Human Brain Performance in Complex Temporal and Spatial Processing Tasks and the Effect of Aging

by

Ali-Akbar Samadani

A Thesis submitted to the Faculty of Graduate Studies of

The University of Manitoba

in partial fulfilment of the requirements of the degree of

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Department of Electrical and Computer Engineering

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ABSTRACT

This thesis presents psychophysical experiments investigating the healthy human brain performance at different ages in repetitive motor tasks with simple and complex spatiotemporal patterns. A 2DOF manipulandum and two sets of interactive computer games were used in this study. The first game is a falling target that should be caught under different temporal constraints changing in every new trial by a change in the target's falling rate. This game is aimed to investigate the temporal perception in human. The second game is to test the sense of spatial orientation. In every new trial of this game, the subject must take the cursor to a desired final destination that is assigned randomly from a total number of four final destinations. These games were tested on healthy young adult subjects (20 to 30 years old), elderly (65+ years), and children (7 to 12 years old).

Results show human brain efficiency in well-performing less complex temporal and spatial processing tasks; in addition, it is found that young adult subjects significantly outperform elderly and children groups in such tasks, with a similar performance observed for the later groups.

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Finally, I would like to thank my Lord for helping me to take a step forward along the path of self actualization.

Dedications

To My Parents

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CHAPTER I

INTRODUCTION

Studying the human brain and behavior has been of interest for researchers during the course of history. This involves different sciences ranging from physiology, psychology, neuroscience to engineering, each studying a specific aspect of the human body. Discovering structural and functional features of this significant biological system has assisted scientists in finding treatments for different diseases.

Ability to process temporal and spatial information is one of the brain's important features. Time and space perceptions are the fundamental blocks of recognizing everything in our world. They are critical for coordinating human body's internal operation and external interactions. Naturally, every physical movement is described over time and space in which it is performed. For instance, a journey between point "A" to point "B", takes place over a spatial distance of "X" with the duration of "t" (Figure1.1).

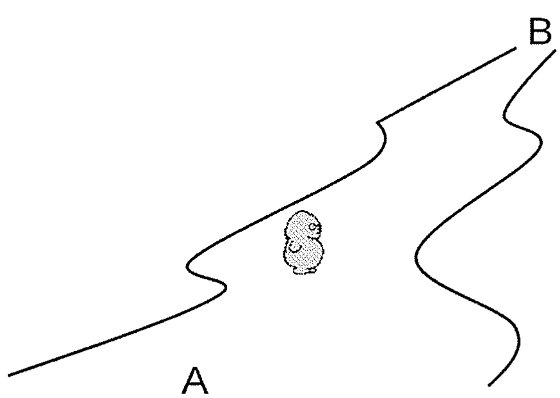


Figure 1.1: Journey from A to B, a typical spatiotemporal task.

Well-developed temporal and spatial perceptions are critical factors in optimizing the journey between points A to B. In this sense comes the importance of identifying the underlying mechanisms of temporal and spatial processing in the human brain as it may help to detect neurological disorders at early stages; furthermore, it may pave the way for a shift in the paradigm of treatment of patients with neurological disorders in restoring the impaired spatiotemporal abilities.

1.1 Motivation

The primary motivation behind this study was to investigate the extent of human brain's spatiotemporal processing abilities in learning different temporally and spatially constrained motor and/or perceptual tasks. This potentially leads to a better understanding of the human brain underlying mechanism encountering a repetitive motor or perceptual task, which results in the skilled human movement in terms of temporal and special accuracy. For this, two sets of interactive computer games have been developed that are played with a 2DOF manipulandum.

1.2 Goals and Objectives

This study was aimed to investigate the objective measures for sense of time and sense of orientation. Through this study the temporal and spatial perceptions and adaptation to changes in spatiotemporal elements in specific game environments were monitored, and characteristic information was logged for further analysis. The specific objectives were:

- Developing two sets of interactive computer games that can accurately test the human spatiotemporal processing abilities;

- Investigating the application of a 2DOF manipulandum and the computer games in objective assessment of spatiotemporal processing element of the motor control activities in humans (in our case, 2D arm reaching movements);
- Recruiting human subjects and collecting psychophysical data using the games and manipulandum;
- Investigating the extent of the human brain ability in learning complex spatiotemporal patterns;
- Investigating the age dependency of the human brain spatiotemporal abilities.

1.3 Organization of Report

This manuscript is divided into five chapters. The first has chapter presented an introduction to the content, goals and objectives, motivation and scope of the thesis. Background and literature review on temporal and spatial processing and their neuroanatomical involvement are brought in the second chapter. Chapter three explains the methodology used in this study; the hardware and software components and design of the interactive computer games as well as the experimental setup, data collection, and data analysis. Chapter four presents the results followed by discussion. Finally, chapter five draws conclusion based on the work presented in the previous chapters and suggests directions for the future work.

CHAPTER II

LITERATURE REVIEW AND BACKGROUND

2.1 Means to Study Temporal and Spatial Processing

Neuroimaging techniques (e.g. Positron Emitting Tomography, and functional MRI), signal processing (EEG signals - Electroencephalogram), psychophysical experiments and pharmacological studies are some of the means commonly used in studying temporal and spatial processing.

Imaging techniques generally give a map of the change in the blood flow or oxygenation level in brain, while EEG technique records the electrical signals captured on the human scalp that correspond to the neuronal firing of different brain regions. As for the psychophysical experiments, human performance during encountering a stimulus, which is changing systematically in one of its physical dimension (e.g. time), is measured and analyzed [1]. Pharmacological studies investigate the effect of certain drugs on different brain activities such as the effect of dopaminergic drugs on the internal clock of the body.

There is a specific type of electrical potential activity associated with the speeded-response motor tasks or perceptual tasks called Event Related Potentials (ERP). ERPs are detected in the EEG signals recorded, using electrodes placed on the human scalp. Contingent Negative Variation (CNV) is a negative wave ERP signal detected in motor-related areas of the brain in anticipation of a stimulus. It is reported to be strongly correlated with the temporal processing in the human brain. Researchers believe CNV underlies information about the nature of temporal processing in the human brain [2], [3].

2.1.1 Psychophysical Experiments

Psychophysical experiments have been a common way to acquire information about the nature of human perception (e.g. perception of time). Psychophysical experiments, as opposed to other invasive methods of studying human sensory systems and perceptual processes, are especially of interest for researchers in neurobiological fields as the invasive methods are not usually feasible due to ethical limitations.

Orientation of a bar of light, discrimination between pitches of two tones, duration of a flashed bar of light and the time interval between presentation of two tones are examples of the psychophysical experiments commonly used to test human temporal and spatial processing [4].

An example of psychophysical experiments is the study reported in [5] to identify the centralized or distributed nature of temporal processing. In that study the performances of human subjects in discriminating intervals demarcated with either visual or auditory cues were compared. The results showed better performance in discriminating the interval demarcated by auditory cues.

According to the centralized clock model, the brain uses the same neural circuitry to determine the duration of a visual flash of light and an auditory tone. Therefore, the results reported in [5] is a counter example that rejects the centralized clock model hypothesis, and proposes a distributed timing one [6], [7].

2.1.2 Pharmacological Studies

It has been shown that neurobiological disorders, which involve dopaminergic pathways (e.g. Parkinson's disease, Schizophrenia, Huntington's disease), result in impaired temporal processing. Considering the internal clock model for temporal processing, pharmacological studies report that the speed of the clock is affected by dopaminergic manipulation, while the memory is affected by cholinergic manipulation [8]. It should be noted that dopamine and acetylcholine are chemical neurotransmitters found in the brain that regulate movement, balance and walking and various cognition systems in the brain [9], [10].

2.2 Temporal Processing

Temporal processing is generally referred to either decoding of temporally coded information or generating timed motor actions [8]. The neural basis of temporal processing in the human brain is still a mystery as different studies suggest different models describing its underlying neuroanatomical mechanism.

Therefore, "Where and how is timing in the human brain generated and processed?" is the question researchers are trying to answer through studying temporal processing in neurogically impaired and control humans using advanced technologies in psychology, neuroscience, and engineering. Here, a literature review on different findings about temporal processing in human brain and its special characteristics is presented in the following subsections.

2.2.1 Brain Regions and Temporal Processing

2.2.1.1 Cerebellum

The Cerebellum (Figure 2.1) has an important role in motor timing, balance and regulating movements of subsecond (less than 1 sec) intervals. Impaired muscular coordination and overshooting (e.g. hand tremors) movements are observed in patients with lesions of the cerebellum. This is due to the delay in transferring a motor command from the motor cortex to the corresponding muscles through the cerebellum.

In [11] the temporal performance of patients with Parkinson's disease was tested, while performing repetitive tasks with either an event-based or an emergent timing requirement. Event-based timing refers to the explicit temporal processing, while emergent timing is implicit timing where the temporal processing is done as a by-product of an ongoing motor or perceptual task without any specific instruction to the time.

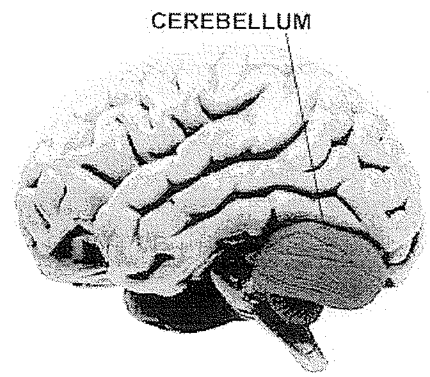


Figure 2.1: Cerebellum [57].

In that study, it was shown the cerebellum was active during tasks that involved event-based timing, while its contribution in the temporal control of emergent timing was reported to be very low [11]. Therefore, impairment on event-based timing tasks results from cerebellar lesions [4].

2.2.1.2 Basal ganglia

In [12] and [13] the role of the basal ganglia (Figure 2.2) is emphasized in the light of clock-like model for the temporal processing. It has been shown in pharmacological studies [8] that certain types of drugs, which act on the dopaminergic system, affect temporal processing and may cause its impairment. On this basis comes the role of the basal ganglia in temporal processing as an important part in dopaminergic system. Imaging studies have also detected the activation of basal ganglia in temporal tasks of less than 1.2 s, which is an important timescale for performing coordinated motor actions. In [11], basal ganglia are suggested to participate mainly in emergent timing and with minimal contribution to event-based movement timing.

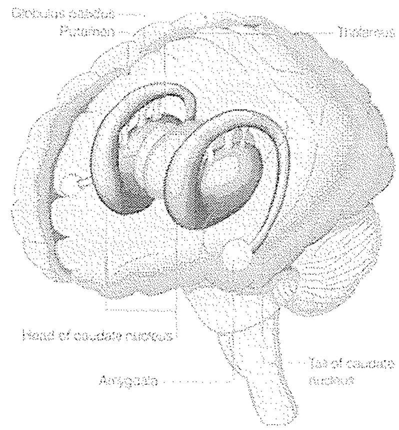


Figure 2.2: Basal Ganglia [58].

In [14], considering the clock-like model for temporal processing it is argued that the periodic activation of the caudate nucleus during speed estimation is due to the basal ganglia's role in providing an internal measure of time during speed-derived timing.

On the other hand, it has been observed that thalamo-cortical-striatal circuits, including the basal ganglia, prefrontal cortex and posterior parietal cortex, are activated in interval timing tasks as well as tasks that involve manipulating a stimulus dimension over time [8]. An example for the later type of tasks is our developed orientation game, in which the target location is changing over time and required to be estimated.

2.2.1.3 Cortico-striatal Circuits

A more detailed study [15] proposes the involvement of cortico-striatal circuits in interval timing. Considering the oscillatory network model for the temporal processing, it is suggested that the suprasecond durations (i.e. hundreds of milliseconds to minutes [8]) are discriminated by striatal medium spiny neurons through detecting coincident activity in cortical oscillators.

Many investigators have suggested that the dorsal striatum plays the role of the central core-timer due to its consistent activation level in temporal processing of perceptual or motor tasks of short interval in the range of few milliseconds up to a minute [15].

2.2.1.4 Lateral Intrapareital Area

Studies on monkeys suggest that it is the responsibility of posterior parietal neurons to process temporal perception while memory-related temporal intervals are suggested to be developed by the lateral intraparietal area (LIP) [16].

2.2.2 Temporal Processing Categories

There have been several attempts to categorize human temporal performance into different groups, so that a clear line can be drawn between different categories and their neuroanatomical involvements. These categories are based on either the nature of the task being performed or the length of the temporal interval involved. Explicit and implicit timing, automatic and continuous-event timing, circadian rhythms, seconds-to-minutes interval and millisecond interval are the temporal processing categories covered here.

2.2.2.1 Explicit and Implicit Timing

Researchers divide brain temporal processing into two broad categories of explicit and implicit timings each of which includes both motor and perceptual timing. Explicit timing is a deliberate temporal expectation for discrete events, while implicit timing is when a sudden temporal prediction is built without any specific instruction to time [17]. In a perceptual implicit timing task, the temporal estimation of the task duration is either formed using informative pre-cues, or it is incidentally built as a by-product of ongoing stimulus structure. Therefore, temporal estimation can be subconscious and unintentional (exogenous), or conscious and deliberate (endogenous) [18].

*f*MRI studies show the involvement of basal ganglia, supplementary motor area (SMA), cerebellum and right inferior frontal and parietal cortices in explicit timing [17]. These studies report cerebellum sensitivity to subsecond (i.e. milliseconds) rather than suprasecond intervals. On the other hand, *f*MRI studies show the engagement of cortical action circuits, inferior parietal and premotor areas in implicit timing [17].

2.2.2.2 Automatic and Continuous-event Timing

Automatic timing system refers to the system involved in millisecond interval generation. This system is used in discontinuous timing, and it consistently involves the activity of the cerebellum. Other brain regions generally involved in discontinuous repetitive movements, which require very short period timing (discrete-event) include: the supplementary motor area, primary motor cortex and primary somatosensory cortex [8].

Continuous-event timing system is referred to the cognitively controlled timing system and requires the activity of basal ganglia and related cortical structures. The continuous-event timing system is responsible for temporal processing of tasks, which require limited amount of movement [8]. These types of tasks generally involve the activity of the dorsolateral prefrontal cortex (DLPFC), intraparietal sulcus and premotor cortex. DLPFC is involved in working memory in addition to cognitive timing [19].

Researchers in [20] observed different performance in temporal estimation, production and reproduction for short durations of 3 s and less compared with longer duration of more than 3.5 s in patients with right brain lesions. Authors in [21] describe this boundary (3 to 3.5 s) as the boundary line between the automatic timing and cognitive timing which is longer than the period of 1s reported in other works [8]. They also propose the existence of a transitional interval during which the temporal processing is neither completely automatic nor cognitive but a mixture of these two timing systems. If this is true, the existence of such a transitional stage is another matter of the human temporal processing system mystery that requires more research to identify its characteristics.

2.2.3 Temporal Processing Scales

Researchers have studied temporal processing over a range of various timescales in order to identify their specific features and associated neuroanatomical regions. The timescales commonly considered in temporal processing studies are: circadian (24 hrs), few seconds to minute interval and milliseconds to a few seconds interval (Figure 2.3) [8].

Circadian rhythms refer to the 24 hour day/night cycle and include the temporal aspects of sleep and wakefulness as well as the general functionality of internal body system. (e.g. metabolism, body temperature, blood pressure). The inputs to this clock are light and social information from the surrounding environment. It is reported that the suprachiasmatic nucleus of hypothalamus is responsible for generating these rhythms [8]. Interval timing in the range of seconds to minute is involved in tasks such as foraging, multiple step arithmetic while the speeded-response tasks such as speech recognition and playing music require a timing interval in the range of milliseconds.

For activities with a temporal interval of milliseconds to minute, the corticostriatal circuits and dopamine neurons are observed to be active, contributing to different aspects of the performance. The temporal processing interval of 10 ms to a second is referred to as the most sophisticated and complex form of temporal processing [4], which involves the consistent activity of the cerebellum as well as different task-specific brain regions.

2.2.4 Emotion and Temporal Processing

Human temporal processing is subjective and is altered by the emotional state. For instance, time seems to drag when one eagerly anticipates the arrival of a specific event. A boring lecture for a student may seem endless.

Researchers have found that temporal perception is altered during the course of disaster or emergency situations. In [22] it has been argued that, due to distortion of temporal perception in medical emergencies, appropriate treatment in terms of quality and quantity may not be delivered to the patient. According to that study, during medical emergencies, because of a high-arousal and unpleasant situation, responders will likely feel time passing slower and the situation takes a longer time than it really does.

This effect is argued in another study, in which it is proposed that the attentional orienting stimuli distort the interval duration estimation [23]. It was observed that activation of the brain circuitry involved in the tasks that require attended processing (cognitively controlled timing), affected temporal estimation in the range longer than hundreds of milliseconds [24]. For instance, in the case of a car accident, those who are present at the crash scene process information received through their sensory systems more extensively; this results in a higher activation level of attentional circuitry in the brain and as a consequence, the time is perceived to slow down [25]. Another study suggests that time was distorted for the subjects who participated in a freefall experiment using SCAD diving [27]. At the end of the experiment subjects were asked to report the duration of the freefall using a stopwatch; all the subjects reported a duration in the range of 36% longer than it actually was [26], [27].

As for the neuroanatomical involvement, an increase in the activity of the cortico-striatal network and pre-SMA was detected through *f*MRI studies on subjects whose attention was selectively directed to the temporal duration of a stimulus disrespect to motor planning [24].

2.3 Spatial Processing

The importance of studying spatial-processing in humans stems from the fact that space is a common feature of everything observed through our senses. Spatial processing is involved in judging an object's size, orientation, distance to other objects and relative location in the horizon coordinate system (i.e. north, south, east, and west). Special features of a landmark or an object include distance, relative and absolute position, size, and orientation.

Therefore, how well we can locate and describe ourselves and certain landmarks spatially in the surrounding environment is a measure of spatial processing abilities. This is also referred to as spatial cognition [28], [29]. In this section, a literature review on spatial processing studies is presented.

2.3.1 Frame of Reference

Location, direction, or the orientation of an object is defined relative to the frame of reference where that object is presented in. There are two frames of reference considered here; egocentric and allocentric. Egocentric orientation involves cues that depend upon the position of the observer (i.e., left-right, front-behind), while allocentric orientation is maintained through the use of either environmental features such as landmarks, or horizon coordinate systems (i.e., north-south, east-west), which are independent of the observer [30].

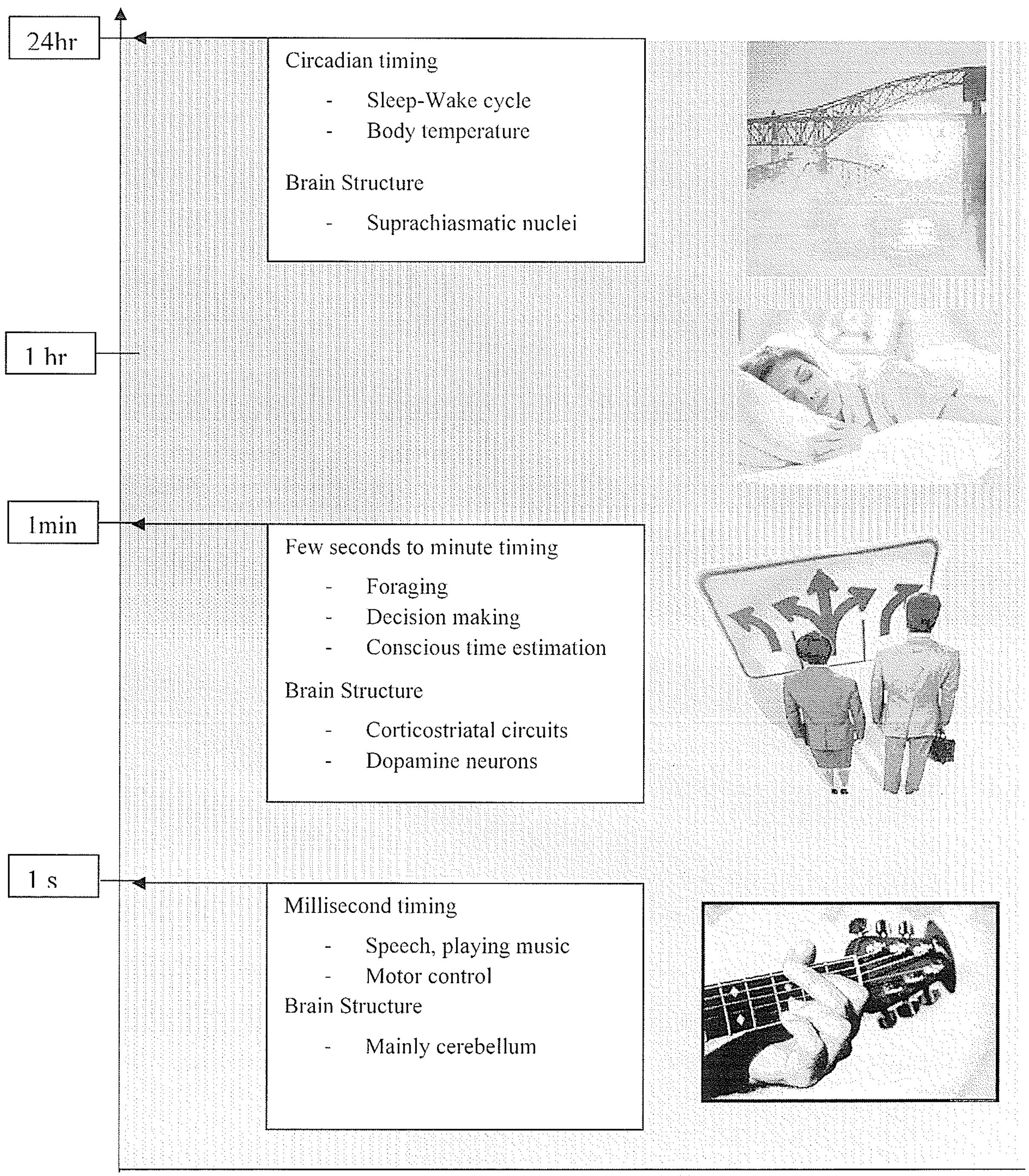


Figure 2-3: Time across different scales.

2.3.2 Spatial Processing Tests

Morris water maze is the first experiment to test spatial memory in rats. In this experiment, the rat is placed in a tank of water which contains a hidden escape platform. Therefore, the rat starts swimming and trying to get out of the water by finding the escape platform. It is observed that on subsequent trials the rat learns the location of the hidden platform and with enough practice; it finds the hidden platform directly from any point in the water maze. The rat's desire to escape from water reinforces the learning procedure [31].

In [30], human version of Morris water maze is used in real and virtual environments. The goal in that game is to find a hidden spatial spot. This is referred to as the hidden goal task. The real navigation space consists of a cylindrical arena 2.9m in diameter surrounded by a 2.8 m high dark-blue velvet curtain. There are eight digital numerical displays on the wall equally spaced at 45° intervals used as orientation cues. A video recording system on top of the cylindrical room enables position recording. In the computer game design, top view of the arena is shown to the subject with the goal indicated as a red circle, cues as green and blue lines and the starting point was marked as a circle on the arena contour. Then, the goal was disappeared and the subject had to locate its location using the computer mouse. The game divided into two categories of egocentric and allocentric orientation test. For the egocentric orientation, the subject had to locate the goal solely with respect to starting position without any use of cues, while in allocentric experiment the subject is instructed to locate the goal with respect to the cues.

In other works, allocentric orientation is tested by navigation through a virtual town using landmarks as spatial cues [32], or by remembering the location of objects on a table placing different object at fixed locations [33].

2.3.3 Spatial Processing Neuroanatomy

To study the perception of orientation in human subjects, first the mechanism behind the development of spatial perception should be known. Studies report differences between the spatial processing of finding the way and that of object locating as the former one involves sequential processing of the spatial information and the later one involves retrieving knowledge of spatial layouts (absolute and relative spatial coordinate and objects features) from spatial memory [34]. Each group of these spatial memories is divided into subcategories to cover more specific spatial functionalities [34]. Furthermore, researchers draw a line between real time spatial processing and a long-term spatial memory [35]. On the other hand, brain stroke studies report selective impairment of spatial abilities in patient with different brain damages, which supports the idea of having separate underlying neural mechanism for different types of spatial abilities [36], [37].

Brain regions commonly reported to be actively involved in spatial processing are prefrontal cortex [38] and posterior parietal regions [39], [40]. Among these regions, hippocampus (Figure 2.4) is reported to have an important role in memory in general and hence spatial memory [41], [42]. Place and direction of an object are found to be processed in hippocampal formation which code location, direction, speed and distance specially in the case of allocentric spatial processing [43]. Hippocampal lesions cause spatial abilities impairment as brought in [44], [45]. Right hippocampal activation was observed while scanning London taxi drivers' head during recalling routes around London [46]. An interesting finding reported in [47] is that London (UK) taxi drivers have enlarged hippocampi compared to the normal people, and also the size was correlated with the years of professional driving experience.

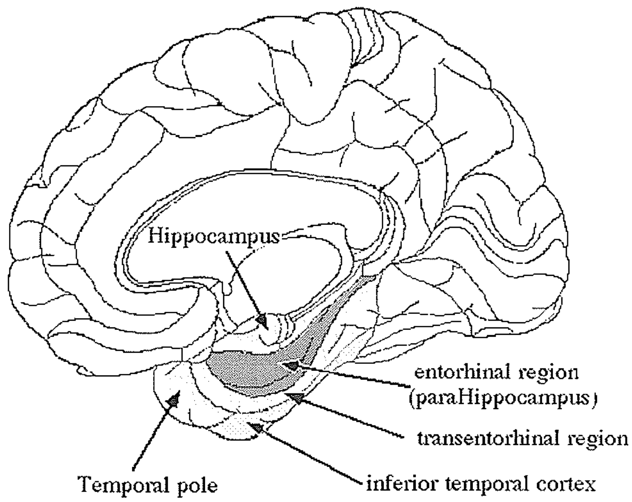


Figure 2.4: Hippocampus [59].

There are three theories proposed in the literature about the involvement of hippocampus in spatial processing as the followings:

1. **Cognitive map:** hippocampus stores spatial information about the objects in the environment without regard to the observer (allocentric type of spatial processing) and therefore builds a cognitive map of the corresponding environment where the objects exist [42]. This is supported with allocentric impairments in subjects with hippocampal lesions [48]. This functional property forms the basis for way finding, goal identification and calculation of trajectories [43].
2. **Working memory:** hippocampus serves as a place for general short-term working memory including spatial memory but not specialized solely in the later one [49], [50].
3. **Binding device:** hippocampus integrates different sensed information processed in different brain regions [51], [52]. Therefore, this binding functionality is important in a situation where different features of an object are to be processed for its identification.

In [53], *f*MRI technique was used during verbal description of spatial relation of landmarks by participating subjects to investigate the underlying neural mechanism for egocentric and allocentric orientation. In that study the spatial relation of the objects in a virtual environment was described to the subject using auditory stimulation eliminating any visual stimulation. After the descriptive auditory stimulus, the subjects were asked questions about the relative position of an object to another object(s) (allocentric) or to themselves (egocentric). The result showed constant activation of a bilateral fronto-parietal network and primary visual area in both hemispheres during egocentric and allocentric spatial tasks. Furthermore, the authors have reported the activation of precuneus mainly in tasks involving egocentric spatial coding, while allocentric spatial coding was observed to activate a network of the right superior and inferior parietal lobe and the ventrolateral occipito-temporal cortex bilaterally. On the other hand, the activity of bilateral hippocampal was only observed during allocentric spatial coding.

2.3.4 Spatial Perception and Age

Human spatial abilities decrease with age. Through using *f*MRI imaging, a recent study shows less neural activities were captured in older subjects compared to younger ones in the hippocampal complex, parietal cortex and other regions of the brain involved in navigaition [54].

2.4 Spatial-Temporal-Velocity Bond

One general outcome reported in imaging studies is the involvement of similar regions of the brain in temporal processing as in spatial processing and motor control. This is more evident for the case of speeded response tasks in the milliseconds scale. In some species of animals, spatial information is obtained through temporal processing [8]. For instance, bats use the difference or coincidence in phase between emitted ultrasound waves and the reflected echoes for localization and recognition of the surrounding objects.

In psychology, the kappa effect is described as the error in perceiving visual events as being longer or shorter, depending on the spatial positions associated with that event. Considering an equal travelling time to two different destinations, the journey which covers a longer distance is perceived to be more time consuming even if it is passed with a higher speed [55]. In physics, the temporal relativity theory of Einstein in 1905 proposes that a moving clock is measured to tick slower than a stationary clock [56]. According to this theory, it takes 32.167 years for a spaceship travelling at the speed of 99.5% of the speed of light to reach Aldebaran as measured in our time. For people onboard the spaceship, this travel time is much shorter: around 3.2 years only! ([56], Page.92). Hence, there is a close tie between the elements of time, space and velocity in physics and psychology. In fact, these elements are the intrinsic characteristics of any motion.

In a recent study [14], *f*MRI imaging technique is used to detect the activated areas during temporal, spatial and velocity processing. The authors also investigated the level of activation in these areas. In order to trigger spatial and/or temporal processing, movement of a ball was considered. Subjects were presented with a moving ball that repeatedly disappeared, and they were asked to estimate where and when the ball would hit the bottom of screen, where it actually disappeared and with what speed. It was shown that the posterior parietal region was activated in both spatial and temporal predication. Other left cerebellar regions including right prefrontal and pre-SMA were consistently firing during solely temporal processing tasks. On the other hand, velocity estimation analysis showed the activity of caudate nucleus in addition to the similar neural activities in parietal and cerebellar-prefrontal regions as those observed in the temporal prediction tasks [14]. From these observations, the authors inferred parietal-based spatial information is a requirement for temporal processing, while prefrontal and cerebellar activities correspond to working memory and feedforward processing of the differences between past and future spatial states. The authors proposed that the temporal component is extracted from the speed by which the smallest perceptible interval between two spatial cues is passed, and this temporal manipulation is done at cerebellum. According to this close bond between time, space and velocity components of motor tasks, any change in one of these components should result in a change in the others; furthermore, these components are processed together by the same neural circuits [4].

2.5 Our Approach

We have investigated the extent of human brain temporal and spatial abilities by analyzing the subjects' performance encountering a stimulus with varying temporal and spatial dimensions. For this, two sets of interactive computer games have been designed; each of which addressing the need for a module to study human's temporal and spatial processing, separately.

These two interactive computer games consist of repetitive goal-oriented temporarily and spatially constrained motor tasks; in particular, a falling target game where the subject must catch a falling target with variable falling rates in successive trials of the game, and an orientation game in which the subject must move toward desired spatial cues varying in every new trial of the game.

Considering the implicit and the explicit timing definitions brought in section 2.2.2.1, the temporal perception formed during playing the falling target game would be of implicit timing type, while the exogenous or endogenous type of this temporal perception is a factor of subject's awareness about the changes in the successive cues. This has been the premise of our first game design, called the falling object (flower) game. Generally, weak or deficient sense of time can show itself in the form of not noticing the duration of an event that results in missing to catch the flower.

The orientation game was aimed to test sense of orientation. The subject has to be able to orient him/her self with respect to the final destination from a new starting location in each trial.

2.6 Hypotheses

Through this study a set of hypothesis as follows were considered:

1) Performance in adapting to less complex temporal or spatial patterns of change applied on a consecutive set of goal oriented motor tasks (e.g. reaching movement) would be significantly better than that of a complex pattern.

2) The brain uses a piece-wise linear function to estimate complex nonlinear patterns (falling target games).

3) Elderly and children subjects have similar performance in terms of achieving the spatiotemporal goals in these games.

4) Young adults outperform elderly and children subjects in goal-oriented temporally or spatially constrained perceptual or motor tasks.

CHAPTER III

METHODOLOGY

3.1 System Components

This chapter represents the system setup used in this study, including the system components, detailed games description, experiments, and data analysis. A robotic arm (manipulandum) and two sets of interactive computer games were used in this study. Figure 3.1 shows the overall system setup.

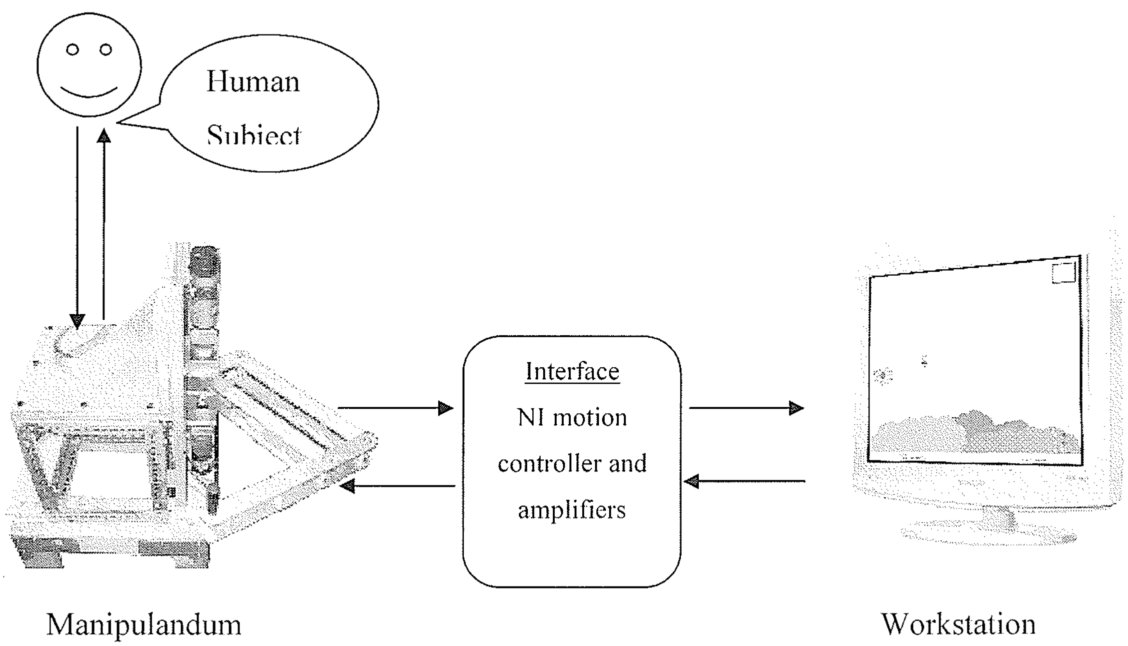


Figure 3.1: Overall System Configuration.

3.1.1 Manipulandum

The custom-designed manipulandum (robotic arm) used in this study is a 2DOF parallel four-bar linkage with two drive motors mounted at the base [60]. The manipulandum consists of two segments representing the human arm and forearm in a 2D plane. The first segment is connected to the base and rotates around an axis parallel to the base representing the shoulder joint, and the second segment is connected to the other end of the first segment and rotates around an axis representing the elbow joint (Figure. 3.2). Subjects were instructed to play the game using the manipulandum, through which the movement trajectories and their velocity in the 2D plane were measured and recorded.

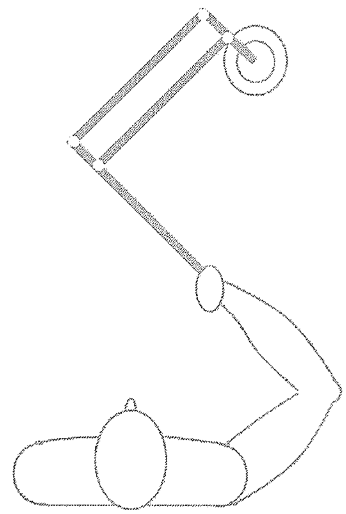


Figure 3.2: Top view schematic of a subject holding manipulandum.

The manipulandum is interfaced with workstation through a motion controller card (PCI 7344) from National Instruments. The control signals from the workstation are sent to a digital to analog converter, D/A, while the position feedback from motors sent as input to the workstation through an encoder resource. Positions and velocities of the manipulandum end effector are obtained through National Instruments FlexMotion C++ API used to interface to PCI 7344.

3.1.1.1 Motors

The motors used to drive manipulandum are Electrocraft E560 brushed DC servo-motors accompanied with a servo amplifier drive system, Max-100 PWM. The joint torque requirement for generating at least 20N of force at the manipulandum end-effector (i.e. the human hand) has been examined and determined in [61]. It has been found that a torque of 10 Nm is needed in order to generate the desired force in all the directions, while the DC servo motors used are only capable of generating a maximum torque of 0.15 Nm. Therefore, a gear reduction ratio of 70:1 was selected to provide for the torque requirement.

3.1.1.2 Gear-Heads

The gear-heads previously used had a fairly large backlash of 16 arcmin resulting in a dead-zone of rotation at the output shaft of the gear-heads which as a consequence caused difficulties in starting and stopping the robotic arm smoothly. Circular non-goal oriented motions has been observed at the end of the trajectories due to the subject's attempt to stop the robotic arm at the target location. Moreover, this backlash effect was resulting in extra errors during a given trial caused by shaky nature of the trajectories.

To reduce this effect, gear-heads were replaced with the new ones of a lower backlash of 5 arcmin from CGI systems. The new gear-heads helped in having more stable hand movements with less non-goal oriented portions previously seen in subjects' trajectories.

Detailed documentation of the manipulandum design, hardware and software structure can be found in [61].

3.1.2 Games

Interactive computer games developed in this study are called "Falling Target" and "Orientation" games. The set of Falling Target games was designed to test the sense of time, and also to investigate the brain capability in learning different temporal patterns of change, while the set of Orientation games was designed to test the sense of spatial orientation.

Games' screen is of size of 880X880 pixels^2. This space corresponds to a planar square area in the robotic arm work space with the center of this workspace matching with the screen coordinate of (0.4, 0) defined in the robot's base reference frame [61]. The game screen was projected on a larger screen during the experiment sessions, and subjects sat on a chair in front of the projected game screen holding the manipulandum arm that was placed parallel to the data show facing subjects as shown in Figure 3.3.

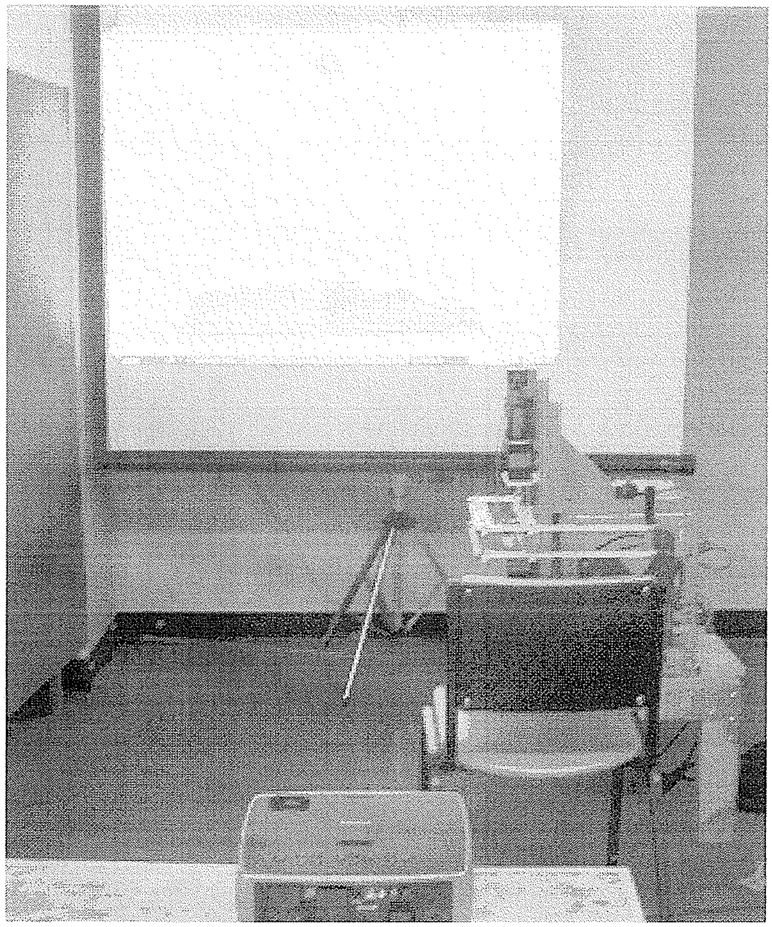


Figure 3.3: Experimental Setup.

3.1.2.1 The Falling Target Game Set

This game is about catching a falling target (a flower) with moving the cursor (a honey bee) by an appropriate velocity to reach the target before it touches the ground (Figure. 3.3). The starting location for the subject is a fixed location (the top right corner of the screen indicated with a black outlined square) throughout the game. The subject must move the bee to its starting location at the beginning of the game and after each trial to start a new trial. In every new trial, when the cursor was remained inside the start square for 400 ms, a "GO!" message appeared on the screen and the target started to fall.

To test the brain's temporal performance and its adaptability to different patterns, the velocity of the falling target was designed based on the following patterns: (Note that the velocity of the target in each trial was fixed but changed from trial to trial)

1) Linear incremental change,
2) Piecewise constant (Step) function in which the falling rate changes for every new sequence of trials of a total of 3 sequences, and remains constant during that sequence of trails,
3) Piecewise linear function consisting of three equal sets of trials each of which has its falling rate linearly incremented by a constant amount,
4) 2^{nd} order polynomial,
5) Uniformly distributed random function.

During the games, subjects received visual and auditory feedbacks on their performance. Three time thresholds were selected: the target's color was turned to red if the subject caught the target at a time less than or equal to the first threshold, to green if the subject met the second threshold, and to yellow if the second threshold was passed. The thresholds were adjusted in each trial with respect to the target's falling rate. These thresholds satisfy the lower bound of ~ 220 ms reaction time reported in [62]. This lower bound corresponds to the time required to detect and discriminate the visual stimulus and then to execute the motor action.

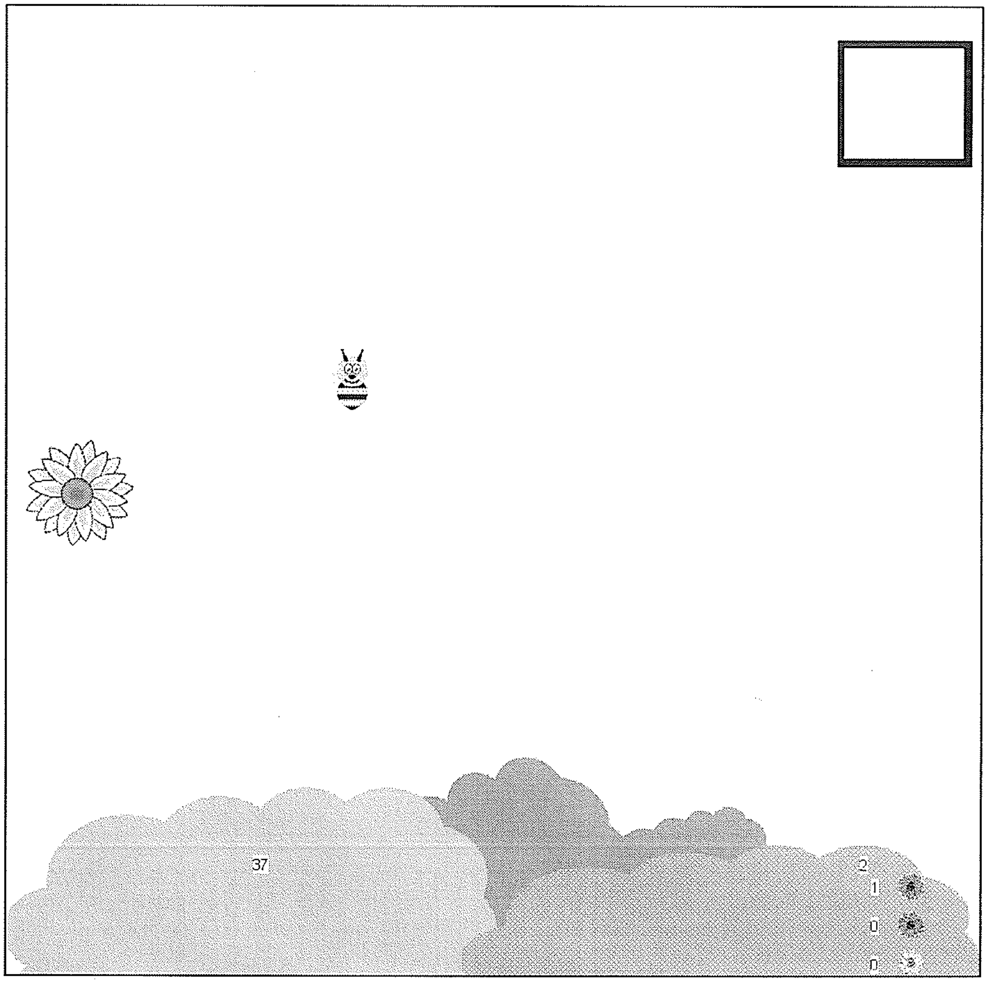


Figure 3.4: Falling flower game screen.

On the other hand, an auditory feedback indicating a successful trial (when catching the target in green color) and another indicating a failed trial were added. In order to make the game more attractive and drive subject's motivation to continue the game attentively, a score bar was also added to the bottom right corner of the screen showing three numbers with a flower beside each number. Each one of the flowers represented a timing constrain indicated with different colors (red, green and yellow), and carried the subject's score in catching the target under those timing thresholds.

The subjects were only instructed to try catching the target within a time zone that made the target's color green; in another word, to maximize their green score.

3.1.2.2 Orientation

This game has two versions of fixed and rotating final destinations. The interest is to see how the subject can correctly orient his/her hand trajectory and reach the desired final destination in every new trial.

Through this game, where the aim is to test spatial orientation, the cursor (mouse) as a virtual object slaves the human subject to play the game as if he/she is moving through a 2D virtual environment. Since Manipulandum is used to perform this motion, we assume that there is a mapping between the coordinates of arm movement and location of the mouse on the screen, which is the kinematic type of transformation done in our brain. In essence, the position of the mouse on the screen is mapped to the position of the shoulder and elbow joints, relative to the position of the subject's head (sensed by proprioceptors). This way we can catch the sense of orientation and also the process of learning the virtual environment and reducing the error in reaching the target in the consecutive trials. In this game, the subjects are only instructed to score by trying to reach the desired final destination without worrying about the time that it may take.

Fixed Final Destinations

In this game, there are four final destinations (rooms) out of which only one of them is the desired room to reach in every trial. These rooms are located at the upper half of the game screen at an equal distance from the center of the screen. The game has 36 trials. The starting location of the cursor (mouse) was shown as a black outlined square moving in the bottom of the screen from trial to trial with a random horizontal amount of displacement, while the final destinations were fixed and equally spaced at 45° angular distance from one another with respect to the center of the screen as shown in Figure 3.5.

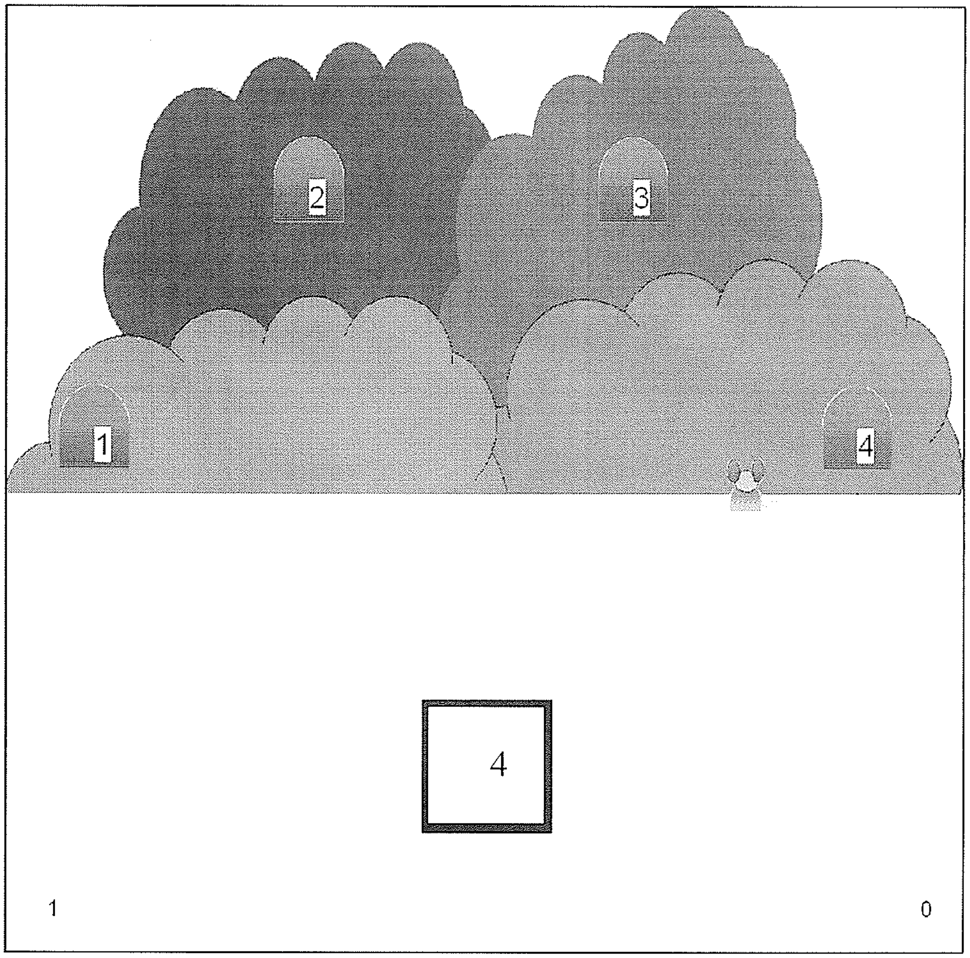


Figure 3.5: Orientation game screen.

Each trial started when the cursor (mouse) was observed for 400 ms inside the starting location. Final destinations with the associated numbers were visible and shown to the subject before the start of the experiment session and also at the end of each trial. However, at the beginning of each trial the final destinations became invisible, requiring the subject to remember the position of the desired final destination and choose the correct direction that would lead the mouse to the desired final destination.

As a visual feedback, the destinations became visible one after another when the subject reached the vicinity of the final destinations, and as a correct reaching trial, the desired room turned to red with the success audio feedback being played. On the other hand, in the case of an unsuccessful trial, a red X indicative of failed trial was shown with specific failed audio feedback being played. The desired final destination was shown inside the starting location square at the beginning of each trial.

As can be seen in Figure 3.5, each destination is placed inside a virtual landmark marked as a green bush on the game screen. Therefore in this case, the subjects may locate the desired final destination through using the associated landmark, which results in allocentric type of spatial processing.

Rotating Final Destinations

The game screen is the home for 4 final destinations (rooms) colored in brown, a starting location indicated as a black outlined square and a cursor (mouse). In this game, the subject should move the cursor to the desired final destination whose number is shown in every new trial for a total number of 72 trials.

The final destinations 1-4 are at equal distance from one another and located at a relatively fixed clockwise angular distance of 120°, 160°, 200°, 240° from the starting location, respectively. The starting location and the four final destinations are located on the circumference of a virtual circle of a radius of 400 pixels centered at the center of the game screen. In another word, if we divide the virtual circle into two semicircles, the starting location will be centered along the arc of the semicircle no.1 while the final destinations are distributed along the arc of the semicircle no.2 with equal distance between them (Figure 3.6).

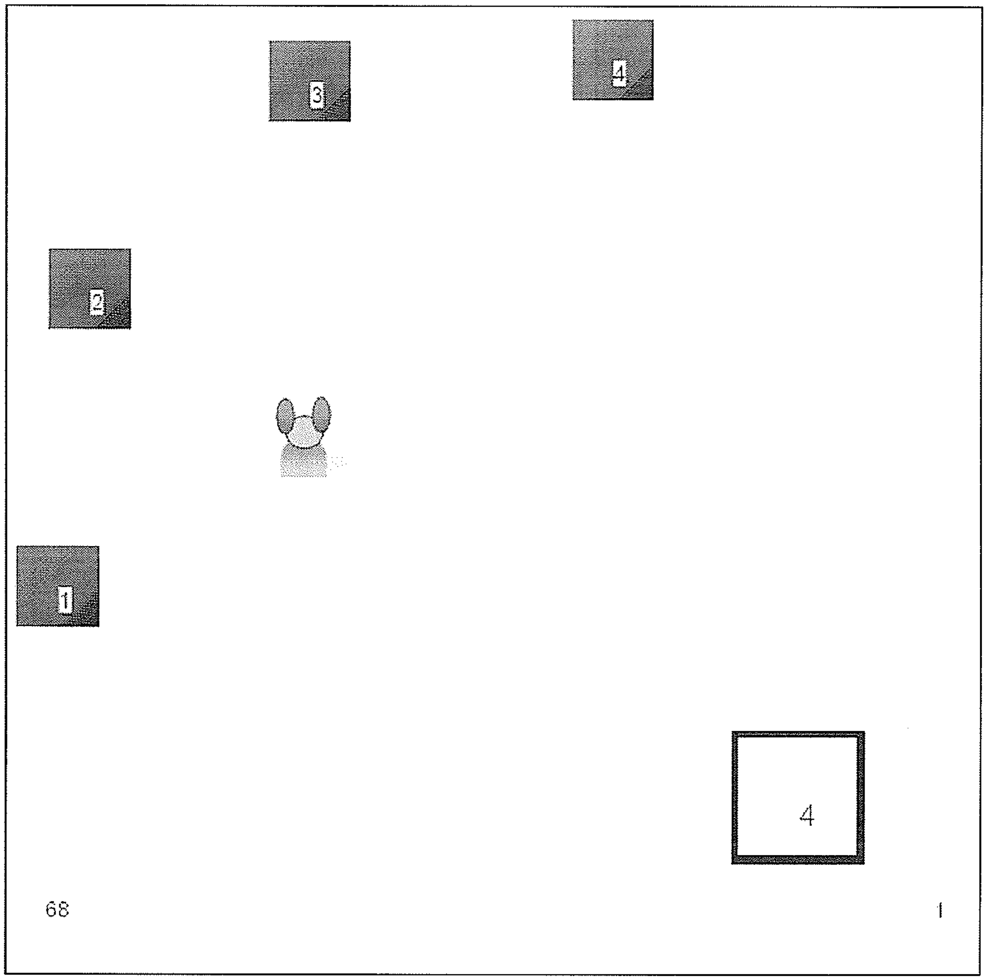


Figure 3.6: Rotating orientation game screen.

In every new trial of this game, the entire screen rotates with a clockwise amount based on a rotation model applied. Any change in the starting location would result in the same amount of change in the final destinations' location, keeping the relative distance between the starting location and the final destinations unchanged. Only the starting location is visible to the subject, while the rotation in transition to a new trial happens. Therefore, the spatial processing applied here would be of type egocentric spatial processing, since the subjects need to locate the desired final destination relative to themselves (e.g. landmark is located on the right of the mouse, egocentric coordination).

In order to start a new trial, the subject must move the mouse to its starting location at the beginning of the game and after each trial during which the final destinations are invisible. In every new trial, when the mouse is observed for 200 ms inside the starting location, the desired final destination number is shown inside the starting location square and a "GO!" message appears on the game screen. However, as long as the mouse remains inside the starting location, the subject has time to think of the correct direction that would lead the mouse to the desired final destination. When the subject decides which direction to head, he/she is given 0.8 sec to finish the trial. The clock starts counting as soon as the mouse is detected moving at the minimum speed of 0.1 m/s outside the starting location. This time margin is chosen based on the minimum temporal duration required to accomplish a motor task (e.g. goal-oriented arm movement) as reported [62].

The thinking time (the time given to a subject prior to the start of a trial) along with the trial time (the temporal margin set to finish a trial after a hand tremor was detected) are considered to minimize corrective non-goal oriented movements that may occur in other directions than the initial direction chosen by the subject. Ideally, in the case of a correct estimation of the direction to the desired room, the trajectory would be a straight line connecting the starting location to the final destination.

The trial clock count and the trial number are shown on the bottom left and right sides of the screen, respectively. At the end of each game session, the score for that particular session is shown to the subject. This game has two versions in which the entire game screen rotates either with the following pattern in each trial:

- Constant clockwise amount of 30°, or
- with a random amount of CW angular displacement

In the first trial of the game the starting location and the final destinations are shown with each final destination carrying its corresponding number, (1-2-3-4), allowing the subjects to familiarize themselves with the game and spatial relation between different objects on the game screen. As a visual feedback, when the subject crosses a virtual boundary that indicates the start of final destinations' region, the rooms become visible one after another. As a successful reaching trial, the desired final destination turns to red with a success audio feedback being played, while in an unsuccessful trial a red X indicative of a failed trial is shown with an associative failure audio feedback being played.

3.2 Games' Input and Output Files

There is a specific input file (target file) associated with each game, which defines the speed, starting location of the target, and controller parameters for the falling target game and the amount of rotation or displacement, starting and final destinations' locations as well as the control parameters for the orientation game. Each line of the target file corresponds to one game trial for a total of 120, 36 and 72 trials for the falling target, the fixed and rotating final destinations orientation games, respectively.

The output file is a text file initiated in the experiment module and the subject performance captured by manipulandum is saved there. The output file contains lines for every clock count, even when the subject is not on a run. The start of a trial is signified by the presence of a '1' in the first column of the output file. One clock count is equal to 10 ms.

3.2.1 Falling target

Input file

"Null120.txt" is used as the input file for linear incremental, piecewise linear, step, and polynomial falling target game. For the random falling target game, the input file is "randomTarget.txt". A line in the input file of the falling target game has the following format: [TAR_No = Target number, (X,Y) = target location, X0_? = virtual position, V0_? = virtual velocity, Kij = stiffness matrix elements, Bij = viscosity matrix elements]:

TAR_No. X Y X0_X X0_Y V0_X V0_Y K11 K12 K21 K22 B11 B12 B21 B22

Output file

Each line of the output file of the falling target game has the following format [CLK = clock count, *?_POS* = Cartesian position, *?_VEL* = Cartesian velocity, fRate = Trial's falling rate, Success = Success trial (0 or 1), Red = red score, Green = green score, Yellow = yellow score, y_Pix = y coordinate of the falling target, runTime = Trial's runtime]:

CLK X _POS Y_POS X_VEL Y_VEL fRate Success Red Green Yellow Y_Pix runtime

3.2.2 The Orientation Games

Input file

In the orientation game, the format of an input line is: [TAR_No = Target number, (X,Y) = target location, X0_? = virtual position, V0_? = virtual velocity, Kij = stiffness matrix elements, Bij = viscosity matrix elements, (Xn1,Yn1) = 1st nest location, (Xn2, Yn2) = 2nd nest location, (Xn3, Yn3) = 3rd nest location, (Xn4, Yn4) = 4th nest location, Ang = Rotation angle, LOC = Desired location]:

TAR_No. X Y X0_X X0_Y V0_X V0_Y K11 K12 K21 K22 B11 B12 B21 B22 Xn1 Yn1 Xn2 Yn2 Xn3 Yn3 Xn4 Yn4 Ang LOC]

The input file used for constant and random CW rotations are "OriCW.txt" and "OriRandom.txt", respectively.

Output file

Each line of the output file of the orientation game has the following format: [CLK = clock count, *?_POS* = Cartesian position, *?_VEL* = Cartesian velocity, LOC = desired location, Ang = Rotation angle, Success = Success trial (0 or 1), idis = the straight line distance passed from the starting location, ?_Pix = Cursor Cartesian coordinate, ThinkClock = Thinking clock before the start of the trial]:

CLK X _POS Y_POS X_VEL Y_VEL LOC Ang Success iDis X_Pix Y_Pix ThinkClock

3.3 Subjects

These experiments were run on three groups of subjects as follows:

1) Young Adult Subjects (20 - 30 years old)
2) Elderly Subjects (65+ years old)
3) Children (7-12 years old)

This age range for children is used because cognitive developmental theories suggest the period of 7 to 12 years is the stage where the rationality and active thinking start to develop in human being [72], [76]. Also, all the subjects within a group belong to the same generation with the same level of health, and skills in playing computer games.

3.4 Falling Target Experiments

Experiment I

The above mentioned patterns of the falling target's velocity were used in three sets of experiments on 30 young subjects (26.6 ± 3.1 years, 10 females, all were university students). The 30 subjects were divided in 3 groups of 10. Each subject played the game with the three falling rate patterns of random, polynomial and one of the linear patterns (linearly incremental, piecewise linear and step), for 120 trials in each game. Figure 3.7 shows the games played by each group of subjects.

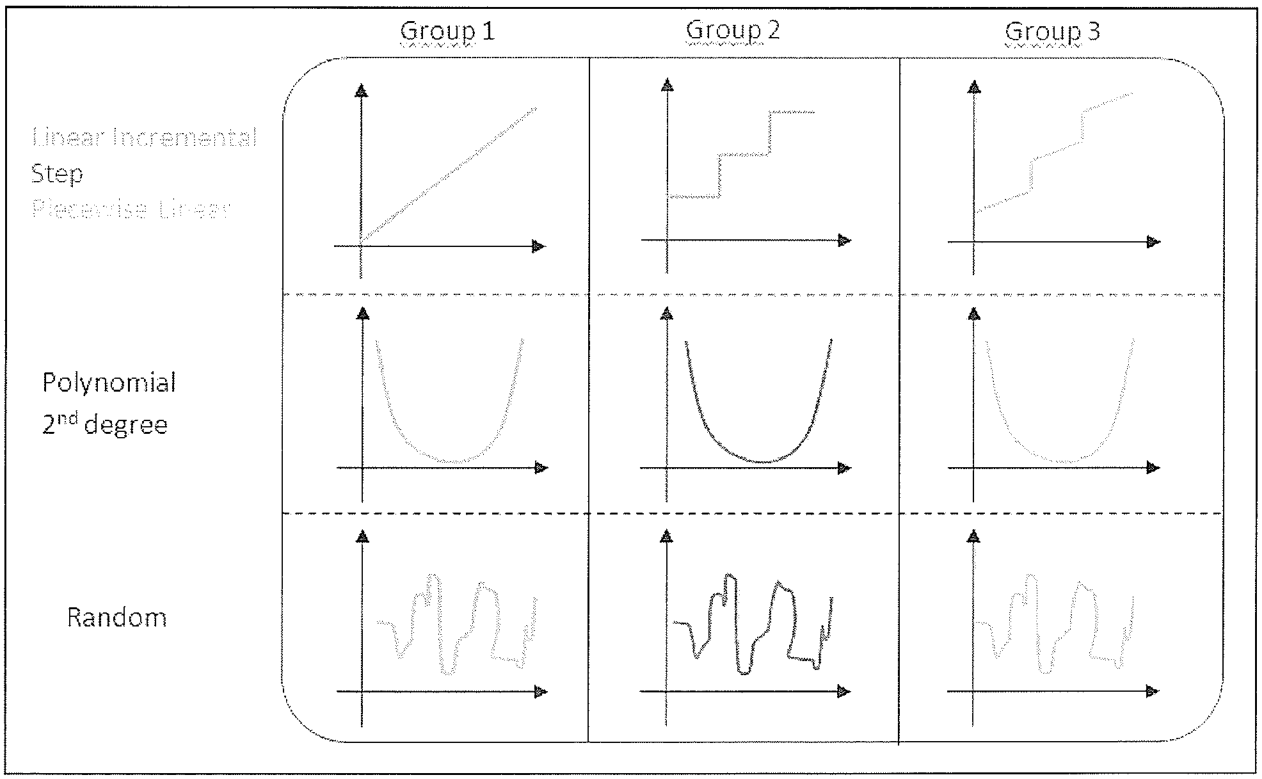


Figure 3.7: Different falling rate patterns used in this study, Linearly incremental, Piecewise Linear, Step, 2nd order polynomial, and random.

Experiment II

To study the effect of aging on temporal processing, the linear incremental pattern was tested on 12 elderly subjects (73.25 ± 7.6, 6 females) and 10 children (9.22 ± 2.1, 6 females) and the outcome was compared with corresponding one from young adult subjects.

3.5 Orientation Game Experiment

Experiment I - Fixed final destinations

The fixed destination orientation game was played by 9 elderly (74.67 ± 8.4, 5 female) and 11 children (9.72 ± 2.0, 7 females) subjects.

Experiment II - Rotating final destinations

30 healthy young adult subjects (26.4 ± 3.4, 10 females) participated in this game in two groups of 15 subjects. Subjects in each group played the games with either constant or random rotation for 72 trials, and their performance was recorded in the form of XY trajectories and velocities for further analysis.

Experiment III – Rotating final destinations

The constant spatial pattern of change (constant rotating orientation game) was tested on 12 elderly subjects (73.25 ± 7.6, 6 females) and 10 children (10.14 ± 1.6, 6 females) and the outcome was compared with the corresponding performance in the young adult subjects.

3.6 Data Analysis

For any goal oriented motor action, in order to achieve an optimal performance, the maximum-velocity (V_{max}) and the time for the movement should be correctly estimated. Therefore, the subjects' arm movement velocity and time profiles plus their trends of change following the change in the target's falling rate were investigated in the falling target game.

On the other hand, for the orientation game, subjects' trajectories toward the desired spatial cues were studied in terms of onset angle and the thinking time (the time before the onset of the trajectory) to assess subjects' sense of orientation.

A general GUI object (in MATLAB)has been developed that enables checking individual hand movement trajectories, velocity profiles, maximum and average perpendicular displacements, onset angles, and trial duration on the run as well as the score. In addition, this GUI plots the colormap of the trajectories' velocity profiles, calculates and stores the individual maximum and average perpendicular displacements, onset angles, average score and maximum velocity in separate text files for later retrieval and analysis. Figure 3.8 shows a screen shot of the GUI.

3.6.1 Falling Target Data Analysis

In reaching movement studies, it has been shown that after adaptation period the subjects' trajectories become close to a straight line between the starting and target points with a single bell-shaped velocity profile (Figure 3.9) spread out on the trajectory's time interval [63], [64]. Hence, analyzing the velocity profile of the subjects in the three sets of experiments of this study should reveal the nature of learning and adaptation to a temporal pattern of change.

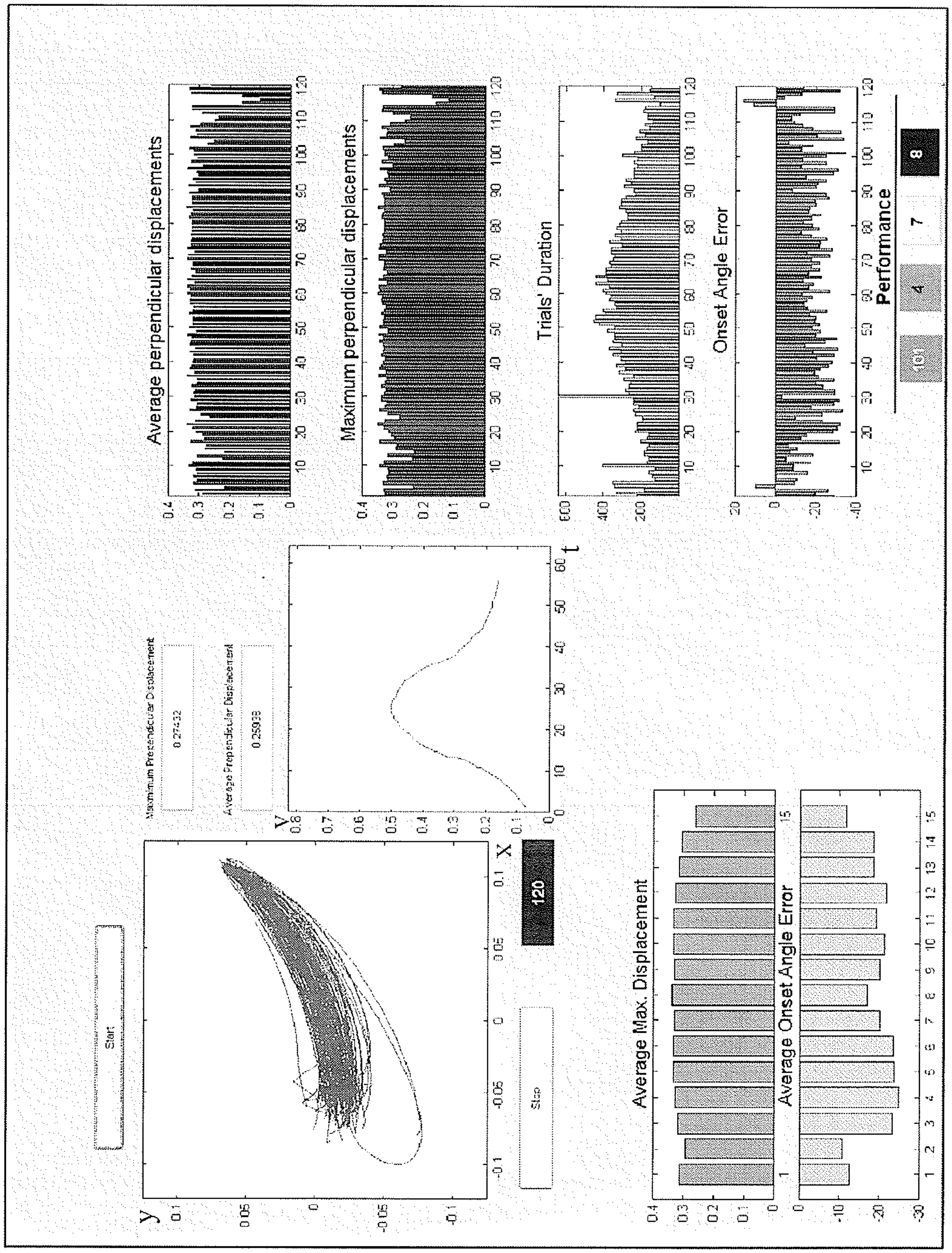


Figure 3.8: Performance analysis GUI.

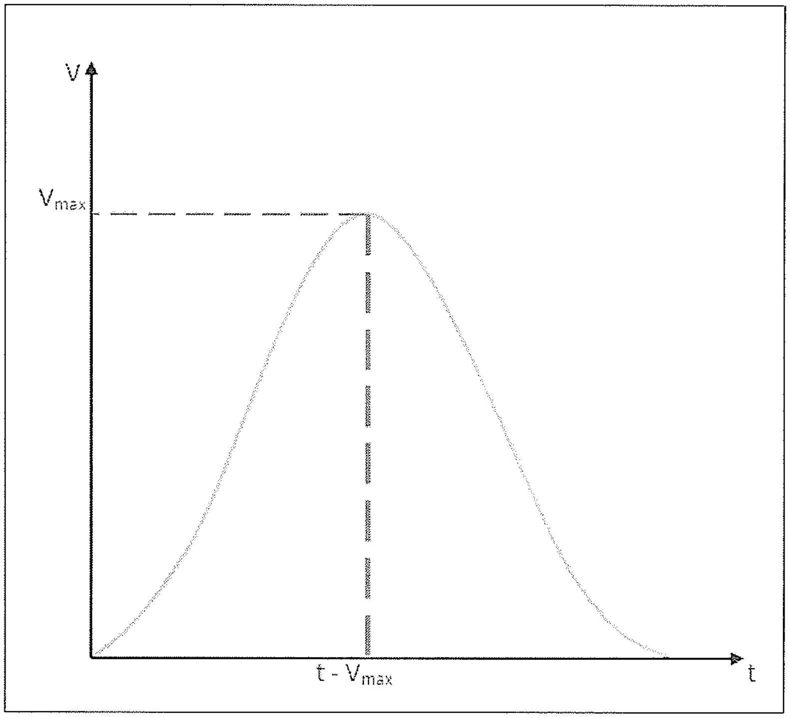


Figure 3.9: Typical velocity profile of a minimum-jerk goal-oriented reaching movement.

To maximize the Green score in the games, one must predict the target falling velocity, and adjust his/her hand velocity in order to catch the target on time. In a perfectly predictable scenario the subject's velocity change will follow the actual falling target velocity closely. Therefore, the amplitude of the V_{max} in each trial and its corresponding time were measured and averaged over the bins of 8 trials resulting in 15 bins in total, which cover all the 120 trials in each game. This was done to investigate the trend of change in the V_{max} amplitude and its occurrence time in comparison with the actual pattern of the falling target velocity.

To measure the performance in the case of linearly incremental, piecewise linear and step patterns of falling rate, the difference between the slope of the actual falling rate and that of the fitted linear line to the averaged V_{max} amplitude trend was used. To measure the performance in the polynomial games, the following parameters were considered:

- Rate Of Change (ROC) in the two sides of the averaged V_{max} amplitude and time trend parabolas,
- The bin where the extrema points in the averaged V_{max} and its corresponding time trend occur.

These parameters were calculated and compared for the averaged V_{max} and its corresponding time trend in the polynomial games.

Movement Error

The Mean Square Error (MSE) between the actual signals and the observed ones for the averaged V_{max} amplitude and its corresponding time trend for all the games (linearly incremental, piecewise linear, step, polynomial, and random) was calculated using (1):

$$MSE = \frac{\left(\sum_{j=1}^{15}\left(x_{ij} - x_{oj}\right)^2\right)}{n}, \quad (1)$$

where x_{ij} represents the points along the actual signal, x_{oj} represents the points along the observed signal and n represents the total number of bins (15). In addition, the difference in the amplitude at the minimum of the actual V_{max} trend and that of the observed one was used as the measure for the time perception error in the case of polynomial games.

The student *t*-test statistical analysis was used to investigate the existence of any significant difference between the MSE of the V_{max} amplitude, the V_{max} occurrence time and the subjects' Green scores between the games with different falling target velocities. In all instances, the p-value was set at 0.05.

The consistency between the pattern of change in the falling rate and the subject's V_{max} trend is investigated through correlation analysis of the difference beween the actual and observed V_{max} in successive trials of the falling target game. This analysis would show the general performace characteristics for different groups in different games, in addition to the role of the memory in remembering pervious errors and reinforcing the learning in a present trial.

3.6.2 Orientation Data Analysis

Thinking Time Trend

As described before, in every new trial when a subject took the cursor inside the starting location, a desired destination was shown. At this point, the subject was given an open time period to think about the correct direction that would lead the mouse to the desired destination. The time subjects spent thinking prior to the start of the movement is referred to as the thinking time and was recorded and averaged over the bins of every 6 successive trials resulting in a total number of 6 and 12 bins covering all 36 and 72 trials in fixed and rotating orientation games, respectively.

General Angular Error

In this game, the onset angle is a measure of how well a subject can orient him/herself to reach the desired destination after a displacement or a rotation in every new trial. The difference between the observed onset angle (Onset_ang) and the actual angle (Actual_ang) which leads to the desired final destination is referred to as general angular error (ε) and was calculated for each trial (Figure 3.10). The individual general angular errors were averaged in the bins of every 6 consecutive trials resulting in a total number of 6 and 12 bins in fixed and rotating orientation games, respectively.

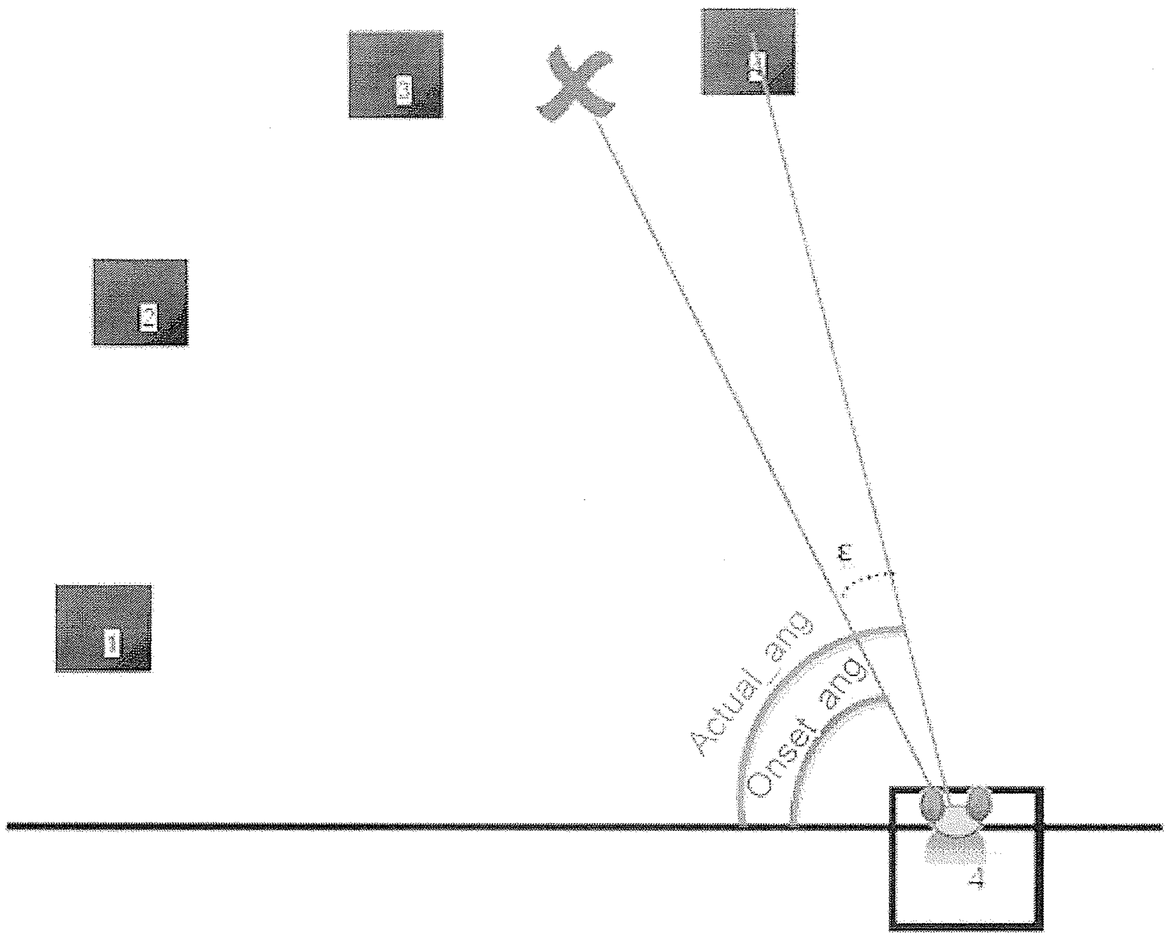


Figure 3.100: Orientation game angular error.

Directional Angular Error

In the rotating orientation game, a full rotation was divided into 12 regions of 30° and the angular errors within each region for those trials falling in that region were calculated, averaged and plotted using a polar plot. This refers to directional angular error.

Movement Error

The Mean Square Error (MSE) (Eq. 1) along with the Standard Error (SE) between the actual onset angle trend and the observed ones was calculated for all the subject groups (young, elderly, and children). In this particular case, n represents the total number of elements in the signals.

The statistical student t-test was used to investigate any significant difference between the MSE of the onset angle, and the subjects' scores between different games and groups. In all instances, the p-value was set at 0.05.

Finally, the relationship between the current and past angular errors is investigated using autocorrelation of the recorded error sequence. This analysis would particularly reveal if the subjects were adapting to the spatial patterns of change and hence accomplishing the goal with less angular error towards the end of the trials or they were just simply applying real-time spatial processing without any use of memory (i.e. previous errors). In the case of real-time spatial processing, there would be no correlation between the successive errors and hence the autocorrelation function would oscillate within a certain boundary throughout the length of the function.

Ethics approval was granted prior to recruiting participants by the Research Ethics Board of the University of Manitoba, Faculty of Medicine.

CHAPTER IV

RESULT AND DISCUSSION

4.1 Falling Target

4.1.1 Experiment I

In Experiment I, different falling target patterns as shown in Figure 3.7 were tested on young adult subjects. As mentioned before, in order to achieve optimal performance, the maximum-velocity (V_{max}) and the time for the movement should be correctly estimated. Therefore, the maximum velocity during each trial was captured and averaged in the bins of 8 consecutive trials for different falling target patterns. Figure 4.1 (a-e) shows the 2D representation of the V_{max} amplitude (shown by a color code) versus its occurrence time for a typical subject playing the linear incremental, piecewise linear, step, polynomial and random games, respectively. As can be seen, the V_{max} occurrence time trend throughout the 120 trials inversely follows the linear incremental, piecewise linear, step and polynomial patterns of change implying that the subjects were able to predict the pattern of change and adapt to it. On the other hand, Fig. 4e doesn't show any deterministic pattern; this was expected as the game with random falling rate was supposed to be unpredictable.

Figures 4.2 to 4.6 show the averaged V_{max} and its corresponding time trend for linear incremental, piecewise linear, step, polynomial and random games, respectively. The slope difference between the actual V_{max} and the observed one in the linear incremental game was found to be 0.01, implying that the subjects were able to estimate the target falling velocity pattern closely.

The slope difference between each individual segment (3 segments of 40 trials starting from trial number 1) of the actual V_{max} and its corresponding segment in the observed one of

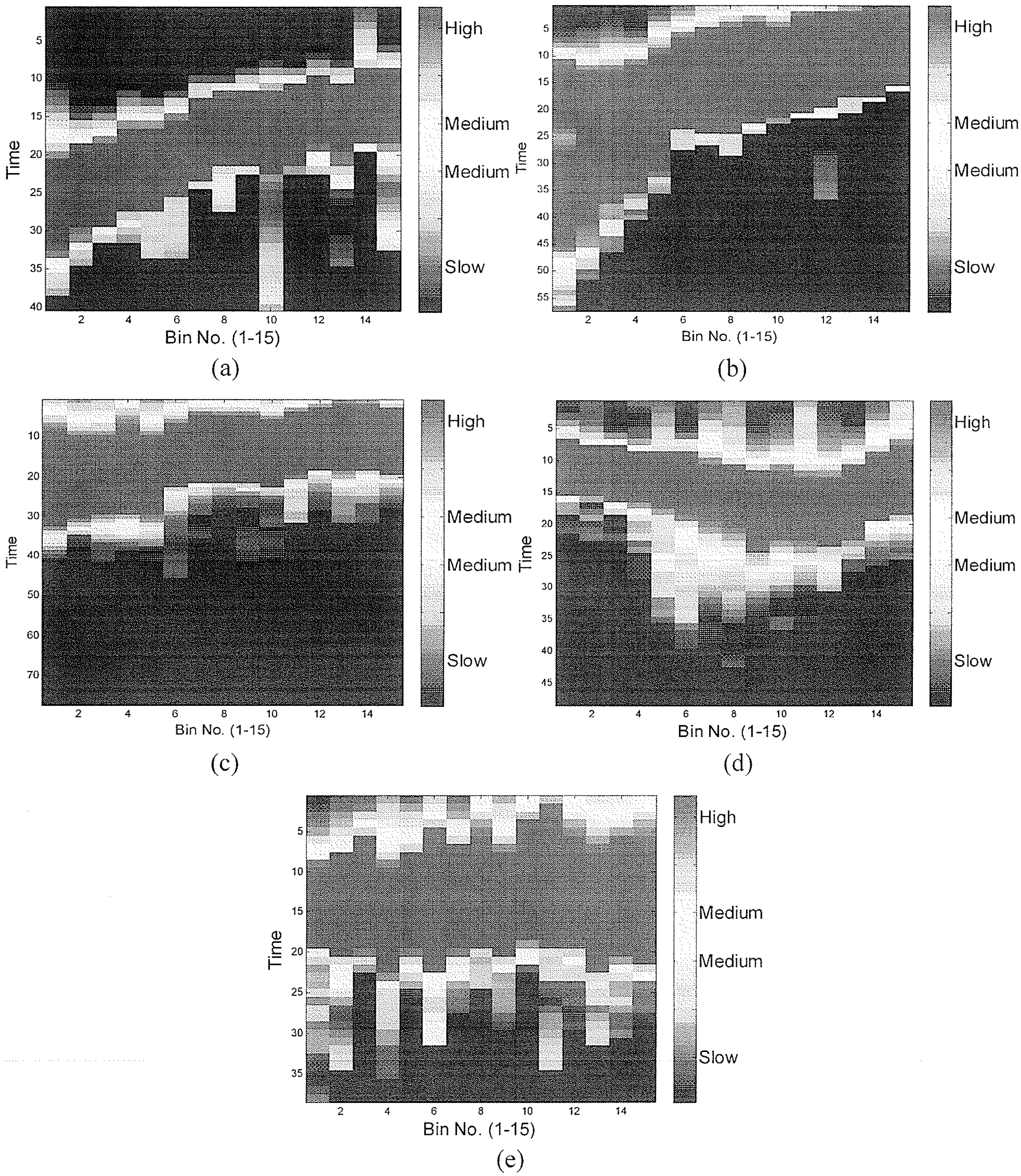


Figure 4.1: Vmax occurrence for a typical subject through a) linear incremental, b) piecewise linear, c) step, d) polynomial, and e) random falling target games, respectively.

piecewise linear game were found to be 0.021, 0.012, 0.002, respectively. As can be seen, the slope differences are small and descending toward the end of the trials and this shows an almost perfect estimation of the piecewise linear pattern of change.

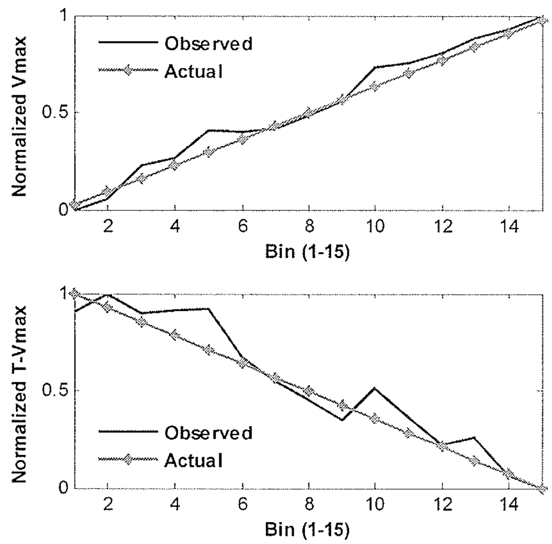


Figure 4.2: Falling Target - Young Adult, Linear Incremental Vmax and Vmax corresponding time (T- Vmax) trends, respectively.

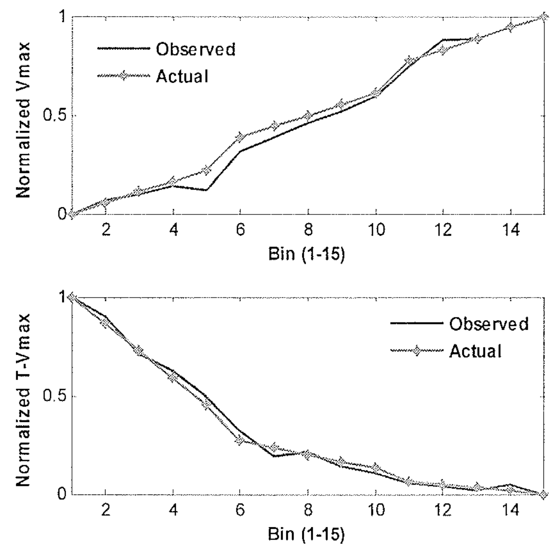


Figure 4.3: Falling Target -Young Adult, Piecewise Linear Vmax and Vmax corresponding time (T- Vmax) trends, respectively.

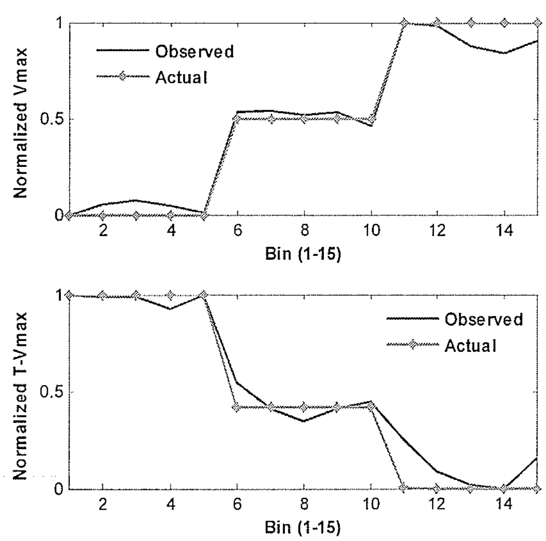


Figure 4.4: Falling Target - Young Adult, Step Vmax and Vmax corresponding time (T- Vmax) trends, respectively.

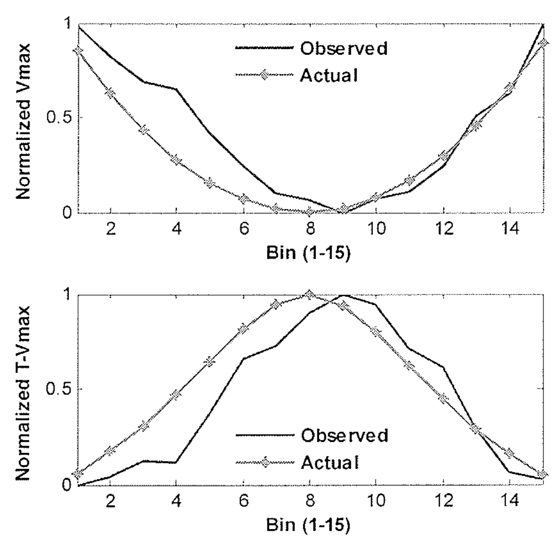


Figure 4.5: Falling Target - Young Adult, Polynomial Vmax and Vmax corresponding time (T- Vmax) trends, respectively.

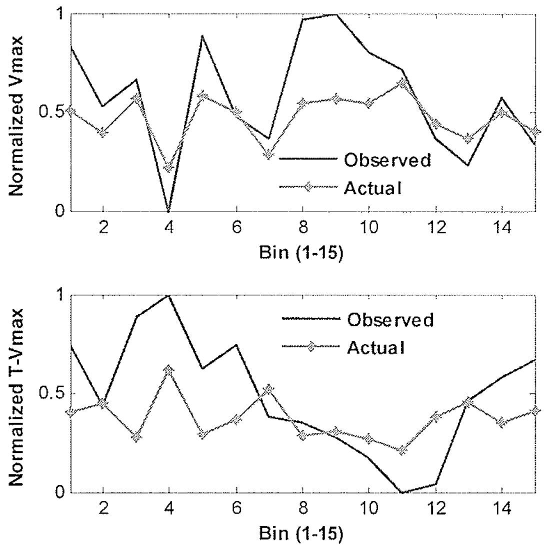


Figure 4.6: Falling Target - Young Adult, Random Vmax and Vmax corresponding time (T- Vmax) trends, respectively.

Step averaged V_{max} and its corresponding time trend are shown in Figure 4.4. The slope difference between the actual and observed V_{max} along each step for a total of 3 steps were found to be 0.001, 0.015, and 0.034, respectively. In this game, the falling rate changes only three times and remains constant during the 40 trials of each segment. Since, the range of velocity change for all the games is fixed, the first and third segments of the trials in the step game are of the minimum and maximum falling rate, respectively. The continuous maximum falling rate during the last 40 trials of the game with the step target velocity pattern, requires fast and accurate response of the subject to score green flowers; hence, the lower performance due to the subject's fatigue. This is evident in the V_{max} trend for this game and its corresponding time trend shown in Figure 4.4, as well as in the ascending slope differences toward the end of the trials. Overall, these slope difference values were relatively small that imply subjects' correct estimation of the pattern of change in the falling rate.

On the other hand, the observed V_{max} trend in the game with polynomial pattern of target falling rate and its corresponding time trend are left skewed resulting in an asymmetric shape as shown in Figure 4.5; this observation is consistent with that in Figure 4.1.d. It was observed that the minimum of the averaged V_{max} amplitude and the maximum of its corresponding time occur in the bin 9, which is to the right of the bin containing these extrema points in the corresponding actual V_{max} trends (bin 8). On the other hand, the calculated values for the ROC of the first and second sides of the parabolas in Figure 4.5 (a.b) are 0.11, 0.17 and 0.13, 0.16, respectively. As can be seen, the ROC values are relatively higher for the second side of the averaged V_{max} amplitude and time trends. This is due to the higher variations observed in the trend of subjects' hand velocity happening in the second half of the trials (i.e. trails 60–120) to follow the target's velocity. This result is congruent with the subjective perception of the participants in the experiments about the pattern of target's velocity. After the experiments, they were asked to draw their perceived pattern of change, where all of them drew something close to a "✓" for the polynomial pattern of change. In fact, their perceived pattern of change for the polynomial game was close to a left-skewed parabola with a longer right tail. Furthermore, the time perception error for the polynomial game was found to be equal to 0.0540 which corresponds to the 5.4% difference of the maximum value.

The calculated MSE values for all the games, averaged among the subjects ($\mu \pm SE$) are shown in Table 4.1. As can be seen, the errors are significantly higher for the random game than the other games, implying poor estimation of the target's velocity for random pattern of change, as expected. Table 4.2 shows the probabilities that the null hypothesis (i.e. performance difference is due to the chance) should be accepted between each pair of data groups, and whether these probabilities are significant with 95% confidence interval. The results of Tables

4.1 and 4.2 along with those depicted in Figure 4.6 show that no learning occurred in the case of random game.

TABLE 4.1
MSE (M ± SE) OF VMAX AND ITS CORRESPONDING TIME TRENDS IN DIFFERENT GAMES AVERAGED AMONG THE SUBJECTS.

Game	MSE Vmax	MSE Time
Linear Incremental	0.02±0.01	0.05±0.01
Piecewise Linear	0.02±0.00	0.02±0.01
Step	0.03±0.03	0.04±0.03
Polynomial	0.03±0.00	0.06±0.01
Random	0.07±0.05	0.09±0.06

TABLE 4.2
THE *P*-VALUES OBTAINED BY STUDENT *T*-TEST BETWEEN THE MSE VALUES AND THE GREEN SCORES OF DIFFERENT GAMES. THE * INDICATES THE SIGNIFICANCE OF THE TEST.

	MSE		Score
Test	Vmax	Vmax time	Green
Linear Inc. – Piecewise	0.89	0.08	0.16
Linear Inc. – Step	0.51	0.80	0.40
Linear Inc. – Polynomial	0.34	0.49	0.18
Linear Inc. – Random	0.00*	0.01 *	0.00 *
Piecewise – Step	0.14	0.21	0.09
Piecewise – Polynomial	0.47	0.01 *	0.02 *
Piecewise - Random	0.00 *	0.00 *	0.00 *
Step – Polynomial	0.80	0.25	0.63
Step – Random	0.01 *	0.01 *	0.01 *
Polynomial-Random	0.01 *	0.03 *	0.01 *

The Green scores averaged among the subjects for the linear incremental, piecewise linear, step, polynomial and random games were recorded as 94.5, 101.5, 90, 84.5, and 62.2, respectively; these show degrading in performance as the pattern of change becomes more complex in terms of linearity.

The subject's performance was also studied through the use of correlation analysis. This analysis would demonstrate the role of memory in learning the error in consecutive trials as well as the adaptation to the different patterns of change in the falling target game. Figure 4.7 (a-e) shows the autocorrelation results along with SE for the subjects' V_{max} trends in the falling target game. As can be seen, the V_{max} error exhibits high correlation in the case of linear incremental falling target game at the beginning with a descending trend toward the end of the trials which shows the learning and adapting to the pattern of change using previously experienced errors. Moreover, toward the end of the trials, higher required speed caused higher errors in terms of variability and amplitude which in its turn resulted in lower amount of correlation between the successive errors (Figure 4.7.a).

In the case of polynomial pattern of change, the correlation function is nearly symmetrical with higher correlation values toward the ends of the pattern which decreases approaching the middle of the trials from both sides. This shape of correlation function can be due to the minimum amount of noticeable change by humans. As a result, in the middle trials, the amount of change between the consecutive trials is not noticeable; therefore, this resulted in lower amount of correlation between the consecutive errors, which implies the no learning state during these trials. On the contrary, the amount of inter-trial changes toward the two ends of the polynomial is relatively higher and hence more noticeable. This resulted in higher amount of correlation between the consecutive errors during these trials which on its turn shows subjects' adaptation to the pattern of change using the previously experienced errors (Figure 4.7.d). The correlation analysis for the movement error in the random falling target game does not show any relation between the errors in successive trials of this game as expected.

Piecewise linear movement error correlation shows higher error correlation toward the end of each sequence in the function (i.e. 1-40, 41-80, 81-120) as well as a decaying pattern at the transition between the function sequences. The high correlation is due to the subject's adaptation to the constant speed change from trial to trial along a portion of the piecewise linear function, which falls down at the transitions to a new portion and rises again toward the end of the portion. On the other hand, the piecewise-linear movement-error correlation shows a relatively higher trend along the third sequence and toward the end of the trials; this can be due to the subjects' inability to closely follow the high falling rate of the target.

The movement-error correlation in the step falling target game clearly shows drops at trails 40, and 80 where a transition to new steps occurs. In this case, the high amount of correlation between successive errors toward the end of each step implies subjects' adaption to the constant pattern of falling rate within that step. On the other hand, the drops in correlation values show the subjects' inabilities to accurately follow the high and sudden amount of change in transition to every new step.

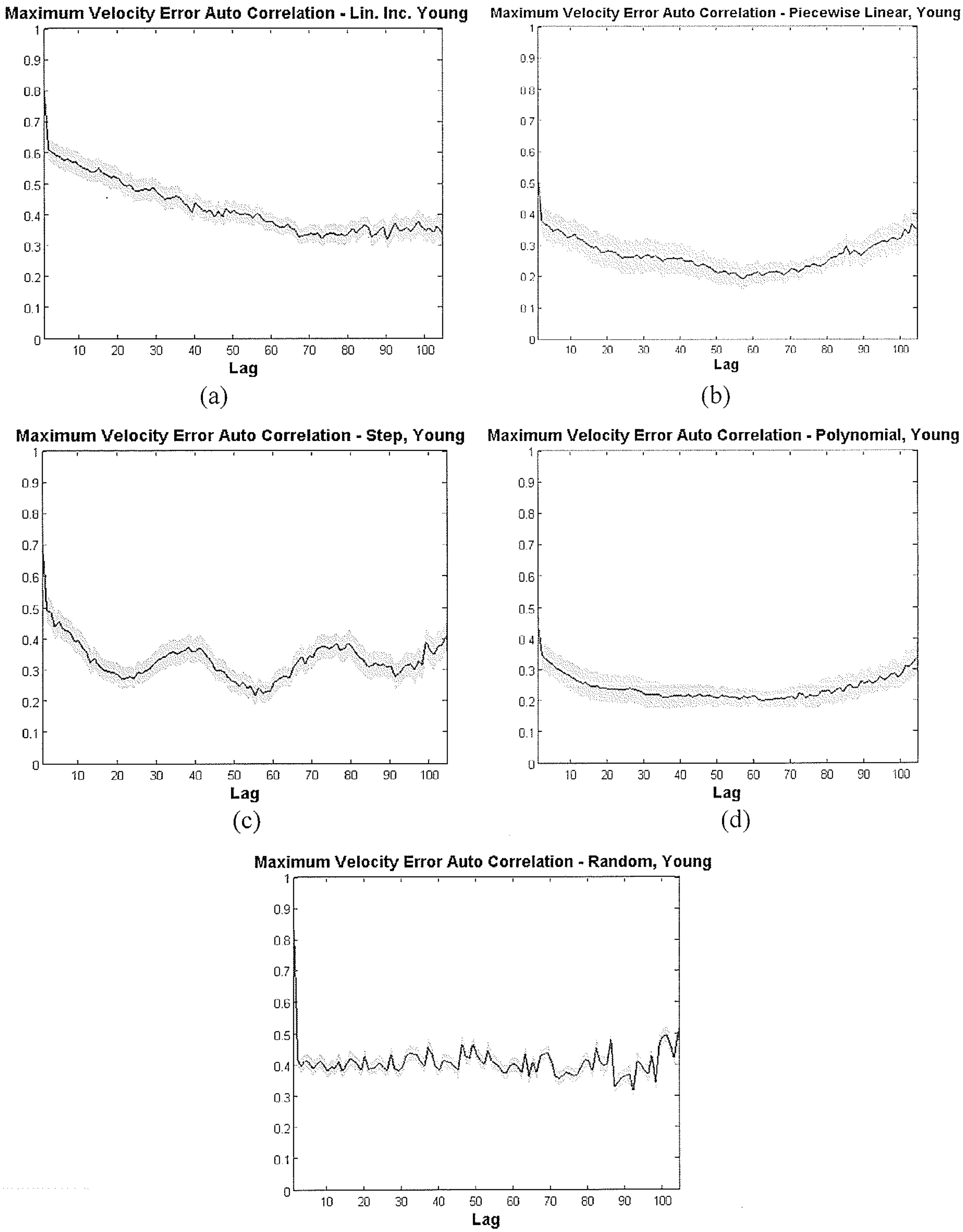


Figure 4.7: Falling target movement error autocorrelation for young adult subjects, a) linear incremental, b) piecewise linear, c) step, d) polynomial, and e) random games, respectively. SE is presented by shadow.

4.1.2 Experiment II

In this experiment the effect of aging on adapting to the linear incremental falling target pattern was tested on elderly and children groups and their outcomes were compared with each other and with the corresponding performance from young adult group. Figure 4.8 (a-b) illustrates the average V_{max} and its corresponding time trend for the linear incremental game played by elderly and children subjects, respectively. The averaged green score and the slope difference between the observed V_{max} trend and the actual one are found to be 65.7, 0.056 and 54, 0.062 for elderly and children subjects, respectively.

Table 4.3 shows the MSE values calculated for the V_{max} and its corresponding time trend in the linear incremental game played by young, elderly and children subjects. The results of student *t*-test to find any significant difference between the MSE of the V_{max} amplitude, and the subjects' Green scores, are also brought in Table 4.4.

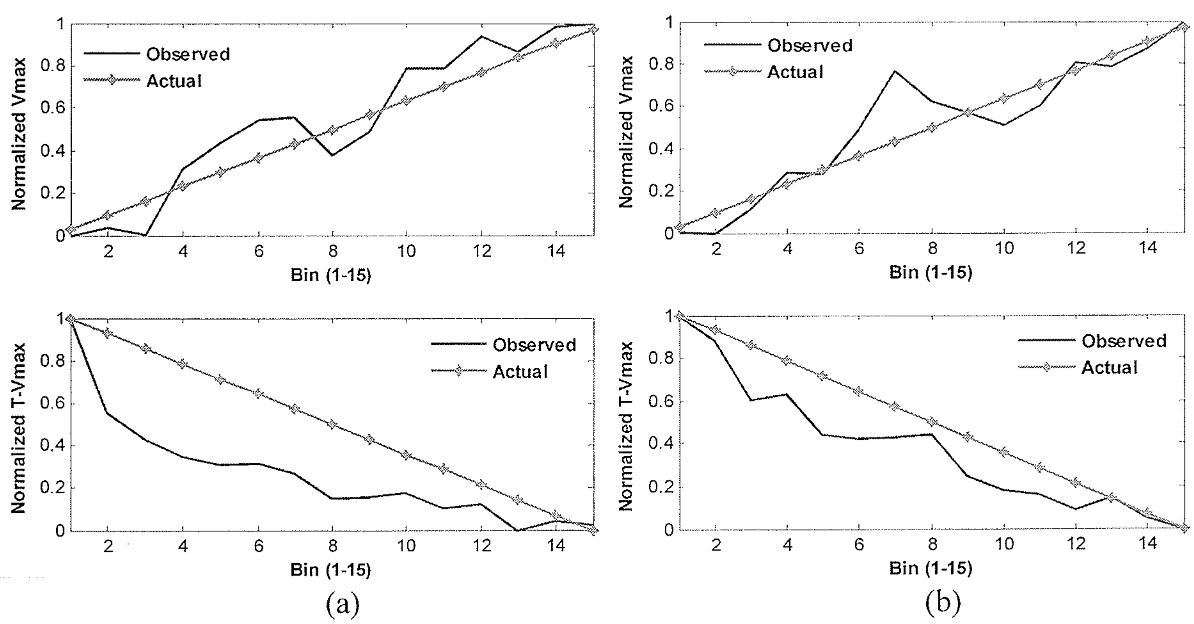


Figure 4.8: Falling Target Linear Incremental Vmax and Vmax-corresponding-time (T- Vmax) trends for a) Elderly, b) Children subjects.

TABLE 0.3
MSE (M ± SE) OF VMAX AND ITS CORRESPONDING TIME TRENDS FOR DIFFERENT AGE GROUPS, LINEAR INCREMENTAL GAME.

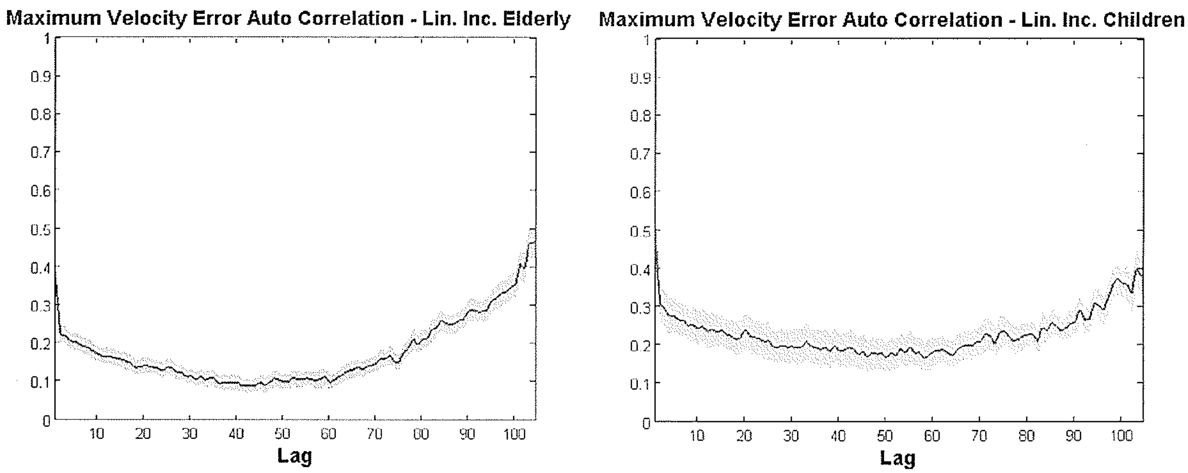
MSE	Velocity	Time
Young	0.02 ± 0.01	0.05 ± 0.01
Elderly	0.08 ± 0.002	0.09 ± 0.01
Children	0.064 ± 0.004	0.06 ± 0.01

TABLE 04.4
THE *P*-VALUES OBTAINED BY STUDENT *T*-TEST BETWEEN THE MSE VALUES AND GREEN SCORES OF THE LINEAR INCREMENTAL GAME AMONG DIFFERENT SUBJECT GROUPS.

	MSE	Green Score
Young - Elderly	0.042*	0.0007*
Young - Children	0.05*	0.0006*
Elderly - Children	0.36	0.33

The correlation analysis for the movement error in the elderly and children subjects is shown in Figure 4.9 (a-b). These plots show a decreasing trend similar to the corresponding young adult error correlation; however, the error correlation for elderly and children subjects goes high at the end trials, which might be due to the learning process through remembering the previously experienced errors or it is just due to the subjects' inability to move at the required high velocity in these trials.

Considering the results brought above, it can be clearly seen that elderly and children subjects performed poorer in learning the linear incremental temporal pattern of change compared with young adult subject (Figure 4.2).



(a) (b)

Figure 4.9: Falling target movement error autocorrelation for a) Elderly, b) children subjects in the linear incremental game. SE is presented by shadow.

4.1.3 General discussion on the results of falling target game

In the falling target game, the only instruction given to the subjects was to catch the flower when its color turns to Green; there was no specific instruction on how the trajectory of the arm movement should look like. This resulted in different strategies used by the subjects in playing this goal-oriented game. The following strategies were observed in the subjects' performance during the slow trials:

- Curvy trajectories (Figure 4.10.a),
- Piecewise linear movements, in a way that the entire trajectory consisted of a many sub-trajectories each of which has a bell-shaped speed profile (Figure 4.10.b),
- Linear but delayed arm movement, in a way trajectory starts with a delay after the start of the trial (Figure 4.10.c).

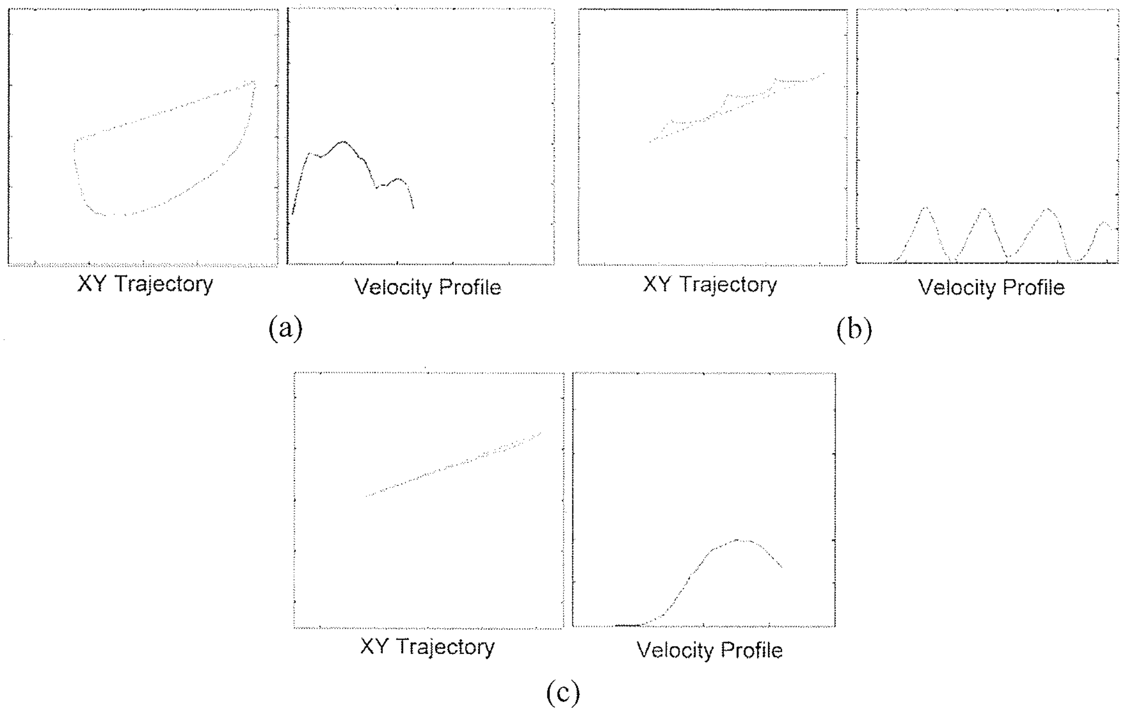


Figure 4.101: Observed strategies in the subject's performance during slow trials in the falling target game; a) Curvy movement, b) Piecewise linear movement, c) Linear and delayed movement.

Definition of a "slow trial" is a matter of subject's perception and motor control abilities. However, usually a trial with a velocity less than the half of the maximum falling target velocity is considered as a slow trail. As the falling rate increased, the subjects' hand trajectories tend to be closer to the straight line connecting the starting location to the place where the flower was clicked (in the successful trials, this place falls in the margin for Green score). Due to the diversity of strategies applied and different trajectory shapes, the maximum displacement and the onset angle could not be used as measures of performance.

The results of this study congruently prove our hypothesis that a novice subject's brain can predict a linear pattern much better than complex ones and also perform reasonably well as long as the function (i.e. a polynomial) can be estimated by a piece-wise linear function. On the other hand, it is seen that elderly and children subjects have similar performance which is poorer than the young adult group in adapting to the temporal pattern of change in falling target rate.

In addition in the case of falling target game, the results show some commonalities in the subjects' performance encountering different patterns of change such as the skewness of the actual (predicted) performance to the right in the case of polynomial games. It is reported that the patients with deficiencies in cerebellum and fronto-striatal circuits have problem in temporal perception that is considered as an early symptom of dementia [64], [30]. Therefore, the temporal perception error parameter of this study may be used as an objective test for early diagnosis of dementia.

As mentioned before, the target starts falling on a vertical path from top right, down to the bottom right of the screen on a straight path. One may argue that subjects played better in the linear incremental game because they are used to seeing objects falling down due to the gravity. If that argument would be correct, with the same logic one may argue subjects would perform better in polynomial game when the target moves horizontally. To test the effect of this vertical falling path on human perception and whether it helps learning the falling velocity patterns, a horizontal version of the falling target game was also designed and tested on 10 new subjects. In this game, the flower trajectory starts at the top left side and ends at the top right side of the screen moving on a horizontal path with the polynomial velocity pattern, same as the vertical version of the polynomial game. The subjects' performance was recorded in the form of XY coordinates and velocity. The results show similar performance as those observed in the vertical polynomial game characterized by the left skewed performance parabolas with the extrema points in the V_{max} and its corresponding time trend located in the bins no. 10 and 9, respectively (Figure 4.11).

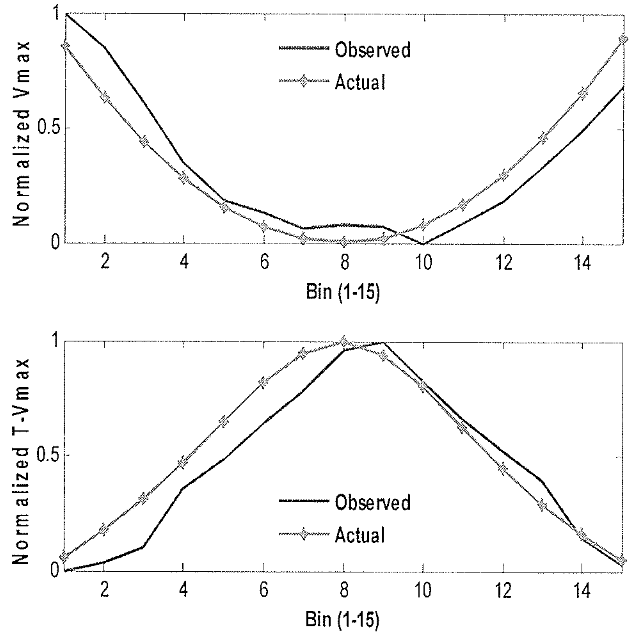


Figure 4.11: Falling Target - Horizetal Polynomial Vmax and Vmax corresponding time (T- Vmax) trends, respectively.

Moreover, the MSE values for the V_{max} and its corresponding time trends for the horizontal polynomial game were found to be 0.04±0.01 and 0.06±0.01, respectively, which are very similar to those reported in Table. I. Therefore, the direction of moving target (vertical or horizontal) does not change the hypothesis that our brain adapts to linear patterns of change much faster and better than nonlinear patterns.

4.2 Orientation

4.2.1 Experiment I

The averaged thinking time and onset angular error for elderly and children subjects, played the fixed final destinations orientation game are shown in Figures 4.12 and 4.13, respectively. Table 4.5 gives the movement MSE and scores in this game.

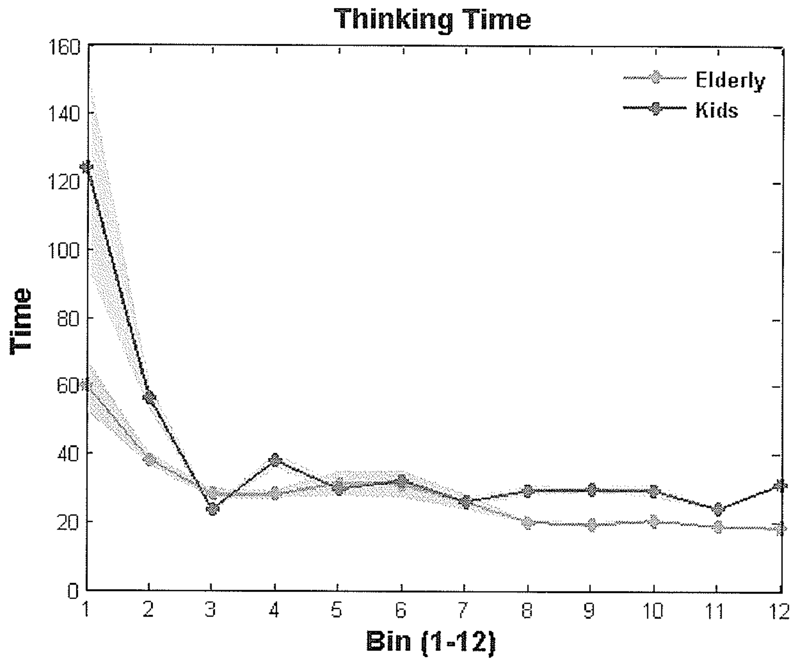


Figure 4.12: Fixed destination orientation game - Averaged thinking time (The time subjects spent thinking prior to the start of the movement) trends for elderly and children subjects, SE is presented by shadow.

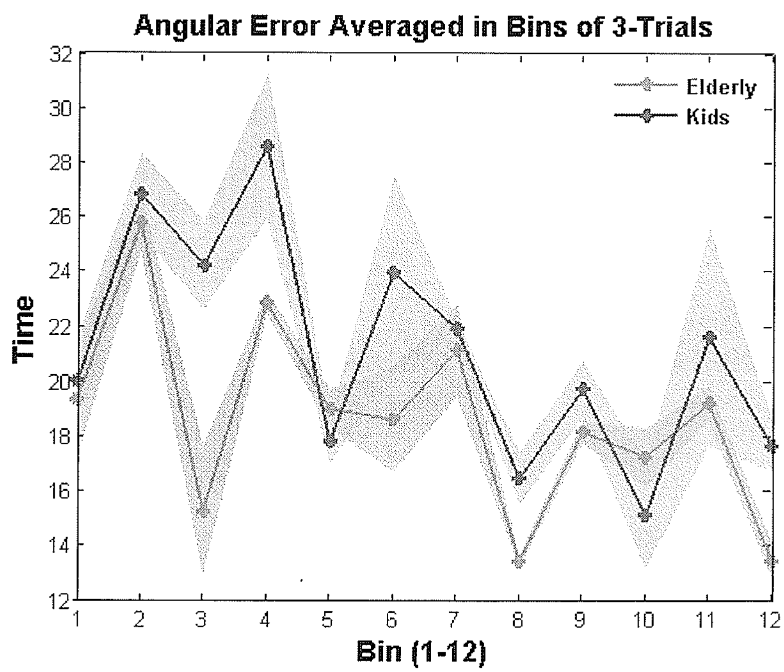


Figure 4.13: Fixed destination orientation game - Averaged angular error (the difference between observed onset angle and the actual one) trends for elderly and children subjects. SE is presented by shadow.

TABLE 4.5
MSE ± SE OF ONSET ANGLE TREND AND SUBJECT'S SCORES IN THE FIXED DESTINATIONS ORIENTATION GAME.

	MSE	Score
Elderly	0.027 ± 0.01	13.5
Children	0.038 ± 0.02	13.7

The thinking time and angular error trends show similar behavior oscillating within the same range for the both groups. On the other hand, the *p*-values found from student *t*-test run between the MSE and scores are 0.68 and 0.79, respectively. As can be seen, elderly and children subjects demonstrate a close performance in achieving the goal of the spatial task in the fixed destination orientation game.

4.2.2 Experiment II

Figures 4.14, 4.15 and 4.16 show the averaged thinking time (in clock-counts), the general angular error and the directional angular error trends along with the standard error (SE) (shown as a shaded area) in constant and random orientation games by young adult subjects, respectively. Both thinking time trends are descending toward the end of the trials with lower amplitude and variability in the case of constant games. Similarly, Figure 4.15 and 4.16 show a generally lower and less variable general and directional angular error trends for the case of clockwise game comparing to the random game played by the young adult subjects.

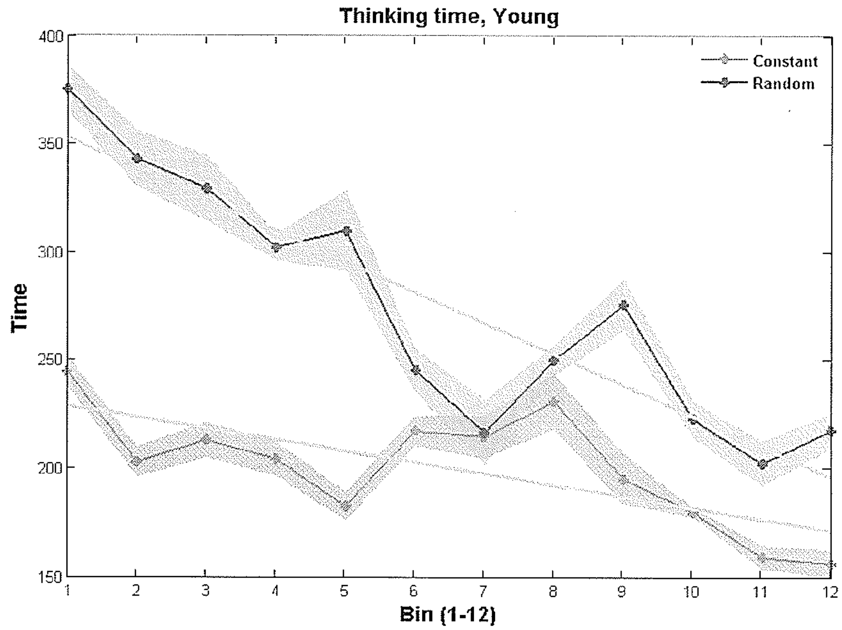


Figure 4.142: Rotating destination orientation game - Averaged thinking time (The time subjects spent thinking prior the start of the movement) trends for young adult subjects in constant and random rotating patterns. SE is presented by shadow.

Table 4.6 carries the MSE values calculated for the onset angle in the constant and random games played by young adult subjects. As can be seen, the errors are relatively higher for the random game comparing with those of the constant games, implying poorer performance in estimating the target's direction with random spatial pattern of change.

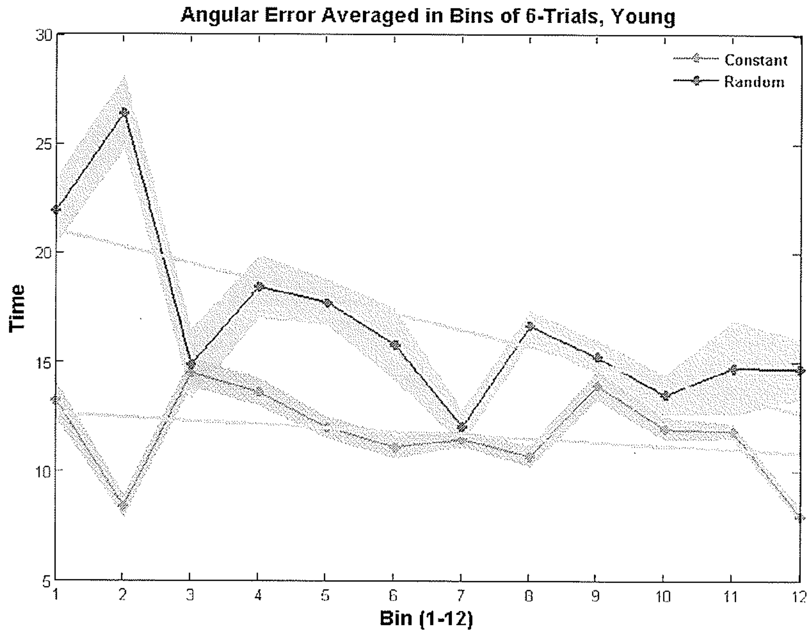


Figure 4.153: Rotating orientation game - Averaged general angular error (the difference between observed onset angle and the actual one) for young adult subjects in constant and random rotating patterns. SE is presented by shadow.

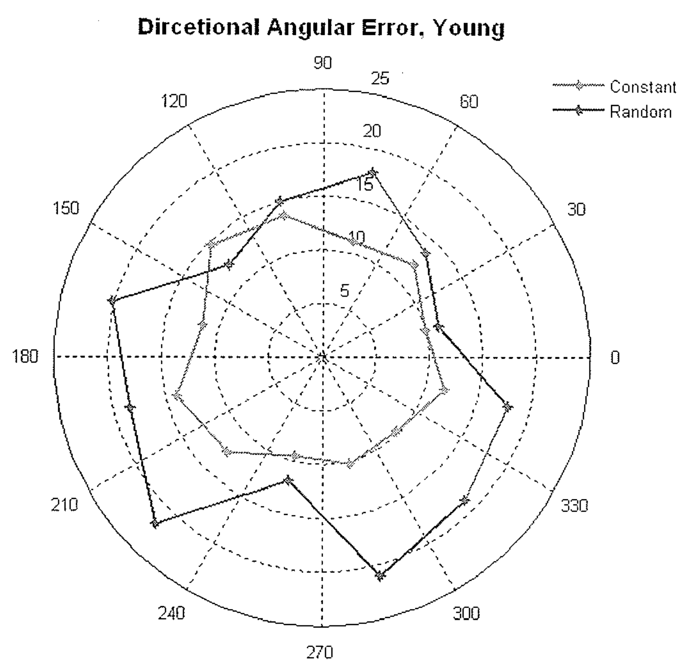


Figure4.16: Rotating orientation game - Averaged directional angular error for young adult subjects in constant and random rotating patterns.

TABLE 4.2
MSE AND SE OF ONSET ANGLE TRENDS IN THE CONSTANT AND RANDOM ORIENTATION GAMES.

Game	MSE
Clockwise	0.007 ± 0.01
Random	0.026 ± 0.01

The success rate was considered as another measure of performance. The success rates were averaged over the subjects of each group in a specific game. The averaged success rates for the constant and random games played by the young adult subjects were found to be 40.3 and 31.2, respectively, which show degrading in performance as the spatial pattern of change becomes more complex.

The p-values obtained by student t-test among the MSE and scores of the young adult subjects who played the constant and random orientation games are 0.03 and 0.005, respectively. As can be seen, for both MSE and scores, the p-values and hence the probabilities for accepting the null hypothesis (i.e. performance difference is due to the chance) fall below the confidence interval which is chosen to be 95%.

4.2.3 Experiment III

Figure 4.17 shows the averaged thinking time trends in the constant orientation game observed in young, elderly, and children groups. As can be seen, the thinking time trend looks similar for all the participating groups in the constant orientation game showing a decaying pattern toward the end of trials.

The averaged general and directional angular error trends for the constant orientation game played by young, elderly and children groups are illustrated in Figures 4.18 and 4.19, respectively. The averaged general angular error trend for the case of young adult subjects is noticeably lower and separated from the elderly and children trends which are seen to occur in the same margin. On the other hand, Fig. 4.19 shows similar trends for elderly and children groups in terms of amplitude and variation with the young adult group trend clearly demonstrating less directional error comparing to two other groups. These results confirm the hypotheses 3 and 4 in this population.

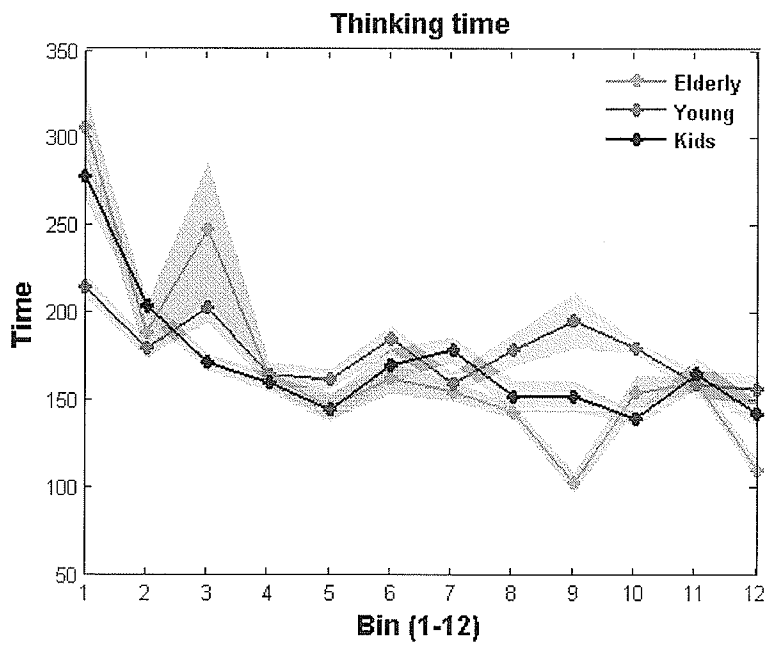


Figure 4.17: Constant rotating orientation game - Averaged thinking time (The time subjects spent thinking prior the start of the movement) trends for elderly, young and children groups. SE is presented by shadow.

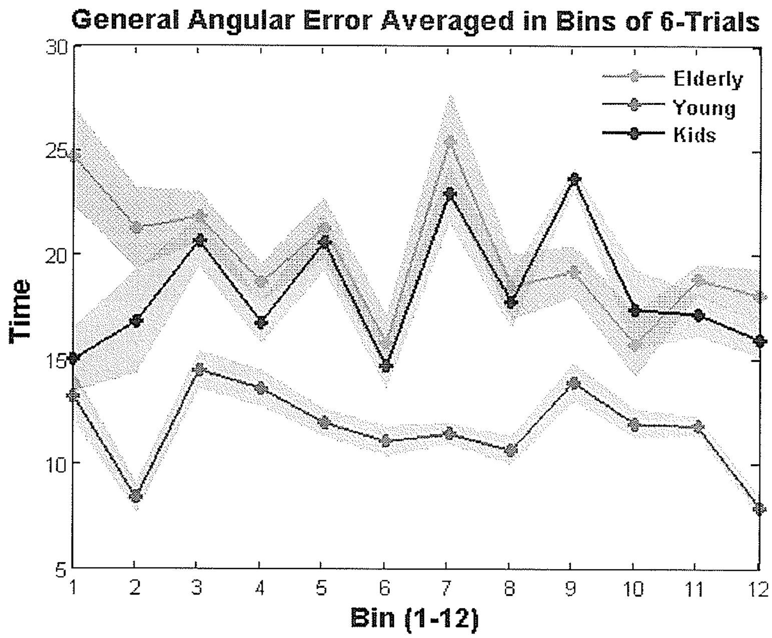


Figure 4.18: Constant rotating orientation game - Averaged general angular error (the difference between observed onset angle and the actual one) trends for elderly, young, and children groups, SE is presented by shadow.

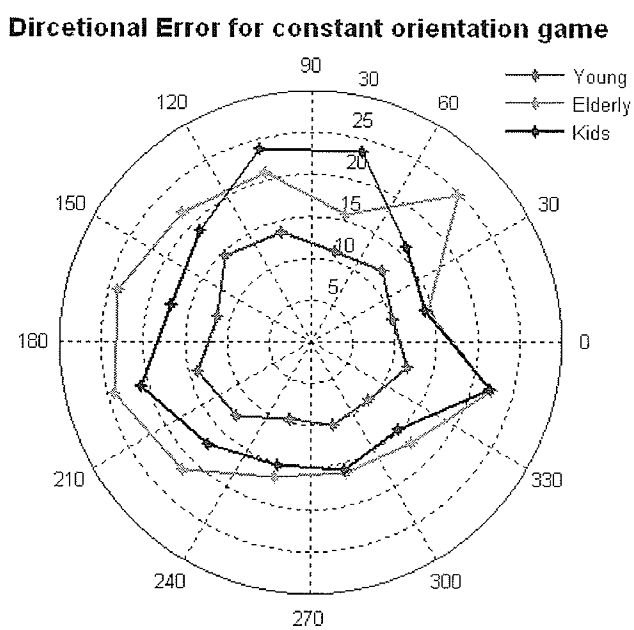


Figure 4.19: Constant rotating orientation game - Averaged directional angular error trends for elderly, young and children groups.

MSE of the onset angle observed in the constant orientation game played by young, elderly and children subjects are shown in Table 4.7. As can be seen, the table reads relatively lower MSE values for the case of young adult subjects compared with other two groups.

TABLE 4.3
MSE AND SE OF ONSET ANGLE TRENDS IN THE CONSTANT ORIENTATION GAME FOR ALL THE GROUPS.

Game	MSE
Young	0.007 ± 0.01
Elderly	0.033 ± 0.01
Children	0.023 ± 0.01

Table 4.8 carries the results of the student *t*-test ran among each pair of the subject groups for the MSE and scores values in the constant orientation game. The probability for accepting the null hypothesis between the young adult group and either groups of elderly and children is lower than the set *p*-value of 0.05, while the high *p*-values for the pair of elderly and children groups confirm similarities in their performance.

TABLE 4.4
THE *P*-VALUES OBTAINED BY STUDENT *T*-TEST BETWEEN THE MSE VALUES AND SCORES OF THE CONSTANT ORIENTATION GAME BETWEEN DIFFERENT GROUPS. THE * INDICATES THE SIGNIFICANCE OF THE TEST.

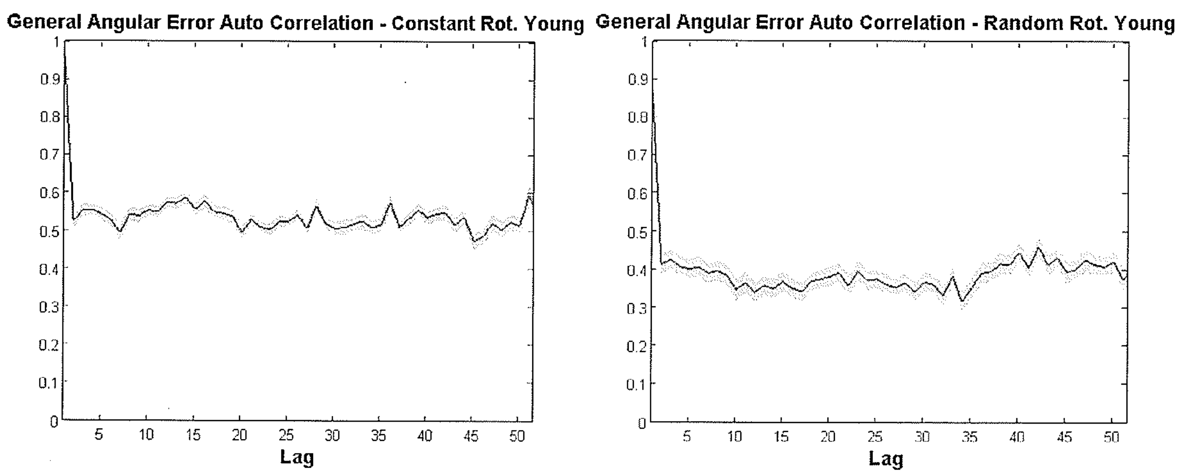
	MSE	Score
Young – Elderly	0.011*	0.0026*
Young – Children	0.010*	0.0040*
Elderly – Children	0.30	0.31

Furthermore, the averaged success rate for the constant orientation games played by young, elderly, and children groups were found to be 40.3, 24.45, 28.3, receptively.

4.2.4 Orientation Correlation Analysis

The correlation analysis was done for the successive angular errors in different orientation games for all the groups. Autocorrelation results for the angular error in the orientation games are shown in Figure 4.20.

As can be seen, these correlation functions do not show any specific learning pattern throughout the trials of the orientation games. Considering these correlation analysis results, it can be concluded that the spatial processing involved in playing this game is of the real-time spatial processing type with the least involvement of memory. This might be due to the conditional appearance of the special cues in every trial of these games as described in the methodology (section 3.1.2.2) section, which results in remapping of the spatial cues relative to the starting location in every new trail.



(a) (b)

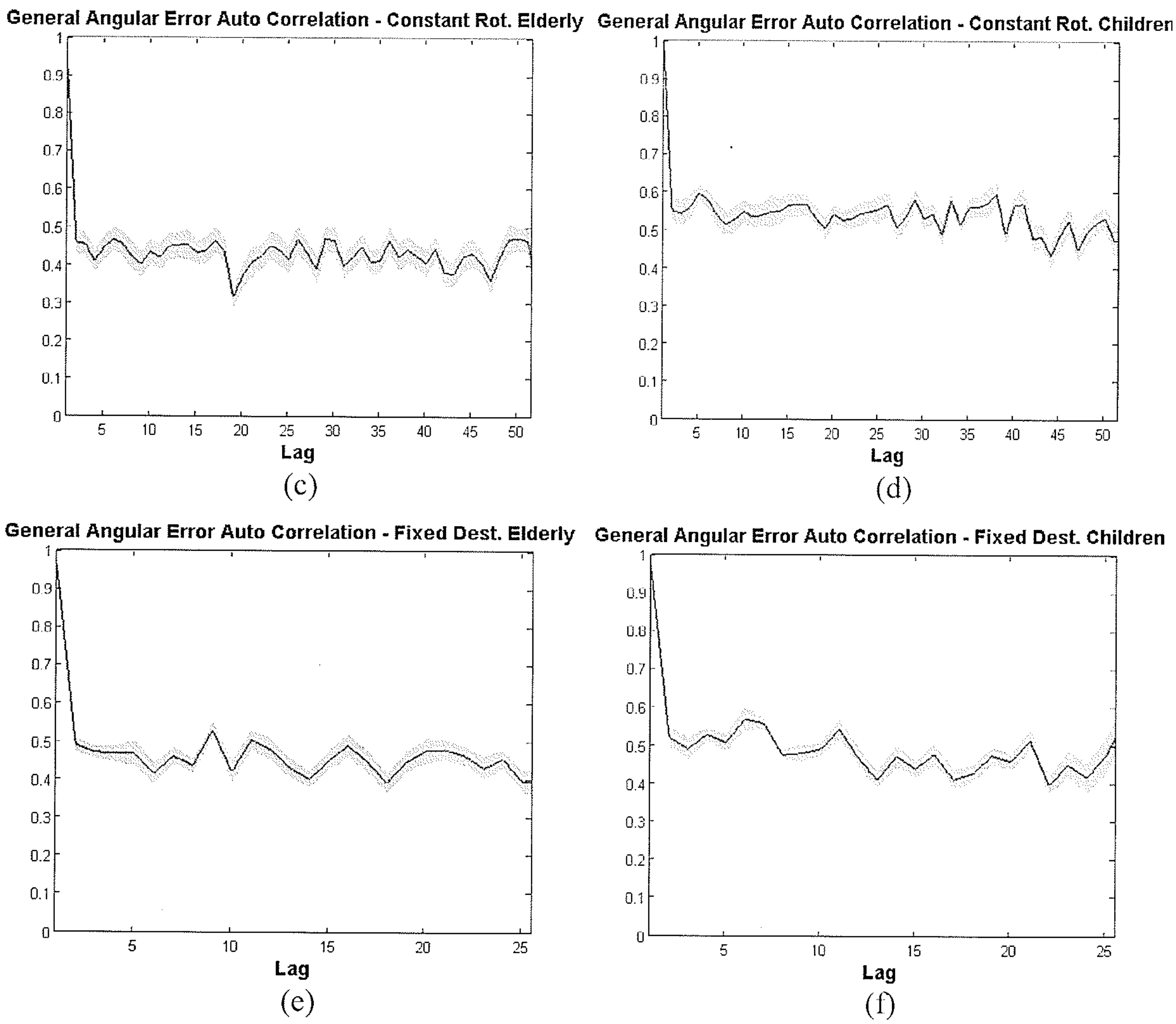


Figure 4.20: Orientation game movement error autocorrelation for a) constant rotating orientation – young adult, b) random rotating orientation– young adult, c) constant rotating orientation – elderly, d) constant rotating orientation – children, e) fixed orientation – elderly, f) fixed orientation – children. SE is presented by shadow.

4.2.5 General discussion on the result of orientation game

Young adult performance in constant and random rotating orientation games confirms the hypothesis (2.6.1). Moreover, the comparison between the young, elderly and children subjects' performance played the constant rotating orientation game verifies the hypotheses (2.6.3) and (2.6.4). This result is congruent with the findings in [54], [65], [67], [68], [69], and [69][65] that suggest declining in spatial processing abilities with age.

In [67], the effect of age on spatial processing ability was tested between different age groups through observing their performance in memorizing a route using a 2D map and then finding it in 3D environment. It was found that elderly participants accomplished the goal of spatial processing tasks slower and with higher amount of errors compared to their younger counterparts. In another study, it is shown that elderly participants tend to be slower than young adults in acquiring spatial cues to find their way in a novel environment (supermarket) [70].

There are many attempts to classify different stages of human development in a variety of aspects such as mental, moral, physical, social, emotional, etc. The cognitive or mental development is the human developmental aspect, of interest to us due to the nature of tasks involved in our experiments, which require enhanced learning, remembering, and problem solving skills.

Jean Piaget's theory of mental or cognitive development is the oldest theory describing the cognitive development in humans. According to Piaget, the period of 7 to 12 years is when the active and rational thinking in child starts to develop. This stage is where the egocentric thoughts of self diminish and the child starts to find a relation between self and other objects in his/her surrounding environment [62]. Piaget work suggests that, age 12 is the maturity age for the spatial abilities in humans [73]. According to [74], the development of spatial abilities in children occurs through three stages of preoperational stage, concrete operational stage, and formal operational stage. The first stage, preoperational stage, is where the spatial judgment is egocentric, meaning that the position of the objects in the child's surroundings is described with respect to the "self". The second stage is referred to as concrete operation stage. In this stage, children start to develop a cognitive map and a better topological understanding of their surrounding environment in terms of proximity, order and positional relationship. The last stage is the formal operating stage in which children start using different frames of reference and understanding Euclidean spatial relations which helps them to optimize the spatial tasks. On the contrary, Huttenlocher and Newcombe suggest that children complete their mental development of spatial abilities by the age of 10 [75].

In addition, Erikson's theory of psychosocial development suggest the age range of 6 to 12 is where children become more aware of themselves and work hard on accomplishing goals of complex tasks [76]. Children start to grow a more logical understanding of the concept of time and space during the priod of 7 to 12 years old [77]. Furthermore, this stage is when children pass through the transition from home to school where they start actively acquiring skills.

Taking these developmental theories into account, one can elaborate on the children's performance compared to that of young adults that it might be due to the developing and not yet completed underlying neural spatial processing mechanism.

CHAPTER V

CONCLUSION AND FUTURE WORK

5.1 Summary and Conclusion

"The nature of temporal and spatial processing in the human brain; how these two critical dimensions, time and space, are perceived, processed and identified qualitatively?" is the central question confronted in this work and its possible answers were investigated. Furthermore, the age dependency of these capabilities in human subjects is another issue studied here.

A set of psychophysical experiment were used for this purpose consisting of interactive computer games played by a robotic arm, manipulandum. The games are falling target and orientation game for testing temporal and spatial processing capabilities, respectively. We hypothesized that the human brain performance in adapting to a less complex spatial or temporal patterns of change is significantly better than a complex one (Hypothesis 1). On the other hand, we tested the hypothesis that the brain is more efficient in predicting the temporal patterns which can be approximated by linear or piece-wise linear functions (i.e. a polynomial is approximated by two linear lines in its two tails), (Hypothesis 2). In this work, we also elaborated on the hypothesis that elderly and children subjects perform similarly in temporal or spatial processing tasks (Hypothesis 3) with young adult subjects outperforming the other two groups in such tasks (Hypothesis 4). The results of the falling target experiment brought in the chapter IV of this thesis confirm these hypotheses.

According to the results of analysis done on orientation game data, it can be concluded that elderly and children subjects perform similarly in spatial orientation tasks which is poorer compared with young adult subjects (Hypotheses 3 & 4). On the other hand, the results show that young adult subjects perform much better in predicting a constant spatial pattern of change compared with the complex ones (Hypothesis 1).

Finally, the results of this study show the applicability of the developed interactive games in assessing the effect of age on human spatial abilities. Such psychophysical experiments can be useful in detecting deficiencies in temporal and spatial processing; hence in identifying the neurological disorder causing these spatiotemporal impairments, in their early stages of development. Furthermore, the results of such study can be used in developing rehabilitative methods and devices that can restore brain spatiotemporal abilities.

5.2 Future Work and Recommendation

First, more subjects are needed to participate in these experiments, specially from the elderly and children groups. The next in this work would be to test these games on subjects with neurological disorders and brain diseases. It would be of interest to see their performance in achieving the goal of the temporal and spatial processing tasks in these experiments and hence compare it with other groups already participated in this study.

For instance, as for Alzheimer disease (AD), one of the most common degenerative brain diseases with no known cure, by the time an elderly individual is diagnosed with AD by current techniques, there is already irreversible brain damage. Early diagnosis is also difficult as many AD victims have similar symptoms and brain-scans as those of a normal aging brain. However, with the aid of experiments using robotic rehabilitative devices, such as manipulandum, there might be some hope for the objective early diagnosis as well as the rehabilitation or slowing disease progression.

As mentioned before, a successful accomplishment of any motor task is a factor of accuracy in spatiotemporal information processing in our brain. It has been speculated that the patients with AD lose their sense of orientation and time in very early stages of the development of the brain disease [30]. Therefore, one of the ultimate goals of this study is to investigate the application of such rehabilitative devices and computer games to objectively measure the changes in spatiotemporal perception for monitoring and assessment of AD progression.

On the other hand, it would be of interest to investigate the dependency of the human brain temporal and spatial abilities to different human factors (e.g. gender, weight, educational background).

In the rotating orientation game, adding visual and auditory cues to the game in a way that a specific visual or auditory cue is associated with a final destination, will turn the game to an allocentric orientation test. The subject in this case has to locate the final destination according to the cues shown in each trial, considering how the target is spatially related to these cues.

To investigate the skewness of the performance parabolas in the Polynomial falling target game, different temporal patterns of change such as multiple consecutive polynomial falling target patterns with shorter domain of 40 trials can be tested. The other idea is to have the falling rate in falling flower game, velocity dependant, meaning that it changes proportionally with the speed of hand movement. This way a complex pattern of falling rate is created.

Recording EEG signals from the participants during the experiment is another direction for this study to move along. Here, the neural activity in different brain region can be monitored and therefore specific neuroanatomical mechanism underlying the temporal and spatial processing tasks in these experiments can be identified and compared between different groups of subjects. This can help in developing treatments for the neurological disorders which particularly result in impairment in temporal or spatial abilities of human brain.

In this study, both of these games (falling target and orientation) were tested under null field where there was no force opposing subject's effort to finish the assigned task. Testing subjects' performance under force field can be a direction for the future work. In the case of force field, a viscous force perpendicular to the subject movement is applied to the Manipulandum end-effecter (human hand) and as a result, subject hand trajectory will be distracted during the early trials and eventually will start to adapt to the force field by considering additional forces to accommodate the opposing viscous force [64].

In this case, subjects' temporal and spatial perception along with adaptability to the viscous forces can be investigated. Particularly, in the orientation game, specific amount of viscous forces can be associated to different spatial cues (final destinations) and the subjects' ability to locate and reach the desired final destination associated with the applied viscous force in every new trial can be inspected. This way, a more challenging spatial processing task will be created that has the amount of viscous force applied as the cue to find the final destination. Here, the human brain performance in adapting to a complex task with multiple varying dimensions (force, space) would be assessed.

Finally, aside from goal-oriented temporal and spatial processing tasks associated with different amount of forces applied, the resulting psychophysical experiment also provide the opportunity to investigate the minimum amount of perceptible force difference between various falling rates or final destinations in the falling target and the orientation games, respectively. Moreover, this force perception can be tested among different age groups.

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