After filling the participant details, different tasks will be available, but you have to choose one as asked by the experimenter and play.
- Whenever you feel that you cannot proceed further in the game or don't want to go ahead, you can exit anytime.
- You will be given a trial session for the game first; you have to play the actual game after that.
- Once you go through the trial session and feel comfortable to continue the actual game, then only, we'll start the game.

If you have any doubt about the instruction or study, you are free to ask again. And if you have understood the instruction properly, let's go for the experiment

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