A CASE STUDY OF PROBLEM SOLVING IN EYE-TRACKING

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A CASE STUDY OF PROBLEM SOLVING IN EYE-TRACKING

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

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ABSTRACT

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Traditional theories of cognition have been critiqued for underestimating the role and contributions of embodied processes, more specifically the role of sensorimotor skills, in higher-order cognitive processes such as reasoning and problem-solving. Embodied theories of cognition have started to emphasize and illustrate the prominent roles of lower-level processes and sensorimotor skills in mental processes. This thesis aims to reveal the connection between higher cognitive skills, specifically problem-solving processes and sensorimotor skills, specifically eye movements. In the thesis, three almost equally hard problems have been chosen in order to observe participants' eye-movements via eye-tracking method (Tobii Eye-Tracker). Participants have been presented three problems in three different conditions and they were asked to solve them while looking at the screen. These problems are the river problem, the Tower of Hanoi, and the Water Jug problem. The three conditions have been presented sequentially; (1) visual-aid (with a picture), (2) blank screen, (3) fixation conditions. The order of the conditions is kept the same among all of the participants, while they are asked a different problem in each condition. The participants are asked to solve the puzzles by reporting the minimum number of actions required and select the correct answer when prompted. The results of the experiment indicated that problem solving performance was not significantly impaired by the restrictions imposed on the availability of visual cues and the restrictions enforced on eye movements. This suggests that sensory modalities (vision) and their bodily extensions like eye movements may not be the strongest factor underpinning the management of higher-order cognitive functions in the context of well-defined visuospatial reasoning tasks, as predicted by the radical embodied cognition view. However, the similarities between scan paths observed during picture and blank condition suggest that eye-movements act as an important facilitation mechanism for the management of attentional resources during such problem solving processes.

Keywords: Problem Solving, Embodied Cognition, Eye Tracking

ÖZ

GÖZ İZLEME İLE PROBLEM ÇÖZME ÜZERİNE VAKA ÇALIŞMASI

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Bilişsel süreçler hakkındaki geleneksel teoriler, somutlaşan biliş süreçlerini, özellikle de duyu-motor becerilerin yüksek bilişsel süreçler olan akıl yürütme ve problem çözme üzerindeki etkisini göz ardı ettiği için eleştirilmektedir. Somutlaşan biliş teorileri daha alt seviye bilişsel süreçlerin ve duyu-motor yeteneklerin zihinsel süreçleri önemli ölçüde etkilediğine dair bulgular sunmaktadır. Bu tez, problem çözme gibi yüksek seviye bilişsel süreçlerle, göz hareketleri gibi duyu-motor süreçler arasındaki ilişkiyi deneysel olarak incelemeyi amaçlamaktadır. Tezde, katılımcıların göz hareketlerini göz izleme cihazı (Tobii Eye-Tracker) vasıtasıyla incelemek için üç adet benzer zorluktaki problem seçilmiştir. Katılımcılara bu üç problem, üç farklı koşulda verilmiş ve katılımcılardan bu problemleri ekrana bakarlarken çözmeleri istenmiştir. Bu problemler, nehir problemi, Hanoi Kulesi problemi ve Sürahi problemidir. Üç koşulda farklı problemler ardı ardına katılımcıya verilmiştir; (1) resimli görsel yardım, (2) boş ekran, (3) göz sabitleme. Her katılımcıya karışık olarak sorular verilirken, soruları çözecekleri koşullar ise aynı sırada verilmiştir. Katılımcılardan her bir sorunun çözümü için gerekli asgari hamle sayısını bulmaları istenmiştir. Göz izleme ve performans verileri Tobii Studio yazılımı ile toplanmış ve analiz edilmiştir. Deney sonuçları, iyi yapılandırılmış bulmacalar içeren görevler sırasında problem çözme performansının görsel ipucunun ya da göz hareketlerinin kısıtlanması sonucunda önemli bir ölçüde azalmadığını göstermektedir. Bu durum, duyular (görme duyusunun) ve göz hareketleri gibi vücut uzantıları ile iyi tanımlanmış görsel akıl yürütme gerektiren görevleri idame ettiren yüksek bilişsel süreçler arasındaki ilişkinin, somutlaşan biliş teorilerinin öngördüğü kadar belirleyici olmadığını göstermektedir. Ancak, özellikle resim ve boş ekran koşullarında kaydedilen göz hareketlerindeki benzerlikler, göz hareketlerinin problem çözme sürecinde dikkat kaynaklarının yönetimi için önemli bir yardım mekanizması olduğuna işaret etmektedir.

Anahtar Kelimeler: Problem Çözme, Somutlaşan Biliş, Göz İzleme

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Chapter 1

Introduction

1.1 Purpose of the Study

Reasoning and problem solving have been a matter of interest and investigation for generations of philosophers and researchers since antiquity. Problem solving research is generally concerned with how human beings (and other species) deal with the difficulties that they encounter in the course of their lives, ranging from fulfilling basic needs such as feeding oneself or seeking shelter to figuring your way back home to solving math problems.

To what extent problem solving competency is dependent upon physical/perceptual factors has been a matter of debate in cognitive science (Kirsh, 2009). On the one hand, the symbolic information processing view within cognitive science argues that problem solving as well as other higher-order cognitive activities are governed by processes that are amodal by nature (Fodor & Pylyshyn, 1988; Newell & Simon, 1988). According to this view, the role of perception is limited to transforming sensory input into amodal symbols, which are then processed by different modules for making inferences and planning actions. This view is particularly emphasized in the AI tradition of Newell and Simon (1972) and the cognitive architectures built along symbol processing principles such as SOAR (Laird, 2012) and ACT-R (Anderson, 2007).

On the other hand, the situated cognition perspective argues that our bodily states and our sensori-motor engagements with the environment deeply affects our higher order cognitive processes (Barsalou, 2008). According to this perspective, the human cognitive system do not just rely on internal representations of the world, but actively seeks for relevant structures to exploit and act upon in the environment to guide the problem solving process (Kirsh, 2009; Clark, 2008). In this view, the external world functions as an extended memory where we seek for the precise information needed at the moment by moving our eyes and bodies (Myin & O'Regan, 2008).

Advances in eye/body tracking and brain imaging technologies have provided new opportunities to systematically investigate how embodiment factors in the shaping and management of problem solving processes. This study aims to contribute to these efforts by investigating the role of eye-movements during visuospatial problem solving processes. The experimental part of the study introduces three different task conditions where participants attempted three different puzzles. In the first condition participants are allowed to look at a picture of the initial state of each puzzle. In the second condition a blank screen is provided without imposing any constraints on eye movements. In the third condition subjects are asked to solve the problem while they are fixating on a specific location in their visual field. The study focuses on identifying how these conditions influence the problem solving performance of the participants as well as the similarities and differences observed in their eye gaze patterns across conditions. The main aim is to observe and interpret the consequences of manipulating the way subjects access visual modality during a problem solving process in reference to the arguments put forward by the symbolic and situated cognition perspectives.

1.2 Research Questions and Hypotheses

In order to explore the possible impact of modalities on cognitive processes during problem solving in a controlled setting, the main research questions are formulated around the visual modality and three puzzles that require the use of visuospatial working memory. Puzzles are chosen to be approximately at equal level of difficulty. Three different experimental conditions are considered in order to test the contribution of visuospatial working memory during the solution process. The guiding research questions for this study are formulated as follows:

> What are the effects of different visual access conditions, such as presenting a visual aid, a blank screen, and a visual restriction like making participants fixate at a point on the solution process?
>
> How do these conditions affect the performance measures like accuracy and task completion time?
>
> How are eye movements related to the problem solving processes?

The current thesis work will test four main and several auxiliary hypotheses. The first one is that a common eye pattern can be observed among participants when a cue is presented to them as a visual resource. The second one is that there would be a similarity between the picture state and the blank state in terms of eye movements. The third hypothesis is that the condition type will affect accuracy and task completion time. The fourth hypothesis is that when participants' eye movements are restricted, the performance of the participant will be impaired dramatically. The hypotheses tested in this study are listed as follows:

H1: People tend to use a common problem solving strategy when a visual cue is presented during the problem-solving period.

H2: Similar eye gaze patterns occur during problem solving when the same problem is attempted in visual cue and blank screen conditions.

H3: The accuracy of the responses drops when a visual cue is presented then a blank screen is presented.

H4: Restricting the eyes decreases problem solving time and decreases accuracy.

1.3 Organization of the Thesis

In this thesis, the following chapter (Chapter 2) contains a general literature review on problem solving. First of all, a general overview of problem solving is given in Section 2.1. Section 2.2 gives a historical background of problem solving research in cognitive science and psychology. Section 2.3 gives brief background information about the embodied cognition perspective and review empirical evidence provided in favor of the embodied nature of problem solving. Chapter 3 gives information on the design of the conducted experiment. In Chapter 4, analysis of the data obtained from the experiments is presented and in Chapter 5, the analyzed data is discussed in detail. Chapter 6 sums up the results of the experiments, discusses the limitations of the study, and suggests pointers for further studies.

Chapter 2

Literature Review

2.1 Problem Solving

Problem solving activity could be claimed to be an inevitable part of everyday routine especially during our conventional daily activities that have been referred as one of the manifestations of human thinking. The examples range from organizing a party to playing chess with a friend and to establishing a professional business (Holyoak, 1995). The ability of solving problems –especially the intriguing puzzles- has long been evaluated as an integral component of intelligence and has become part of several tests of intelligence (Lubinski, 2004). The problems could simply be defined with respect to two integral attributes: (1) as an unknown entity in relation to the initial and goal states, (2) there is a social, cultural or intellectual value behind solving this problem (Jonassen, 2004). The first attribute implicates there is a finite state difference between the initial and final states and this difference could be reduced via the use of a set of available operators (Holyoak, 1995). There might also be path constraints which restrict the use of possible moves/operations in order to prevent a set of undesired states. On the other hand, the problem space contains all of the possible states with the use of the given operators and the presented restrictions.

Problems can be categorized due to different attributes they convey like structuredness, complexity, dynamicity, domain-specificity (or known as context-specificity or abstractness). Problems could mainly be divided into two types based on their structure: (1) well-defined and (2) ill-defined problems. The first one, well-defined problems are the main interest of this thesis study. Secondly, complexity level appears as one of the crucial features of the problems which are related to the number of issues, functions, or variables involved in the problem. Complexity of a problem is also related to the components represented in the problem: clarity, reliability and other factors could be influential in the complexity level of a problem. Text book problems are generally accepted as simple problems whereas problems related to international politics are referred as complex problems. The third category has been about the dynamicity of the problems with referring to whether they are dynamic and static. Static problems are described to have stable factors over time whereas the dynamic ones contain changing factors. For instance, puzzles are known as static problems as they have stable/constant conceptual and rule-based structures. The fourth category is concerned with domain-specificity which implicate that problem solving skills are often domain and context specific. In other words, problem solving processes are situated and embedded in domains of reasoning that are shaped by several factors such as the organizational context, available cultural artifacts and types of expertise (or background knowledge).

Within this framework of problems, the problem solving process can be defined as "any goal-directed sequence of cognitive operations" (Anderson, 1980, p. 257). There are two critical attributes for this cognitive activity: (1) the problem-solver should mentally construct the mental representations of the problem as well as its context (problem space), (2) problem solving activity highly relies on the active manipulation and testing of the models by which the multimodal representations are used accordingly (Jonassen & Henning, 1999).

2.2 Studies on Problem Solving

As a research topic, problem solving became a matter of systematic analysis around the beginning of the 20th century. In the first half of the century, pioneering studies in problem solving were carried out by Gestalt psychologists in Europe. Especially Karl Duncker, Max Wertheimer, and Wolfgang Köhler contributed to these research efforts with empirical studies and data. In contrast to the behaviorist approach, these scientists handled problem solving as a more creative and productive activity, in contrast to the stimulus-response based associationist approach of the behaviorists. They studied how people and animals act when they encounter a problem which they have never faced before, and they observed how they handled the problems and tried to make interferences from these observations.

Between 1914 and 1917 Wolfgang Köhler investigated chimpanzees on Tenerife Island. He was also supporting the idea that animals solve problems in an intelligent way rather than following a pure trial and error strategy (Köhler 1921, 1925). His assumption was that intelligent behavior can be observed when the obvious way to the goal is blocked by a barrier. So the intelligent action would create a Gute Gestalt from a disturbed Gestalt and facilitate the solution seeking process which requires eluding the existing barriers in new and unfamiliar situations. Köhler created situations in which the apes had to solve problems. One of the well-known situations is the fishing a banana situation. A monkey was put into a cage and a banana was placed somewhere the monkey could not reach. However the monkey is provided two sticks lying around in the compound. Köhler observed that after a few minutes apes can purposefully join the sticks together and successfully reached for the banana. These evidences convinced Köhler that some animals were able to solve problems in a more intelligent manner rather than bare trial and error approach.

In 1945, Max Wertheimer published a book "Productive Thinking". Wertheimer was interested in how people restructure the accompanied insight in a given problem. He was the first to contradict one of the most popular ideas behaviorists defend, reproductive thinking (Thorndike, 1911), with his notion of productive thinking (Wertheimer, 1959).Wertheimer believed that productive thinking is superior to reproductive thinking, because he believed that people gain deep insight on the relations of the given problem constituents and their role in the given task, and as a conclusion, they gain insight on their resulting solution. Wertheimer's studies aimed to create a general psychological theory on problem solving that can be applied to various phenomena from low-level perceptual phenomena to great scientific inventions (Wertheimer, 1959).

In his studies, Wertheimer designed various tasks. Wertheimer aimed to show how the correspondence of transformations on disturbed Gestalt into Gute Gestalt with problem solving (Gentner & Colhoun, 2010). Among his various studies, two popular examples are the triangle area problem and the enumeration problem. In the triangle area problem, subjects are given an isosceles triangle given the length of the side s and the angle at the apex (90°). When the subjects are asked to calculate the area of the triangle, some of them tried to remember the triangle area formula. However, rotating the triangle reveals that the triangle can be understood as one half of a square with the diagonal g and the side with the length s. After the rotation operation, the area can be determined by calculating the area of the square and dividing it into half. Restructuring the problem requires more insight than just a trial-error approach as it is suggested by the behaviorists and sees the problem in a new way as part of a larger good Gestalt.

Second problem that was analyzed by Wertheimer is the enumeration problem (Öllinger & Goel, 2010). The task was to add as quickly as possible a series of consecutive numbers, such as 1 + 2 + 3 + 4 + 5 + 6 + 7 + 8 + 9 + 10. Wertheimer discusses that if only the reproductive solution was applied to the given problem, the only solution would be the sum of whole given numbers. However, Gauss found a productive solution in terms of a general principle of arithmetic progression given in Equation 1 below. Even though it seems to add a series of numbers ranging between 1 and 10 is easy, the complexity will increase as the range increases to 100 or 1000 (Gentner & Colhoun, 2010).

$$\sum_{i=1}^{n} i = n+1 \times \frac{n}{2}$$

Equation 1 Sum of Consecutive Numbers

Besides Wertheimer and Köhler, one of the most referenced Gestalt Psychologist working on problem solving is Karl Duncker. Duncker extended the basic principle of restructuring into a more general framework and stated problem solving as a stepwise process situated in a problem space which people navigate by means of strategies or heuristics (Duncker, 1945).

Duncker introduced a set of influential problems that are continued to be used by problem solving researchers till today. Especially within information processing theory, these problems are widely used in order to state the mapping intermittent steps in thinking processes onto cognitive models (Schooler and Engstler-Schooler 1990; Ericsson and Simon 1993; Schooler et al. 1993, Goel and Pirolli 1992). Among Duncker's most famous contributions to problem solving literature are the formulation of radiation and candle problems. Radiation problem states that:

> Given a human being with an inoperable stomach tumor, and rays which destroy organic tissue at sufficient intensity, by what procedure can one free him of the tumor by these rays and at the same time avoid destroying the healthy tissue which surrounds it? (Duncker, 1945, p. 1–2).

The solution for this famous problem is to use more than one laser of weak intensity and arrange them in a way that their rays exactly meet right in the heart of the tumor. The joint radiation cures the tumor and does no harm to the surrounding tissue. Duncker conducted his study by think aloud procedure which requires the participants to verbalize thoughts and ideas as they are attended to, while solving the problem. Duncker analyzed the think-aloud protocols and systematically developed graphs, and tried to determine the underlying problem solving strategy.

In the candle problem, Duncker asked the participants to find a way to mount the candle on the wall given a set of tools that are not obviously related to the task. When the candle is lit, no kerosene should split on the floor. Subjects are provided one candle, some tacks and a box. However, these artifacts are given in two different ways to the subjects in order to observe how the prior information leads them to different solutions. In the first situation, subjects are given these three artifacts separately. In the second situation, the candle and the tacks are given inside the box. The solution to this problem is the same in both situations. Subjects require mounting the box using tacks and place the candle inside the box. However, Duncker observed that when the tacks are given in the box, subjects tended to have difficulty solving the problem. Very small percentage of the subjects could provide a solution for the problem. When the tacks are given outside the box, subjects solved the problem in a higher rate. From these studies, the importance of the prior knowledge is observed. When the tacks are given in the box, the function of the box becomes the container of the tacks, so providing a solution using that box becomes harder to find out. However, when the tacks and the box are provided separately, subjects figured out the solution easier, which led Duncker to propose his famous functional fixedness theory. His theory and studies were further supported by other researchers (Maier 1931; Birch and Rabinowitz 1951).

On the other hand, Luchins (1942) showed that functional fixedness did not only appear when using objects in an uncommon way. Luchins studied how the repeated solutions create a mental fixedness on the problem solving process which prevents people from applying better and efficient solution strategies.

Luchins used water jug problems to demonstrate his theory on mental fixedness. Luchins created a set of water jug problems that could be solved by using a common procedure (B – 2 × C – A). For example he gave three jugs with volumes of 21,127 and 3 units respectively where the goal is to end up with 100 units of water in one jug. The strategy is to pour water into B (127), then use the water in B to fill C twice, leaving 121 units in B. Ending by pouring 21 units from B into A and leaving 100 unit of water in B.

After participants accomplish the set of water jug problems using the same strategy and learn how to solve the problem, they are presented three jugs with volumes of 23, 49, and 3 units and asked to end up with 20 units in one jug. Although this problem can still be solved by the learned strategy, a simpler solution is to directly pour once water from 23 units into 3 units' jug, and leave 20 units in 23 units jug (Luchins 1942; Luchins & Luchins 1959; Luchins & Luchins 1994; Lovett & Anderson 1996; Öllinger et al. 2008).

Gestalt psychologists made great contributions to the problem solving literature. Their empirically supported ideas, experimental designs and problems are used in further studies on problem solving area (Novick & Bassok, 2005). However, despite of their theoretical and empirical contributions, Gestalt tradition is critiqued for using a language that is sometimes vague, unclear, phenomenological, and hard to formalize.

After the demise of Gestalt tradition, for around 20 years the studies on problem solving almost halted. When Newell and Simon presented their General Problem Solver (GPS) (Newell, Shaw, & Simon, 1958) in the Dartmouth Conference, the process of thinking was transformed into a computational issue (Ernst & Newll, 1969). In contrast to Gestalt psychologists, Newell and Simon focused on solution steps of a problem and studied on problem solving algorithms to come up with a general framework for problem solving. Their main inspiration was the information-processing approach to cognitive science and advances in computer science on artificial intelligence. In 1972, Newell and Simon constructed their GPS which they have proposed in 1958. GPS was a computer program that aimed to model human problem solving ability. GPS's main idea is to process the information given to the system to find an appropriate solution by using logical proofs, heuristics and various algorithms.

The computational approach to problem solving have served as the basis of information processing theory of cognition. As the Newell and Simon's GPS propose, a general information processing and problem solving framework was created. GPS was the processing unit of the system; however the studies showed that in addition to an information processing unit, two additional components are required to solve a problem. So, Information Processing Theory consists of three components as shown in Figure 1 below.

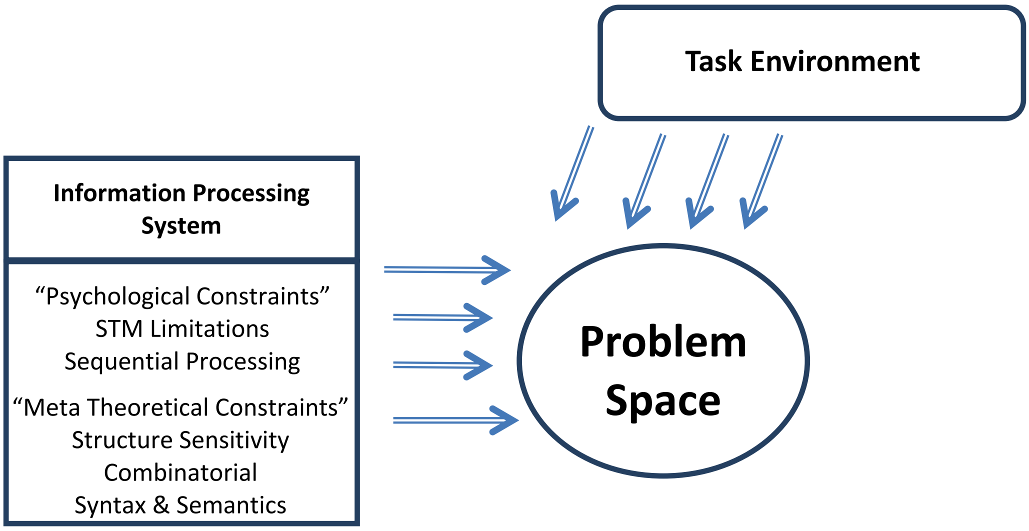

Figure 1 Information Processing Components. Reproduced from Goel (1995)

The three components proposed by Newell and Simon are the information processing system, the task environment and the problem space. The information processing system is the core physical symbol manipulation system consists of memory, processing power, sensory receptors and motor effecters. There are two major limitations of the information processing system; the first one is the limitations of processing power, memory, sensory information and the second one is the syntax and semantic usability and knowledge limitation. The task environment is formed by the goal, the current state, and other relevant external factors or constraints (Newell & Simon, 1972). The final component, problem space consists of operators, rules, interactions, constraints and other problem specific artifacts. Given these structures, Newell and Simon transformed problem solving into a search process within a graph structure where nodes represent states and connections represent possible rule-based transitions.

Information Processing Theory, starting with Newell and Simon has opened a new era for psychology of problem solving, which triggered several studies aiming towards exploring formal structures for generalized, context-free problem solving. These advances have influenced several additional fields besides psychology, such as artificial intelligence, robotics, and servo-systems. However, because the information processing theory not only consists of algorithms or heuristics, it also needs specific domain knowledge to frame those structures to a given problem accordingly. Anderson et.al.'s (2007) and Bransford et.al.'s studies in text comprehension showed the importance of such background information. Another issue is that, even though in well-defined problems where the problem space is clear, the search algorithm is successful, when more complicated problem spaces come into play the complexity of the problem space makes the search process nearly impossible. The information theory can easily apply on a problem such as Tower of Hanoi with three disks with no problem. The Tower of Hanoi problem is well-defined as its problem space and the number of possible actions can be easily iterated. However, when we consider chess, the problem space enlarges and the space of possible moves become 10^{23}. Even though chess is a well-defined problem, its search algorithm would require way more resources than it is requires in the case of Tower of Hanoi. Even when the problem becomes a classical strategy game such as GO, the problem space increases exponentially. Without any simplifying assumptions, prior knowledge, expertise or heuristics, it is very difficult to run a search algorithm in such cases. The difficulty increases exponentially when the problem space cannot be easily observed like most real world problems. Finally, in the case of ill-defined, real world problems, it is difficult to cast relevant factors into a problem space of nodes and operators.

2.3 Embodied Cognition

Embodied cognition is an emerging field in cognitive science that emphasizes the role of the body and the environment for the development and management of cognitive processes. The main emphasis is on the goal-directed nature of the interaction of the organism with its environment, which is fundamentally enabled by the sensorimotor capacities of the agent. Although there are different formulations of the embodiment thesis in the literature, there is a consensus among different formulations that the mutual interaction with the mind, the body, and the world has a direct impact on the agent's adaptive success and survival.

Embodied cognition or the embodiment thesis has been a matter of controversy since the ancient philosophers with different terminology and conceptions. The ancient philosophers such as Epicurus, British empiricists such as Berkeley (1982), Hume (1978) and Locke (1959), and some nativists especially Kant (1965) and Reid (1969) discussed effects of modalities onto the higher cognitive activities (Barsalou, 2010). As cognitive science has emerged as an interdisciplinary field of study, amodal theories have had a visible dominance in the field and the emphasis of the modal theories and embodied cognition has been neglected in academia until 1980's. The number of studies that are directly related to embodied cognition has increased steadily after 1980s. In various areas, embodied and grounded aspects of cognition have been discussed more. The most remarkable advances are; the Chinese Room Problem in philosophy track (Searle, 1980), conceptual metaphor theory in cognitive linguistics track (Lakoff & Johnson, 1980), environmental role of supporting the internal process underlying perception in ecological optics track (Gibson, 1979), paradigms that demonstrate mental imagery in higher cognition in cognitive psychology track (Paivio, 1971; Shepard & Cooper, 1982).

At the beginning of 1990's, embodied cognition studies increased. Especially the grounding problems of problem solving led many researchers to study on embodied cognition (Harnad, 1990). Many researchers studied the effects of situatedness when a task is given. Besides the advances in problem solving, advances in cognitive ecology, cognitive linguistics, robotics, cognitive neuroscience, developmental psychology and cognitive psychology have been observed (Barsalou L. W., 2010)). With the advances in technology that allows further studies on human brain, an explosion in the embodied cognition studies were witnessed in 2000's. Neuroimaging studies investigated the activity of brain's modal systems when engaging a problem (Martin, 2001, 2007; Pulvermüller, 1999, 2005; Thomson-Schill, 2003).In social neuroscience, findings of simulations that are run in motor and affective systems to comprehend social action, generate empathy and engage in other social processes show that these kinds of higher cognitive activities are not only affected by brain (Rizzolatii & Craighero, 2004; Dectey & Grèzes, 2006). The relation between sensory motor variables and some cognitive processes such as action, perception, memory and knowledge are revealed by various studies (Barsalou, 2008; Prinz, 1997; Rubin, 2006; Wilson & Knoblich, 2005;). The effects of bodily states for the face, head, arms and torso are found on higher cognitive processes such as problem solving decision making, evaluation and attribution (Barsalouet.al., 2003; Niedenthal et.al., 2005).

Embodiment and Problem-Solving

In the last decade, several studies have been conducted to explore the mutual interaction between the external world, the body and higher cognitive processes. These studies have been motivated by the limitations of amodal, information theoretic theories in accounting for problem solving in the real-world. Kirsh (2009) has summarized these limitations under four themes; *Framing and Registration*, *Interactivity and Epistemic Activity*, *Resource and Scaffold*, and *Knowledge Rich* (Kirsh, 2009). Information processing theory requires a formalized problem space in order to apply a search to find a solution. The framing problem suggests that constructing such a space for any given problem is not a trivial process. Finding such a structure requires a deep, formal understanding of the relevant factors and mechanisms within the particular frame. The registration problem is more focused on the self positioning in a situation to find the solution. Even though some facts about mapping and navigation are known, if someone cannot register herself on the problem space, the solution would not be applicable. So for a solution to be found, registration cannot be ignored. Interactivity and epistemic activity enables people to reduce the problem space. Most of this reduction can be done while people are interacting with their environment while solving the puzzle. So before the problem is abstracted from the world, some reductions and solutions can be applied interactively. Kirsh argues that we actively use resources and scaffolds surrounding us while solving a problem. In other words, not all the cognitive processing takes place inside the head during problem solving. Interactions with the environment via tools provides a leverage in the solution of the problems. The fourth opposition raised by Kirsh is the importance of knowledge to a real-life problem situation. He argues that most of our daily life problems are not given to us in a vacuum and we do not possibly know all the aspects of the problem space as in the case of knowledge-lean, well-defined problems such as Towers of Hanoi. People bring varying levels of expertise and background knowledge as they try to solve problems in real life.

Classical View versus Embodied Cognition View

The theoretical assumptions of embodied cognition could be compared and contrasted to the theoretical assumptions of the classical information processing theories in several respects as summarized below:

- The classical view has been raised by the computer metaphor of the mind by which the mental processes have been accepted as rule-based and/or logic-based software. The Embodied cognition view suggests a coupling metaphor of mind in which the mutual interaction of the body and the environment determine the nature of cognitive processes.

- The classical approach has promoted an individualistic analysis where the main focus has primarily been on the internal processes of an organism during the study of cognition. On the other hand, embodied cognition has proclaimed a relational analysis by which the interplay among the mind, body, environment and other bodies could be studied from a holistic perspective.
- The classical view has a main emphasis on computation and computational aspects of the human mind whereas the goal-directed action unfolding dynamicallyin real time has acquired a primary role according to embodied cognition view.
- The classical view has characterized cognition as a form of passive retrieval whereas embodied cognition view has accepted cognition as an active construction in relation to the embodied and goal-directed actions of an organism.
- The classical view has assumed that the nature of mental representations are symbolic and amodal (by nature) whereas the embodied view has assumed that these representations are sensorimotor representations.

Although these assumptions have been contrasted as among two rival camps, it is important to note that there are many different accounts especially within embodied cognition view and each of these assumptions are regularly revised by its proponents. In line with the embodied cognition perspective presented in this section, the eye movements have been ascribed a more important role than merely appearing as a tool for acquiring and transmitting visual information. The significance of these eye movements and fixations have been referred as deictic eye movements in the relevant literature.

Eye Tracking Studies of Visuospatial Reasoning

Eye tracking is a well-established methodological paradigm in the investigation of attentional resources during reasoning and decision making processes. Early eye movement studies in the literature found that task dependent cognitive goals strongly influence the eye movement patterns observed (Yarbus, 1967). This study aims to contribute to this line of work by focusing on the role of eye movements during problem solving tasks across conditions where access to visual resources are systematically restricted. In particular, participants will be attempting problems while they are looking at a picture, a blank screen and a fixation cross. Related work that employ eye tracking in similar conditions focuses on the blank screen paradigm in the context of visual scene perception/recall and the deictic roles of eye movements for accessing relevant information on-demand during visuospatial reasoning. This section provides a summary of this related literature.

Studies on visual perception emphasize the importance of the natural settings during the performance of cognitive tasks such as reasoning and recall (Gidlöf et al., 2013). One strategy to illustrate the effect of visual access on such processes is to use a blank screen condition in which the participant is asked to do the given task while looking at an empty screen. This condition is referred as the “blank screen” or “looking at nothing” condition (Ferreira et.al., 2008). Studies that employ this paradigm suggest that the participants tend to fixate on the empty regions that have included the relevant objects in the previous slides/demonstrations. It has accordingly been argued that sparse representations are formed by the visual system via the saccades and fixations, and the movements observed in the blank condition possibly facilitate the retrieval of those structures and inform the necessary cognitive processes (Ferreira et.al., 2008). In other words, these processes are considered to function pragmatically to extract information from the real world for creating and storing internal memory representations. Spivey & Geng (2001)’s findings also suggest that, even at a lower level like coordinating two objects in the visual field, participants tend to use the blank parts of the screen systematically via their eye fixations and movements in order to establish and transform spatial representations.

These findings are claimed to implicate the embodiment of the cognitive processes where the visual images are acted out or enacted by the eye movements. The relevant literature conveys several other empirical findings that support the view that there is a strong interaction between the internal representations and the sensorimotor modalities (Richardson & Spivey, 2000; Richardson & Kirkham, 2004; Hoover & Richardson, 2008). Moreover, these studies provide empirical evidence to support the claim that eye movements have a crucial role in the real-time mediation of visual attention via language and world-knowledge. In other words, the empirical evidence suggests that the eye movements could gain anticipatory role through the online processing of the words and sentences (Altmann & Kamide, 2004; Altmann & Kamide, 2007).

In addition to the literature on memory and linguistic processes, similar roles are attributed to eye movements during problem solving processes as well. For instance, Yoon and Narayanan (2004) conducted an eye tracking study on an engineering problem with senior engineering students which is shown in Figure 2 below.

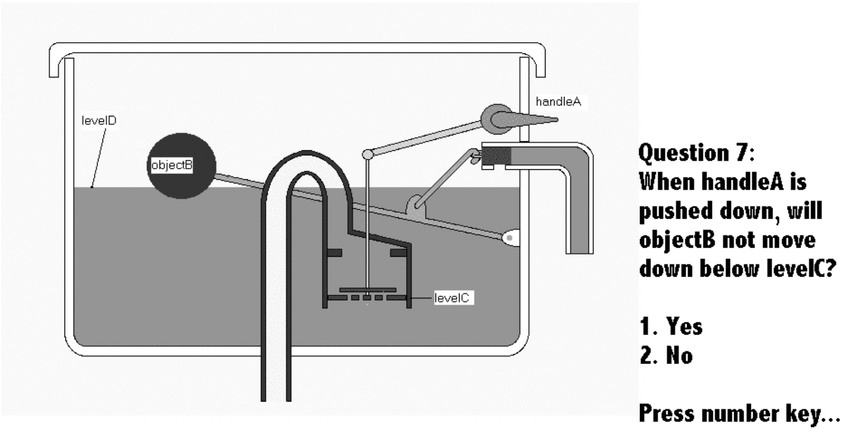

Figure 2 Yoon and Narayanan (2004) Engineering Problem

Yoon and Narayanan conducted the experiment in two groups. In the first group, they gave the visual cue shown in Figure 3 (a) as well as a verbal description of the problem. In the second group, subjects were provided only a verbal cue as shown in Figure 3 (b). All the experiments were conducted using eye tracker device.

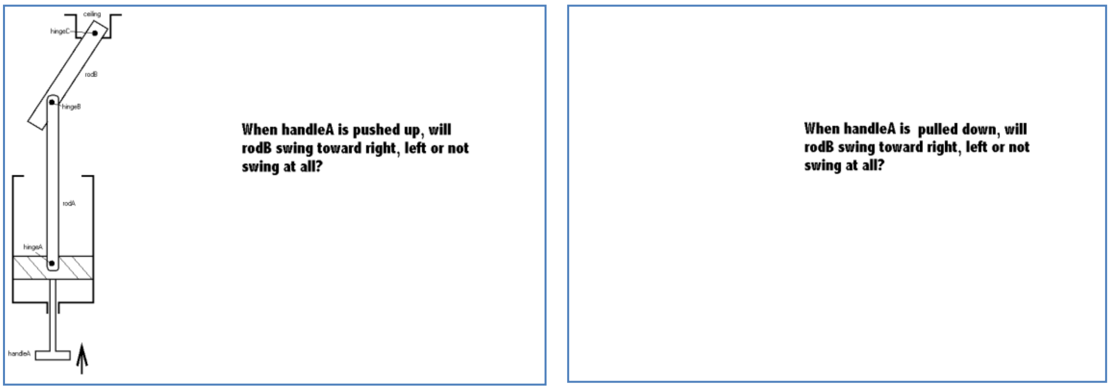

Figure 3 Yoon and Narayanan's screen for the Visual Cue condition is displayed on the left whereas Without Visual Cue condition is displayed on the right.

Yoon and Narayanan investigated the eye fixation patterns as well as the success rates of the participants. They found a similar pattern of eye movements on the visual cue and non-visual cue versions of the experiments. Yoon and Narayanan found out that some subjects who were not provided a visual cue showed a similar eye behavior as those who are provided visual cue over where the picture was briefly shown, whereas some other participants only tend to read and fixate over the instructions. This finding hints at individual differences in the use of eye movements for the facilitation of memory retrieval and attention.

Deictic computation is proposed as another relevant mechanism for representing the integrative features between external sensory data, internal cognitive programs and motor actions (Ballard et al., 1997). The empirical evidence supporting this observation comes from the coordinated use of eye gaze and motor actions in block copying tasks where subjects need to build a target pattern of blocks by positioning the same color blocks one by one. The patterns of eye movements and physical movements suggest that each fixation binds only one piece of information, either the color or the position of the moving block (Ballard et al., 1997). The findings suggest that there is a close interaction and coordination among the environment, internal cognitive processes and motor actions. This perspective underlines that moment-by-moment dispositions of body features like eye movements and hand gestures could be accepted as one of the central features of cognition in direct relation to working memory and more specifically to the visuospatial working memory during problem-solving processes (Clark, 2008).

The present thesis work focuses on the role of eye movements on visuospatial problem solving processes. The study employs the blank screen paradigm in a similar way to Yoon and Narayanan (2004), but it also considers a fixation condition that limits the use of eye movements in an effort to isolate the influence of such movements on problem solving performance. The current study also uses well-defined, visuospatial problems where eye movements could be easier to interpret as compared to an engineering problem. By using the blank screen paradigm, Yoon and Narayanan (2004) demonstrated that people tend to show similar patterns of eye movements and eye gaze during the visually-aided and blank screen conditions. They attributed this result to the prominent role of eye movements in the management of visual attention during mental imagery. In this study, although subjects appear as looking-at-nothing in the blank screen condition, they are expected to use their eye movements and fixations in relation to the requirements of the given problem. For instance, even on a blank screen during the Tower of Hanoi problem, the participants' eye movements might enact the process of carrying the discs from one peg to another, and hence their eye fixations might be used for following their counting work. On the other hand, by forcing participants to fixate on a specific location, the study aims to investigate if such a restriction will significantly impact the problem solving performance.

Chapter 3

Methodology

3.1 Pilot Studies

Several pilot sessions were conducted before the two main experiments in an effort to calibrate the experimental design. We used participants' feedback to develop our task instructions and the way the problems are presented to the subjects.

The first pilot study included a single puzzle, the river problem, where we asked the participants the same question but with different answer screens depending on the experimental condition they were assigned (i.e. picture, blank and fixation). Subjects were presented a single slide that contains both the description of the problem and the task on the same screen. Subjects were asked to press a number key on the keyboard to indicate the number of steps they thought it was needed to solve the puzzle. Our initial goal was to observe the performance differences between subjects on the same question. After the experiments, we found out that 1) the description and question screens had to be split into two screens because before the participants proceed to the answer sheet, they tend to begin solving the puzzle, 2) we had to refine and clarify our instructions because participants commented that they had hard time understanding them.

Second pilot study was designed again over a single puzzle. However, the instructions were split into multiple screens in order to help the participants understand them fully. After stating the problem step by step, the main question was presented at the last slide where participants had to skip the last slide by pressing a key to arrive the answer screen. Again subjects needed to report their answer by pressing a number key on the keyboard. After the second pilot study we observed that participants had hard time relating the initial constraints to the problem as they read them from separate slides and could not go back and forth across slides.

For the third pilot study, which is very close to our final design, several changes were made to the experimental design to address the aforementioned limitations. Firstly, two more puzzles were added to the experiment in order to observe individual differences by exposing all participants to the three problem solving conditions. New problems are chosen so that all problems would be comparable in terms of type and complexity. We designed 3! = 6 experiments where the three problems were presented in a different order, but the order of the conditions were kept the same for all 6 problems. This approach was employed in order to keep the experimental group sizes at a suitable level considering the sample size[1]. We decided to keep the order of the conditions the same as subjects had difficulty comprehending what they are asked to do when they were presented a blank or a fixation screen first. Since a fully factorial design was not feasible, we treated task condition as a between subjects variable and compared only the attempts on the same problem by different subjects across three conditions. Secondly, the definition of each problem was presented at the beginning of each trial, but the question was presented in the following slide. Participants were then asked to move on when they feel confident about the problem and its constraints before moving onto the question screen. Also in order to prevent the participant from solving the puzzle on the question screen, they were allowed 6 seconds to read the main question statement (i.e. how many steps would you need to complete the puzzle). After 6 seconds, the screen automatically switched to the answer screen. Participants were asked to use the keyboard to report their answer. In our third pilot study, we observed that 1) participants can misunderstand where to enter the number asked, 2) although some problems can be understood without visual diagrams, some participants reported difficulty understanding the problem when no visual aid was given in the description.

In the final experimental design we included pictures along with the general descriptions of the problem and its constraints (i.e. no picture in the actual question screen), and we used a list of clickable checkboxes to record the participants' answers so that they could keep their eyes on the screen while answering.

3.2 Participants

47 participants participated in the main experiment. All participants were chosen among volunteered undergraduate and graduate students at METU. No previous experience on the experiment or domain knowledge was required. Demographic information is collected from the participants at the end of the experiment. The experiment was administered with the permission of the METU Human Subjects Ethics Committee (See Appendix D).

3.3 Materials and Apparatus

The main experiment was conducted at the METU Human Computer Interaction Laboratory. Participants' eye movements were captured by a Tobii T120 Eye Tracker and the eye-gaze and performance data was analyzed by Tobii Studio Software. All the experiments were conducted in front of the Tobii Eye Tracker device, approximately at a distance of 60 centimeters from the screen.

[1] Testing all possible combinations of condition and problem type would require 6x6 = 36 groups.

3.4 Puzzles

In problem solving research, problems that are possibly novel for the participants but require minimal domain experience are typically selected, so that they do not need to have any prior knowledge to understand the rules and restrictions of the problem to work towards finding the solution. For example, in seminal studies on psychology of problem solving Duncker used tack, box and a candle experiment to investigate creativity (Duncker, 1945), Luchins used water jug problems to investigate mental spaces of the participants (Luchins & Luchins, 1959), and Posner used trains and bird problem to study differences in performance based on problem representations (Posner, 1973). In his article, Greeno distinguishes the problems into three types as inducing structure, transformation and arrangement (Greeno, 1978). The well versus ill structured problem distinction was first proposed by Reitman (1964), and usually well structured problems are used in order to avoid the unnecessary complexity of the difficulties of understanding the problems and their side effects (Barbey & Barsalou, 2009). In well-structured problems starting states, goal states and acceptable transformations are specified completely. The problems that we choose are well structured and all are from the transformation category according to Greeno's taxonomy. All three problems require visual-spatial reasoning resources to imagine possible spatial moves, infer their consequences and remember specific states reached. The initial states, goal states and transformations/constraints of the three selected problems for this study are given in Table 1.

Table 1 Initial states, goal states and transformations/constraints

Puzzle Name	Initial State	Goal State	Constraints/ Transformations
River Problem	The wolf, the sheep, cabbage, boat and the man are on the one side of the river	The wolf, the sheep, cabbage, boat and the man are on the other side of the river	- Man can carry only one at a time - If the sheep and cabbage left alone on the one side, sheep eats cabbage - If the wolf and the sheep left alone on the one side, wolf eats sheep
Tower of Hanoi	There are three pegs, and on one of the pegs there are three concentric different size disks	All the disks are on another disk	- One disk at a time movement - Only smaller disk can be placed on the larger one
Water Jug	8 liters of water in one jug	4 liters of water in the first two jugs	Water cannot be poured partially to another jug

The first puzzle is the infamous River Problem which presents the following problem. A man bought a sheep, a wolf and a box of cabbage from a village across the river. There is only one way to pass the river, it is a boat. The man has a boat but he can only load one of the sheep, wolf and the box of cabbage at a time. He ties the wolf and sheep to a nearby tree. If he leaves the wolf and the sheep on the same side, the wolf will eat the sheep and if he leaves the sheep and the cabbage on the same side alone, the sheep will eat the cabbage. The problem is how can he pass those across the river without losing any one of them? At the initial state, there are three objects at one side of the river, and a man with a boat on the river. The goal is to pass all of the objects from one side to the other one. The man can pass one object at a time, and the puzzle fails if either the wolf and sheep or the sheep and the cabbage is left alone at one side at any time. The solution tree including failed cases is presented in Figure 4.

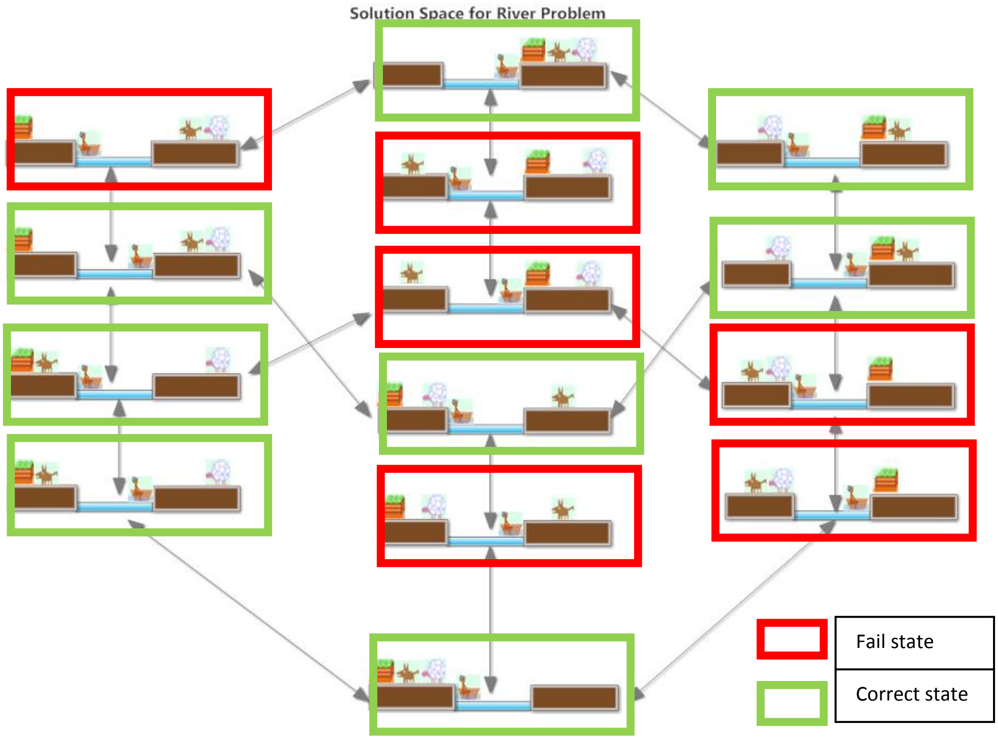

Figure 4 The solution space of the River Problem. States enclosed in a red box indicate failed states, whereas those enclosed in a green box represent permitted stages. The goal state is represented at the bottom.

The second puzzle used in the experiment was the Tower of Hanoi. Even though there are various ancient versions of the puzzle, the modern version roots back to the French mathematician Édouard Lucas in 1883. In this puzzle, the initial state includes three pegs of unequal size and three disks, where the disks are stacked in ascending order in one of the pegs. The goal is to transfer all the pegs on another peg. To achieve the goal, the restrictions are that only one disk can be moved from one peg to another, any disk that is not removed must remain on a peg and a larger disk cannot be placed on top of a smaller one. Because the difficulty of the puzzle exponentially increases by the number of disks, the minimum number of disks is chosen for the experiment. The solution tree is given in Figure 5.

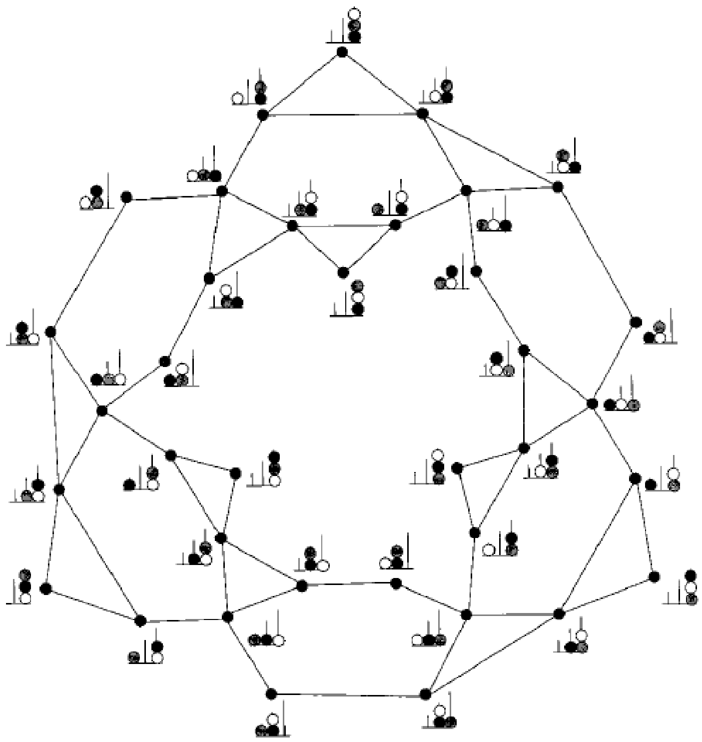

Figure 5 The solution space of Tower of Hanoi Problem (adapted from Dehaene & Changeux (1997, p. 13294)).

The third problem was the Water Jug problem which is also a well-structured puzzle. The puzzle was stated with different distribution of volumes and with different goals. Luchins uses 21-127-3 liters jugs and asks the subjects to end with an amount of 100 liters in one of the jars (Luchins & Luchins, 1994). In our experiment the 8-5-3 liter jugs version is used where subjects aim to reach the goal of producing 4 liters in two of the jugs. Figure 6 below shows that problem space for the water jugs problem.

Figure 6 The solution space of the Water Jug Problem

In all three problems the participants were asked what would be the minimum number of steps needed to reach the desired state. These three problems are chosen because they require comparable set of visuospatial reasoning skills. All three problems have similar constraints regarding how the objects in each problem can be manipulated and moved. Also keeping track of the objects' locations are important for reaching the solution for all problems, so the participants are required to hold location information for the imagined intermediary stages. The optimal solution for all three problems are the same (i.e. 7), which means each problem's optimal solution requires equal number of steps. Also the solution trees provided in Figure 4, Figure 5, and Figure 6 indicate that they are similar in terms of problem space complexity. However, the river problem also includes arithmetic operations where the participant needs to account for the subtracted and added amounts of water. The river and tower of Hanoi problems simply involve the movement of discrete objects.

3.5 Procedure

Participants were asked to attempt three problems in three different conditions. Each experiment took on average 15 minutes. All sessions were conducted in the Human Computer Interaction Laboratory, in front of an eye-tracking monitor. Participants sat in front of the monitor approximately 60 cm. away from the monitor. They were given prior information about the experiment by the experimenter. In an effort to control for individual differences in problem-solving, 6 experimental groups have been created where conditions are administered in the same order (e.g. picture, blank and then fixation conditions) but interchanging the order of the puzzles. So subjects at different groups have attempted a different problem in a given condition. The experimental conditions are given in Table 2 below.

Table 2 Experiment Conditions

Experiment	**Picture Condition**	**Blank Condition**	**Fixation Condition**
Experiment #1	Tower of Hanoi	Water Jug	River Problem
Experiment #2	Tower of Hanoi	River Problem	Water Jug
Experiment #3	River Problem	Tower of Hanoi	Water Jug
Experiment #4	River Problem	Water Jug	Tower of Hanoi
Experiment #5	Water Jug	River Problem	Tower of Hanoi
Experiment #6	Water Jug RP	Tower of Hanoi	River Problem

Participants were told that there would appear 1 problem, 1 question and 1 answering screen and 1 answer questionnaire for each problem. They will be shown the problem screen which defines the problem and states the constraints to the participants. Participants are told that when they feel confident about the problem, they have to press a key on the keyboard and move on to the question screen. This screen is displayed on the screen for 6 seconds and after 6 seconds the screen turns into the answer screen. Participants need to solve the puzzle on the given answer screen, and when they feel that they have solved the puzzle, they continue to the screen where the result is asked by selecting from the options provided (i.e. numbers from 3 to 20). They select the answer they have found on the given screen. There would be no break between problems and each participant would complete 3 problems in total.

Before beginning the experiment, for all the participants, eye-tracking calibration was done. After the calibration, the participant was left alone in the laboratory and observed behind the one-way glass.

At the beginning of the experiment, participants are shown prior information on the screen. After they have read the information carefully, they are required to press a key to continue the experiment. After the prior information, the general concept and constraints of the problem are given to the participant. When the participant understood the problem, she had to press any key to continue to the question page. In order to prevent the participant from solving the problem on the question page, the page automatically passes to the answer sheet in 6 seconds. At the first part, there is a representation of the problem on the answer sheet, and the participant is free to inspect the whole representation with his eyes. There is no time limit, so when the participant counts the minimum number of action needed in order to achieve the task; she presses any key on the keyboard to continue. After she answers the question, general concept and the constraints of the second problem is displayed on the screen. Again, participant needs to press a key when he fully understands the problem and then the question appears. In 6 seconds the question disappears and the answer sheet is shown to the participant. In the second problem, the answer sheet is a blank sheet which the participant can observe the sheet freely with her eyes; however there are no visual cues about the problem on the sheet. When the participant counts the minimum number of action needed to achieve the goal, she presses the corresponding number on the keyboard and continues the last problem. The initial procedure of the third problem is also similar to the first and second one. However in the third problem, the answer sheet contains only one plus sign on the screen and the participant is required to solve the problem while she has fixated his eyes on the screen. Finally after he has found the answer and pressed a key, the participant is shown the final slide which informs the participant that the experiment has ended.

3.6 Data Collection

Five types of measures are used to investigate the effects of the puzzle and condition type. The first type of measure, the task completion time is measured individually based on the elapsed time between the disappearance of the problem slide and the participant's marking of the response on the answer sheet. This time is calculated by Tobii Studio software and obtained by visit time of the participant on the answer sheet. In the second experiment, task completion times is derived from the markers recorded and the screen recordings.

The second type of measure is response accuracy. This data is collected by Tobii Studio over a questionnaire, and analyzed in two different ways. First, a performance scale is created and the answers are graded over this scale, which is given in Table 3 below. ±1 implicates that the participant answered either 6 or 8, which means he/she is 1 off from the correct answer. Similarly, ±2 implicates distance of 2 from the correct answer (5 and 9). Secondly, a binary performance score is computed which distinguishes correct and incorrect responses. In other words, only the correct responses were given the score but not the others.

Table 3 Performance Scale

Puzzle	Correct Answer	Correct Answer Grade	±1	±2	±3	±4
TOH	7	100	75	50	25	0
RP	7	100	75	50	25	0
WJ	7	100	75	50	25	0

Third type of measures are eye fixation count and gaze duration data extracted from the eye tracker. This data is obtained by creating Area of Interest (AOI) of the picture versions of each puzzle, and then the same AOI definitions are applied on the blank versions of the puzzles in order to observe if there is a similarity between eye gaze patterns recorded in each condition. Fixed condition is observed separately in order to check if the participant actually fixated on the cross as instructed. The AOI definitions and feature extraction procedure are performed on the Tobii Studio software.

Demographic information about the participants including their age, gender and major have also been collected via a questionnaire.

3.7 Data Analysis

3.7.1 Analysis of Task Completion Time

The cumulative mean task completion time and the mean task completion time for correct answers are analyzed separately. The effect of condition on task completion time and accuracy are analyzed. The task completion times have been measured from the onset of the problem-solving screen (that could be visual aid, blank screen, and fixation depending on the condition) till the participant's press on the space bar to give her response. While the cumulative task completion times show us the time required for a participant to come up with an answer, task completion times for correct answers will show us if there is a correlation between task completion times and accuracy. Task completion times will be evaluated and tested with a non-parametric Kruskal Wallis test.

3.7.2 Analysis of Accuracy

One of the most important data is how the accuracy effected by conditions, which the participant sees a visual cue, the participant sees no cue but using their eyes freely, and the condition that their eyes are fixed. These analysis will be done by looking at both the correctness of the answers and the scoring of the answers. Scoring will reveal that even though participants could not give the correct answer, how close they have found out the answer. This score system created in order to eliminate little counting errors that participants can do. The relation between accuracy and condition and puzzle type will be tested with a one way ANOVA (Condition).

3.7.3 Scan Path Analysis

Gaze patterns for each puzzle in each condition were analyzed separately by the Tobii Studio Area of Interest editor. The general scan path of the participants was formed by analyzing the order of the transitions between the puzzle parts for each puzzle (River Problem/Tower of Hanoi/Water Jug) and condition (Picture/Blank/Fixation) combination. Areas of interests for each problem were estimated based on the heat maps generated over the screens used in the picture and blank conditions. Each AOI is assigned a letter and then the scan paths of participants were represented as a string of letters.

The analysis of eye gaze data focused on the similarity of gaze patterns observed during picture and blank conditions. This comparison is motivated by the findings of Yoon and Narayanan's study (2004), which demonstrated that some participants made use of eye movements as if they were scanning the diagram shown in a previous screen. We tested if a similar relationship can be detected across picture and blank conditions by using two string similarity measures, namely the Levenstein String Distance (LSD) (Holmqvist, 2011) and the Longest Common Subsequence (LCS) distance (Maier, 1978).

The LSD algorithm is based on the number of operations needed to change string s1 into s2, so higher similarity means lower distance between S1 and S2. The formula used to calculate the LSD distance is given in Equation 2 below.

$$\mathrm{d} = 1 - \left(\frac{\mathrm{d}}{\max(\mathrm{m}, \mathrm{n})}\right)$$

Equation 2 Edith Distance

The LSD analysis has some limitations due to the specific circumstances of this study. The length of the AOI string is influenced by the total time each participant spends on the problem. Moreover, short fixations across AOIs may inflate the AOI strings observed. This is particularly problematic in this study since AOIs are rather approximations of the imaginary entities the subjects are attending to.

In order to address some of these issues, a second algorithm called the Longest Common Subsequence (Maier, 1978) is considered. Longest Common Subsequence algorithm indicates the common subsequence of two given strings. This subsequence finding algorithm enables us to match two strings such as 'aaaaabbbaaaa' and 'aba' which means that the two scan paths exhibit similarity in terms of the transition patterns they contain. Longest subsequence algorithm is based on the Equation 3 given below.

$$LCS\ X_i, Y_j = \begin{array}{rl} \emptyset, & i = 0 \ or \ j = 0 \\ (LCS\ X_{i-1}, Y_{i-1}\ , X_i), & x_i = y_i \\ longest(LCS\ X_i, Y_{j-1}\ , LCS(X_{i-1}, Y_j)), & x_i \neq y_i \end{array}$$

Equation 3 Longest Common Subsequence

The similarity between two strings based on the LCS algorithm is calculated by using Equation 4below.

$$\mathrm{D} = \frac{Len(LCS(s1, s2))}{Min(Len\ s1\ , Len(s2))}$$

Equation 4 Similarity Calculation in LCS Algorithm

LCS returns the ratio of the length of the longest subsequence of both input strings, to the length of the smaller input string. Hence its value varies between 0 and 1, where 0 means no common subsequence, whereas 1 implies that the shorter string is subsequence of the longer string. This measure is more appropriate in our context since the AOIs identified for the picture condition cannot always be directly mapped onto the attention maps for the blank condition. Moreover, the LCS algorithm tolerates noise due to fixations that repeatedly fall on the same AOI (due to large size of AOIs in this study) while the participant is moving from one AOI to another.

Both of the algorithms are implemented in Matlab (see Appendix A and Appendix B). After the similarity of the same cases is investigated, the similarity between picture and blank case is investigated. This comparison was done by making some transformations on one of the AOI's of picture into blank condition. The same transformation is applied to the all of the AOI's. Due to the difficulties of transformations, only Tower of Hanoi problem, is investigated for finding the similarity between picture and blank cases. This investigation is done by using TOH-Corrected values.

Chapter 4

Results

4.1 Analysis of Task Completion Times

The box plot displayed in Figure 7 below shows the distribution of task completion time values for each task across the three conditions. The distribution is highly skewed and larger variability is observed in the water jug problem. Two participants' task completion time values were removed due to their significance as an outlier. One participant took 1370 seconds to answer the water jug problem in the fixation condition. The other participant answered the Tower of Hanoi problem in less than 2 seconds. The eye movements recorded while this participant was reading the task instruction suggest that the subject started working on the problem not during the black screen but on the problem description.

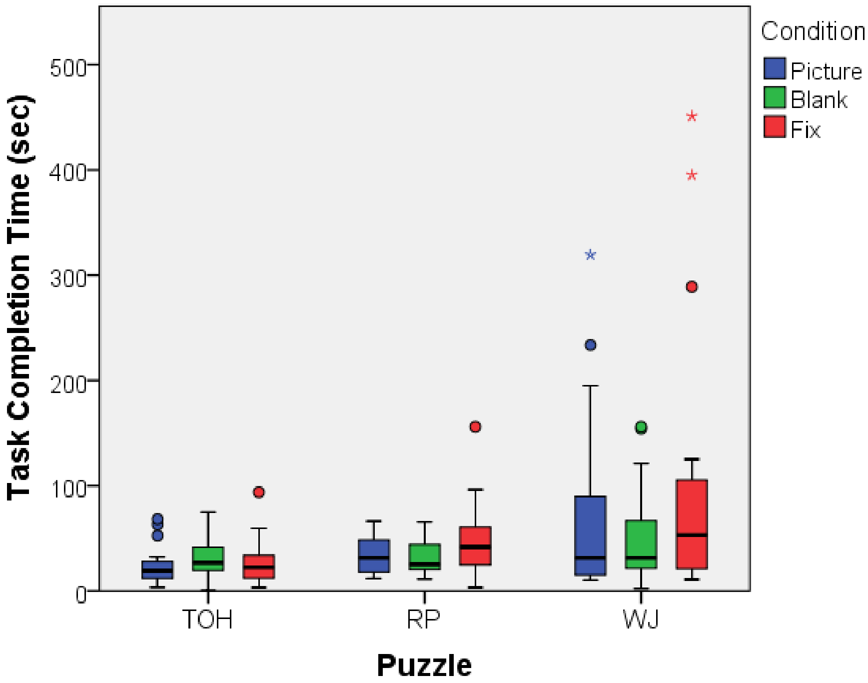

Figure 7 Task Completion Time Distributions across Tasks and Conditions

Kolmogorov-Smirnov tests indicated that the distributions of task completion time values for each condition significantly deviates from the normal distribution. Therefore, three Kruskal-Wallis tests are conducted for each puzzle type over task completion time values where experiment condition (picture, blank, fixation) is the between subjects independent variable. Kruskal-Wallis tests found no significant differences across conditions in the TOH, ($\chi^2(2)$= 2.620, p>.05) RP ($\chi^2(2)$=2.534, p>.05) and WJ ($\chi^2(2)$= 1.525, p>.05) puzzles respectively.

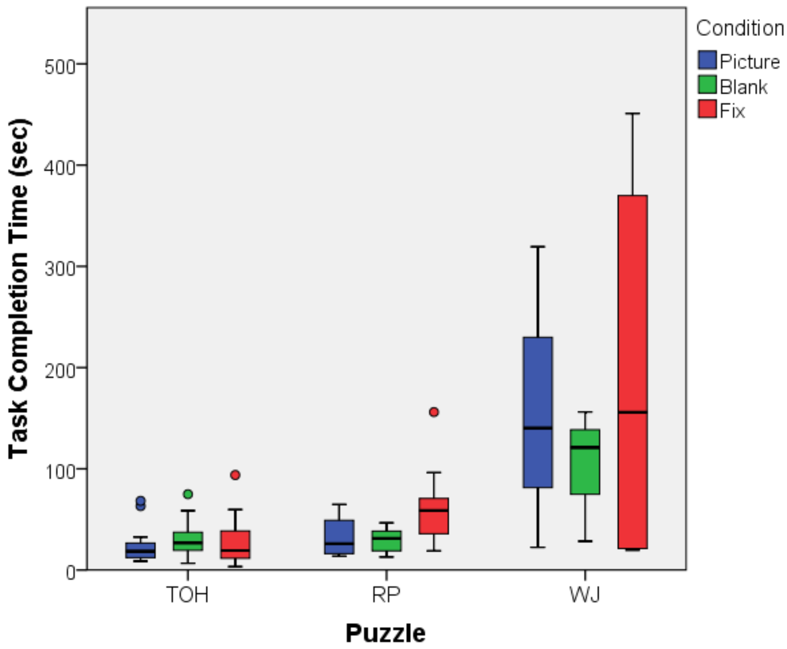

Figure 8 Task completion time distribution across conditions and tasks for only the successful cases.

Figure 8 shows the distribution of task completion time for cases where subjects guessed the answer with an error margin of plus minus 1. Kruskal Wallis tests that compared task completion times across each puzzle type found no significant difference in the TOH ($\chi^2(2)$= 0.726, p>.05) and WJ cases, whereas a marginally significant difference was observed in the RP case ($\chi^2(2)$= 5.590, p=0.06).

The main effect of puzzle type on task completion time is investigated via three separate Kruskal-Wallis tests. The tests indicated that there were no significant difference between the three puzzle types when participants attempted them in the picture ($\chi^2(2)$=3.644, p>.05) and blank ($\chi^2(2)$=0.804, p>.05) conditions respectively. However, task completion times significantly differed across puzzle types in the fixation condition, $\chi^2(2)$=6.164, p=0.46. The mean ranks for TOH, RP and WJ were 16.81, 26.40 and 27.73 respectively, which suggests an increasing trend across puzzles when they are attempted in the fixation condition. A Jonckheere-Terpstra test showed that this trend was significant, J-T(46)=501.0, p=0.018. In other words, subjects tended to spend more time during the WJ problem when their eye movements were restricted. This suggests a potential interaction of puzzle type and task condition, which we could not test since the experimental design is not fully factorial and the order of conditions are not randomized.

When the analysis was restricted to the successful cases only, the same pattern of relationship was observed, where the task completion across puzzles did not significantly differ in the picture and blank conditions, whereas the only statistically significant difference among the tasks was observed for the fixation condition, $\chi^2(2)$=6.691, p<.05. The mean rank values for TOH, RP and WJ tasks in the fixation condition were 9.58, 17.45 and 17.75 respectively. A Jonckheere-Terpstra test also showed that this trend was significant, J-T(27)=167.00, p=0.012. In other words, subjects who performed well also tended to spend more time during the RP and WJ problems as compared to the TOH problem when their eye movements were restricted.

4.2 Analysis of Performance

Analysis of performance is done on two different dependent variables, the first one is scale performance point and the second one is the binary performance. The data is analyzed between puzzle types in order to understand the effect of condition in every puzzle type. Tower of Hanoi, River Problem and Water Jug problems are analyzed independently.

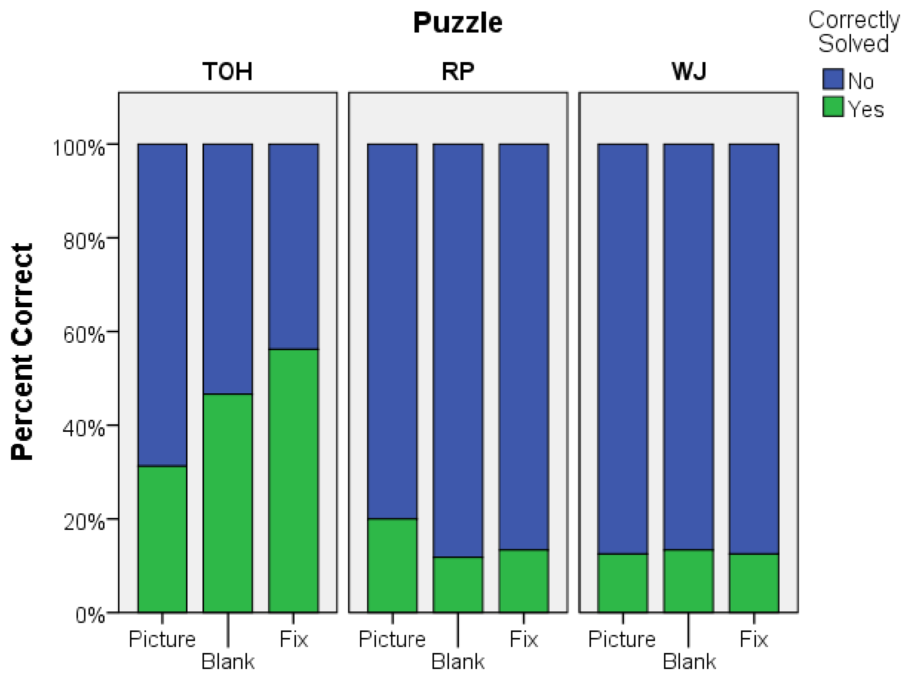

Figure 9 Distribution of correct and incorrect responses for each puzzle across task conditions

Figure 9 shows the distribution of correct and incorrect responses across conditions and puzzle types. Chi-square tests conducted separately for each three puzzle type did not reveal a significant difference (TOH $\chi^2(2)= 2.058$, $p>.05$; RP $\chi^2(2)= 0.469$, $p>.05$; WJ $\chi^2(2)= 0.006$, $p>.05$) in the distribution of correct answers across picture, blank and fixation conditions.

The main effect of puzzle type across task conditions is tested by three chi-square tests in a similar way. There was no significant difference in the distribution of correct responses in the picture condition across puzzle types, $\chi^2(2)= 1.701$, $p>.05$. However, significant differences were found in the picture ($\chi^2(2)= 6.661$, $p=.036$) and fixation ($\chi^2(2)= 9.913$, $p=.007$) cases, all in favor of the TOH puzzle. Overall, subjects were more successful in finding the exact answer in the TOH case.

Problem solving performance of subjects are also assessed in a graded manner by using the performance scale that varies depending on how close the subject get to the correct answer. The mean performance scale for Tower of Hanoi is summarized in the bar chart in Figure 10.

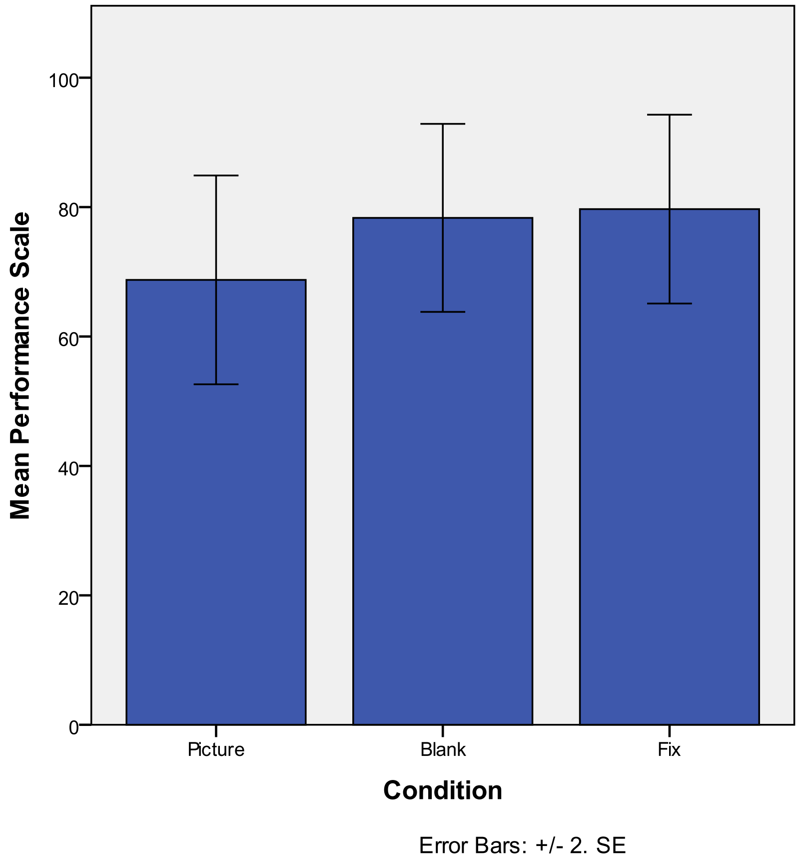

Figure 10 Mean Performance Scale for ToH

Kolmogorov-Smirnov tests indicated that the distribution of performance scores were not normal, so a non-parametric Krusal-Wallis tests is used to compare the three conditions. The Kruskal-Wallis test revealed no significant main effect of the condition for the TOH puzzle ($\chi^2(2)= 1.583$, $p>.05$).

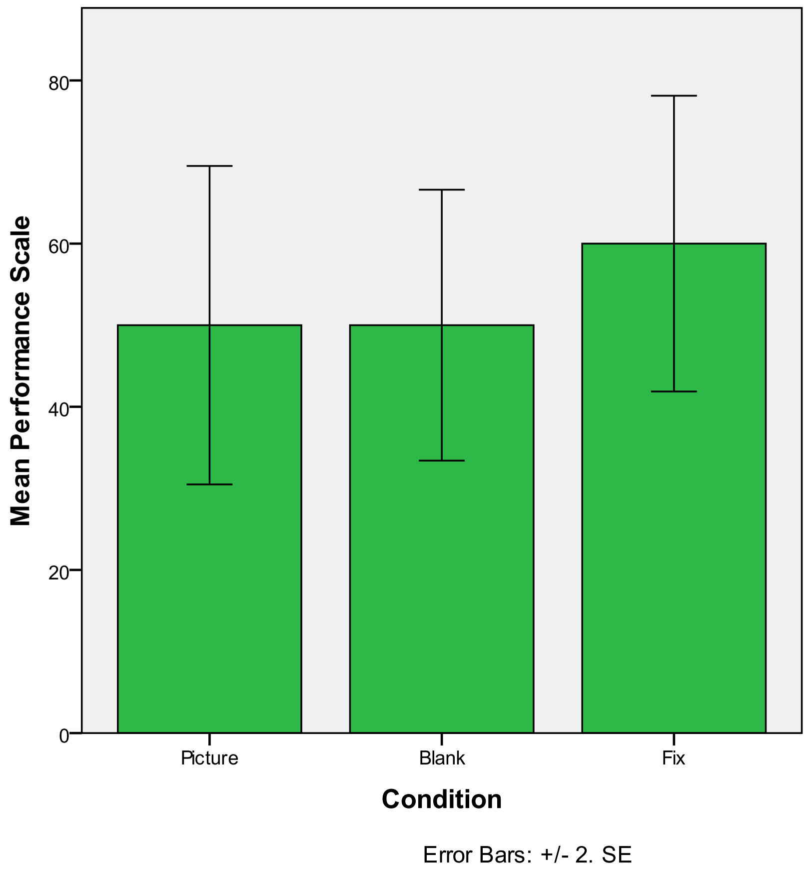

Figure 11 Mean Performance Scale for RP

Mean performance scores observed during the River Problem at each condition is summarized in Figure 11. Since the scores were not normally distributed, non-parametric Kruskal-Wallis test is employed. The Kruskal-Wallis test revealed no significant difference among conditions in terms of performance during the RP problem ($\chi^2(2)= 1.244$, $p > .05$).

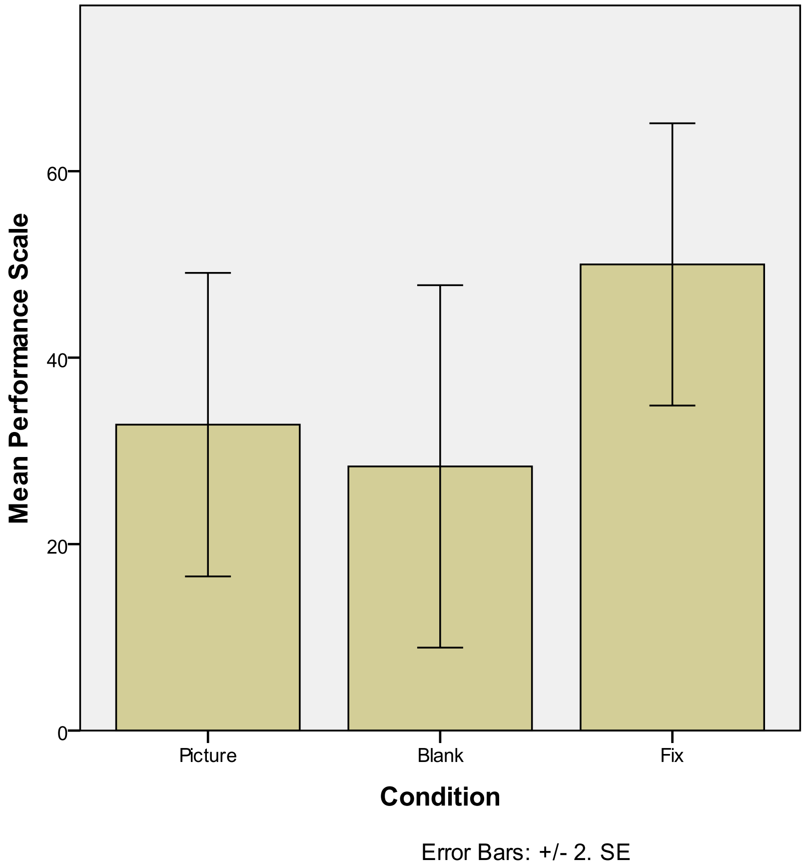

Figure 12 Mean Performance Scale for WJ

Mean performance scores observed during the Water Jugs Problem at each condition is summarized in Figure 12. The Kruskal-Wallis test found no significant difference across conditions, $\chi^2(2)= 4.863$, $p>.05$. In terms of conditions, from the above, blank condition shows less accuracy and the most accurate answers are collected from fixation conditions.

The main effect of puzzle type on performance scores is investigated via three separate Kruskal-Wallis tests. The tests indicated that there was a significant difference between the three puzzle types in the picture ($\chi^2(2)=7.36$, $p=.025$), blank ($\chi^2(2)=12.411$, $p=.002$) and fixation conditions respectively ($\chi^2(2)=8.19$, $p=.017$). In all three conditions the order of the puzzles in terms of their mean ranks were the same. Subjects scored highest in the TOH, followed by RP and WJ. Jonckheere-Terpstra tests showed that these trends were statistically significant for the picture (J-T(47)=231.5, $p=0.006$), blank (J-T(47)=186.5, $p=0.001$) and fixation (J-T(47)=224.5, $p=0.004$) conditions respectively.

4.3 Analysis of Fixation Duration

Only the picture and blank conditions are considered for the fixation analysis. The box plot in Figure 13 shows the distribution of mean eye fixation duration values for each puzzle at each condition. Non-parametric Mann-Whitney U tests were conducted to compare mean fixation duration values recorded for picture and blank conditions across three puzzles. Mann-Whitney U tests found a significant difference between picture (mean rank = 10.66) and blank conditions (mean rank = 21.04) only for the WJ problem, $U = 34.5$, $z = -3.229$, $p<0.002$.

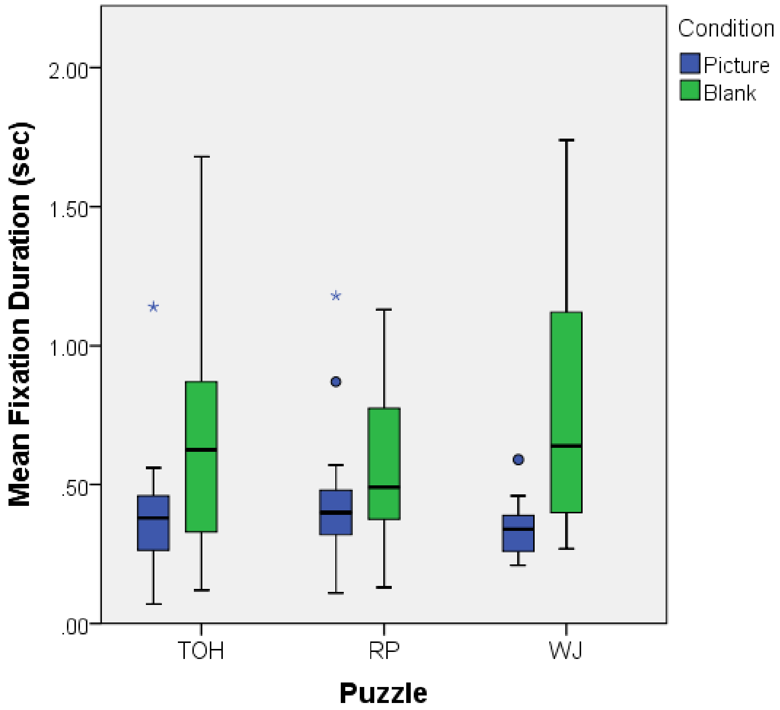

Figure 13 Box plot of mean fixation duration values across picture and blank conditions, organized under each puzzle type.

When the data set is reduced to successful cases, only 5 data points remained in the WJ condition, which made it not suitable for a statistical test. Moreover, Kruskal Wallis tests that compare the mean fixation duration observed for each puzzle at picture and blank conditions did not reveal any significant differences.

4.4 Scan Path Analysis

In order to analyze problem solving strategies indicated by gaze movement patterns during the experiment, a scan path analysis was conducted. As Yoon and Narayanan (2004) reported, some participants' gaze patterns may indicate what problem solving strategy they are carrying out. However, this is not always the case as some subjects' eye movements did not reveal any obvious systematic gaze pattern. For that reason, scan path analysis was conducted over cases with high accuracy and orderly gaze patterns indicative of strategy execution. Participants who scored below 75 and the gaze patterns recorded during the fixation condition were excluded from scan path analysis. After filtering the data we ended up with 14 blank trials and 17 picture trials. The resulting set of trials and their distribution to each experimental condition and puzzle type is given in Figure 14.

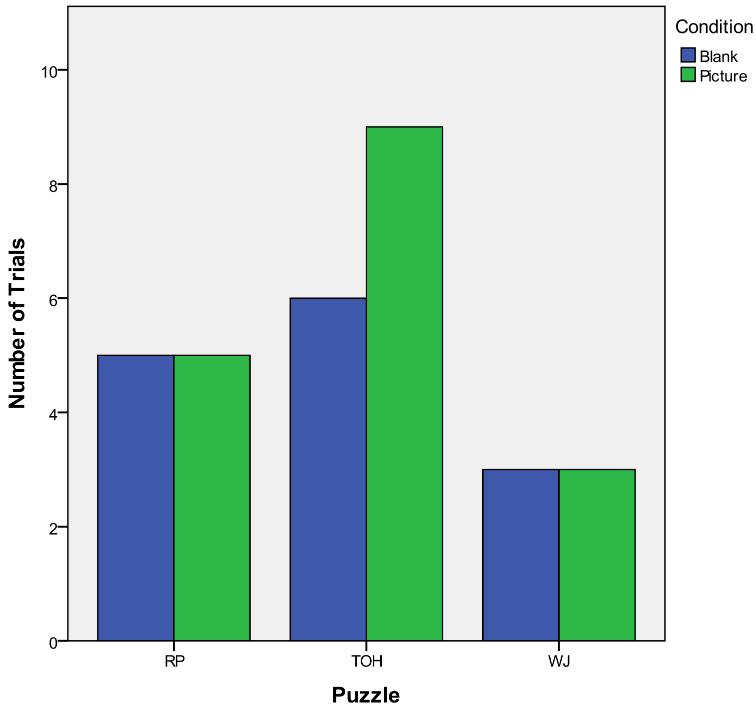

Figure 14 Number of Trials

Since the task completion times for the filtered data set satisfy parametric assumptions, for those trials where a problem solving strategy was indicated by the gaze patterns, the effect of puzzle type and task condition over task completion time was tested with a 2 way ANOVA. Results indicated that only the puzzle type has a significant effect on puzzle type, $F(2,25) = 10.927$, $p<0.01$. As indicated in Figure 15 below, the task completion times observed during picture and blank conditions for the River and Towers of Hanoi problems were close to each other, whereas significantly longer task completion times were observed during the Water Jug problem. The main effect of task condition was not significant, and the average time participants took to respond to each puzzle across these two conditions were very close to each other. Especially the low variability in the TOH and RP cases make them suitable for a scan path analysis since both conditions elicited very similar completion times.

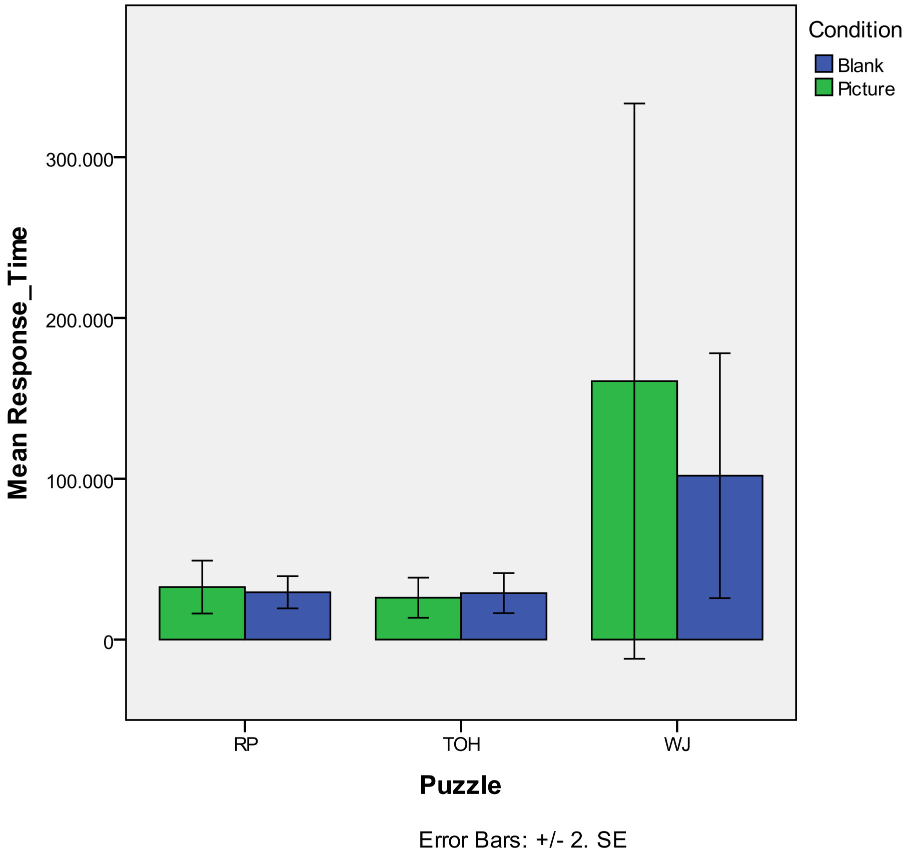

Figure 15 Mean Task Completion Time over Puzzle Type and Condition (Observable Data)

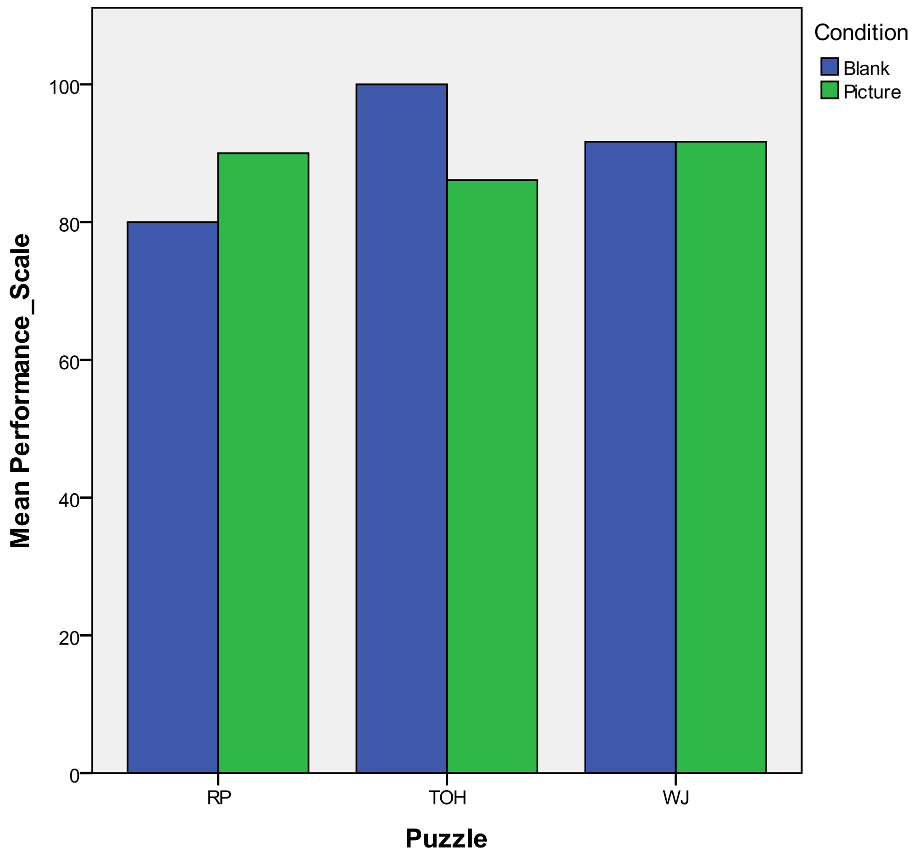

Figure 16 Mean Performance Scale

The mean performance score of trials selected for scan path analysis for each puzzle type and condition are given in Figure 16. A 2-way ANOVA found no significant main effects of puzzle type ($F(2,25) = 1.442$, $p>0.05$) and task condition ($F(1,25)=0.81$, $p>0.05$). Therefore, the 31 trials selected for scan path analysis include highly accurate cases and this accuracy is evenly distributed to each puzzle type and task condition.

Scan path similarity analysis between participants in same puzzle type is done using longest common subsequence and string edit distance methods. These two methods are applied after Area of Interests (AOI) are defined in Tobii Studio and the eye gaze data is exported accordingly. Area of Interests are created using heat map data provided by Tobii Studio. All aggregated heat maps of picture conditions are explored. The heat maps of picture conditions of Tower of Hanoi, Water Jug and River Problem are given in Figure 17, Figure 18, and Figure 19.

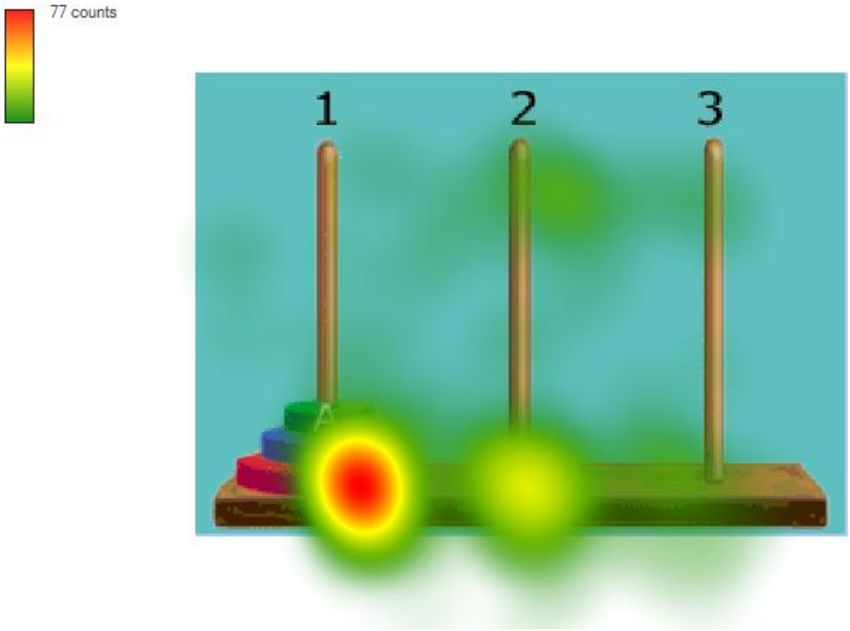

Figure 17 Heat Map for Tower of Hanoi

Figure 18 Heat Map For Water Jug

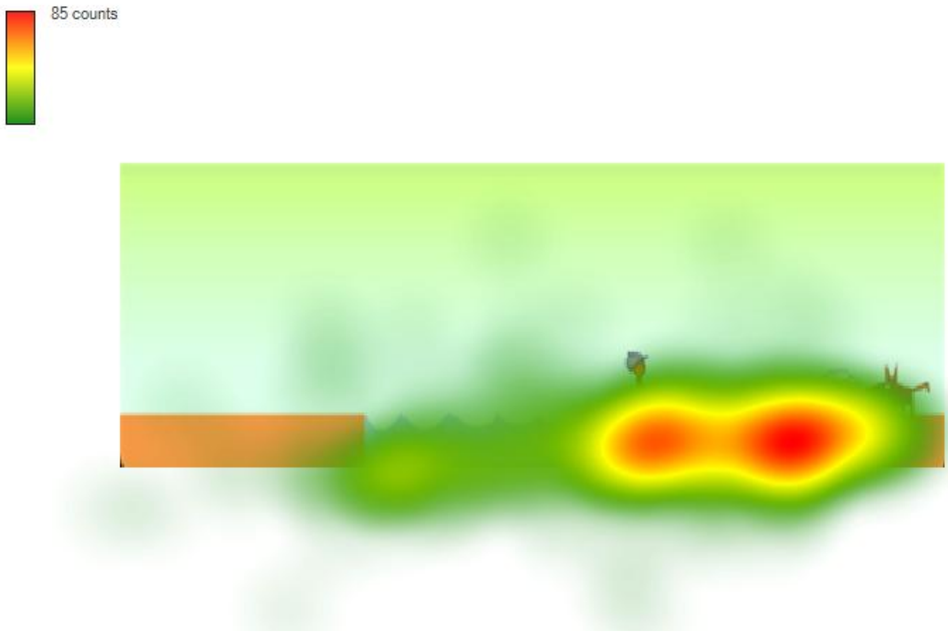

Figure 19 Heat Map for River Problem

From the heat maps above, Area of Interests were drawn to reveal the scan paths and to enable a comparison of the differences and similarities between eye movements recorded for the same puzzle in picture and blank conditions. AOI's are drawn differently for all three puzzle types based on their heat map characteristics. The defined AOIs for each task are displayed in Figure 20, Figure 21 and Figure 22.

Figure 20 AOI's for TOH

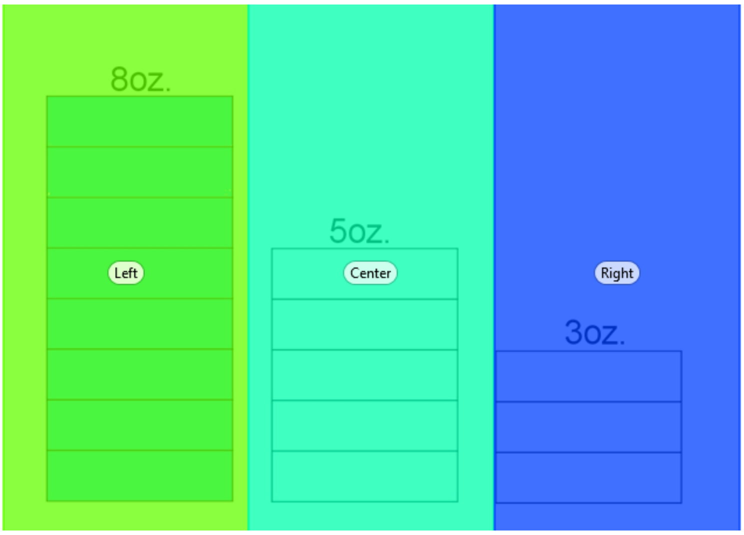

Figure 21 AOI's for Water Jug

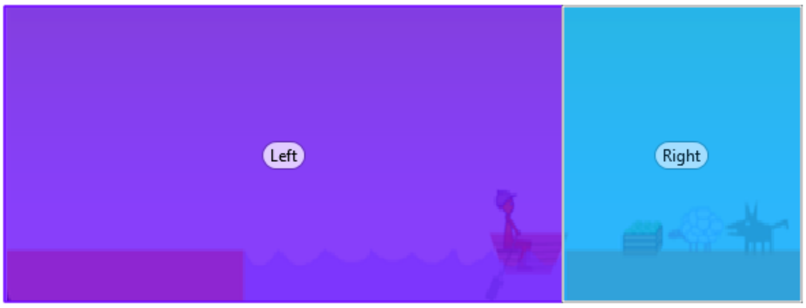

Figure 22 AOI's for RP

As stated before, similarity coefficient D after Longest Common Subsequence algorithm is executed in Matlab given the scan paths obtained from above heat maps and Area of Interests. The analysis done below are performed over this similarity measure.

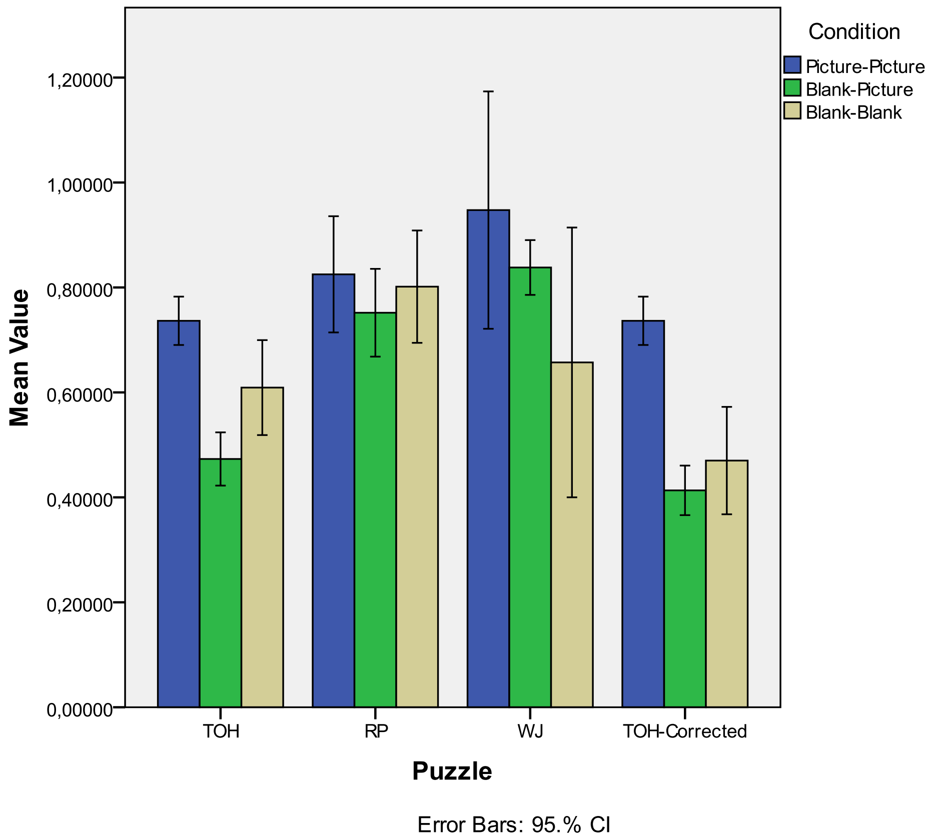

Figure 23 Mean Value Bar Chart for Longest Common Subsequence

Scan path strings are compared across three different conditions, namely picture-picture, picture-blank, and blank-blank for each puzzle type. In the case of Towers of Hanoi, average LCS values in picture-picture, blank-blank and picture-blank conditions were .745, .609 and .473 respectively. In the River Problem, average LCS values in picture-picture, blank-blank and picture-blank conditions were .825, .802 and .752 respectively. In the Water Jug problem, LCS values were .947, .657 and .838 respectively. The fourth value is the TOH-corrected value, which is obtained by simple transformations done in order to adjust a reasonable AOI to the blank condition of Tower of Hanoi.

LCS distances in homogenous cases (i.e. blank-blank and picture-picture) were higher in the case of TOH and RP puzzles. WJ does not exhibit the same pattern, where picture-blank LCS value is higher than blank-blank condition. A 2-way ANOVA conducted over LCS distances revealed a main effect of problem type, $F(2, 153)=19.2$, $p<0.01$, a main effect of condition, $F(2,153)=6.23$, $p<0.05$ and an interaction effect, $F(4,153)=.096$, $p<0.05$.

In short, LCS analysis showed that the most similar scan paths in the picture-blank condition occurred in the WJ problem. In contrast, in the remaining two puzzles the LCS distances between picture and blank cases were large enough to produce a statistically significant difference.

Chapter 5

Discussion

This thesis has focused on understanding the role of eye-movements during problem-solving processes. In order to achieve this, the main emphasis has been given to problems that tap on visuospatial reasoning skills like the Tower of Hanoi, Water Jug, and Wolf-Sheep-Cabbage puzzles. These puzzles have highly been referred in the relevant literature and they require considerable level of visual information processing and integration in order to comprehend and solve the puzzle. On the one hand, it has been hypothesized that problem-solving processes could be dependent on eye-movements and without the contribution of eye-movements mental imagery alone might not suffice to generate and execute the solution strategy. From the grounded/embodied cognition perspective, it could be argued that sensory modalities are an indispensible part of higher-order cognition, so the cognitive processes underlying problem-solving require active contribution of these modalities. On the other hand, according to the classical modular account, cognitive processes underlying problem solving may not be affected by restrictions imposed on the eye movements and sensory information due to the modular distinction between these processes.

To investigate the hypothesis that eye movements are strongly coupled to the visuospatial reasoning processes as predicted by the embodied perspective, a specific condition in which participants were not allowed to make eye-movements has been developed (which is called as the “fixation” condition). In this condition participants had to attempt each puzzle without having the contribution of their eye movements. The results indicate that participants’ task completion times and accuracy ratings across picture, blank and fixation conditions in general did not significantly differ across the three puzzles. Participants were particularly successful in the Tower of Hanoi puzzle as compared to other two puzzles. When the analysis was restricted to successful cases only, a marginally significant difference among conditions was observed in the river problem case, where participants spent more time in the fixation condition. Moreover, when only the performance in the fixation condition is compared across three puzzles, participants spent significantly more amount of time for the water jug problem, which suggests that the performance in this problem is particularly affected by the restriction on eye movements. In short, restricting the eye movements had some influence on the problem solving performance, but not in a straight-forward manner as suggested by our hypothesis. The differential effect across puzzle types could be due to the difference in mental effort required to keep track of intermediary steps. The water jugs puzzle requires more complicated arithmetic operations as compared to keeping track of disk locations in the Tower of Hanoi and the object locations in the river problem, which seemed to contribute to the significant increase in response time and fixation duration measures in the water jug problem.

Secondly, it has been hypothesized that people would highly benefit from the presence of visual aids during the problem solving process. In order to test this hypothesis the blank screen paradigm is employed where the fixation patterns and scan paths observed during the picture and blank screen conditions were compared against each other. The eye tracking data in both conditions hinted at systematic movements that seem to simulate the intermediary steps one has to carry out to solve each problem. This observation is supported by the fact that LCS similarity values between picture-picture, picture-blank and blank-blank trials were generally larger than 0.7 for all puzzle types, except the blank-blank comparison for the tower of Hanoi problem.

Scan path similarity as measured by LCS were the highest for the picture-picture comparison for all the puzzles. This suggests that people tended to look at the areas of interests in a similar order in the picture condition as compared to blank-blank and blank-picture conditions. The increased similarity among scan paths in the picture condition seems to be due to the salient features of the pictures. Scan path similarity between blank and picture conditions were significantly lower in the tower of Hanoi puzzle. This is possibly because each participant envisioned the locations of pegs in the blank condition in a relatively different manner. Scan path similarities across picture-picture, picture-blank and blank-blank were the highest for the river problem. This may be because the problem includes two sides of the river as relevant locations to keep the objects, which may have produced a rather simple gaze sequence as compared to other two puzzles. A similar result was observed for the water jug puzzle in the picture-picture and picture-blank conditions, but a lower LCS similarity was observed in the blank-blank condition. This could be due to differences in envisioning the locations of the jugs on the blank screen.

One of the preceding issues in this study is related to the experimental design by which the comprehension and problem-solving processes have been distinguished with the help of separate presentations. Our pilot studies showed that the participants will attempt to solve the presented problem as soon as they see the question. For that reason, we presented the question in a separate slide just after presenting the general description of the puzzle. Participants had to wait for the question slide which was presented for 6 seconds and then the solution process was initiated by moving to one of the condition slides; namely visual aid, blank screen, or fixation conditions. Our post-experimental reports obtained from the participants have demonstrated that most of them have correctly understood the problem. Only four of the participants reported that they had difficulty in reading and comprehending the question slide that is presented for 6 seconds. For the further studies, we might consider to extend it up to 10 seconds in order to guarantee that all of the participants could easily read them.

Another potential confounding issue has been related to the prior knowledge of the participants about the presented problems. To be more specific, if the problems were known in detail and especially their results, the solution processes might not contain the eye-tracking data that we have been looking for. The post-experiment tests showed that even though most of the participants could remember the wolf-sheep-cabbage puzzle, they did not have any idea about the final outcome (in other words, the result of the question). Since many of the participants who declared that they could remember the puzzle have responded incorrectly, we have not regarded this factor of prior knowledge as a special problem. However, there is also the possibility of learning effect across the questions, thus, it might be expected an increase within the performance from the first problem till the last one, since all of these problems contained a similar structure.

In addition to this, it could be the case that in some situations participants may have responded to the problems by using their intuitive judgments based on the predictions they could develop as they engage with the puzzle. Our main aim has been to obtain their deliberative reasoning processes relying on the algorithmic solution they could develop. For the visual aid and blank screen conditions, it was possible to track their eye movements and to observe if the participant attempted to solve the puzzle on algorithmic grounds or if they preferred to give their estimations.

The puzzles used in this study were selected with the assumption that they had similar level of difficulty, since they required exactly the same number of solution steps. It was expected that the performance levels among the participants would be similar but the results have demonstrated that one of the puzzles (Water Jug) was more difficult than the other two puzzles. Although their solutions required minimally 7 steps in order to solve the problem, participants performed poorly on the water jug puzzle in terms of task completion time and accuracy (for all conditions). This is most probably due to the higher cognitive demand required for this puzzle (WJ) than the other puzzles, since the participants needed to keep track the amount of water inside all of the three jugs –meaning that both location and content information are required. On contrary, for the other puzzles (TOH & RP), the participants needed to keep track of the locations of the items given in the puzzles. This observation is also supported by the significant increase in the average fixation duration values observed in the water jug problem.

Overall, the main findings of this study suggest that people have an observable tendency to make use of eye-movements and eye-fixations when they use mental imagery to execute their strategies even in the absence of a relevant visual background. Based on the results obtained from this thesis work, eye-movements could be considered as a facilitator mechanism for the retrieval and maintenance of relevant information in working memory during problem solving. This finding is in line with the Extended Mind Hypothesis (Clark & Chalmers, 1998) which argues that some of the cognitive work during problem solving can be offloaded to external resources acted on by sensori-motor processes such as fixations and saccades. However, our results did not reveal a significant impairment on problem solving performance when the eye movements were restricted, which suggests that the relationship between external and internal phenomena is not so straightforward.

Chapter 6

Conclusion

This thesis work has been an exploratory study to investigate the role of eye movements during problem-solving processes. The obtained results have revealed that eye movements might have a prominent role during the retrieval and management of relevant information during problem-solving. The results for the fixation condition in which the participants' eye movements were deliberately restricted did not support the initial hypothesis derived from the embodied cognitive perspective. In other words, the participants could solve the problems with these three conditions at almost similar levels of performance as indicated by their task completion times and levels of accuracy for these conditions. Although this result does not support our initial prediction based on the grounded/embodied cognition framework, our scan path analysis indicated that there are similarities in between gaze patterns observed between picture and blank conditions, which suggests that visuospatial reasoning processes may still be informed by physical saccadic movements in the absence of a visual cue. The similarities in scan paths suggest that an imaginary visual scene seems to be monitored by a majority of the participants during the blank condition. However, results for the fixation condition suggest that such saccades may not be indispensable to engage with these problems.

6.1 Limitations and Future Studies

The present study has some limitations that may motivate further investigations on the relationship between gaze patterns and visuospatial reasoning. The first limitation is related to the tasks selected for the study. Knowledge lean, well-defined tasks that do not require any sensori-motor engagement with the puzzles were used in this study. An important observation in the embodied/situated cognition framework is that problem solvers tend to exploit sensori-motor contingencies such as epistemic moves during problem solving. Such actions possibly inform the cognitive processes recruited during problem solving activity by offloading some of the work to sensory processes. In this study we could test the effects of limited motor engagement, namely eye gaze movements.

In addition to this, it is also possible that small gaze events that resemble orderly eye movements in the fixation condition may have been suppressed by the fixation algorithm used in Tobii. A further analysis with a higher resolution eye tracker would provide better data regarding whether eye gaze movements can be fixed as desired. The location of the fixated object and its shape could be varied to further test the influence of different fixation locations, to see if problem solving performance would be significantly influenced or not by constraining the eye movements.

Another limitation is related with coming up with an experimental design that adequately delineates between the representation and solution process. This was particularly challenging to control for, since participants tend to start thinking about the problem while they are reading the instructions, even though they do not know which specific question will be asked later. Problems of understanding the given scenario was another challenge as the information provided on the slides was not adequate for a small number of subjects. Animated instructions could be used to improve the instructions, but such representations will probably guide the subjects' thinking in more complicated ways. A series of experiments could be performed with the use of near infrared spectroscopy technique (fNIRS) in order to compare the working memory load among the conditions as well as the given problems.

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APPENDICES

APPENDIX A: Matlab Code for Edith Distance Calculation

```
function d = EditDist(s1,s2,varargin)
%EDITDIST Finds the Edit Distance between strings s1 and s2. The
Edit Distance
%          is defined as the minimum number of single-character edit
operations
%          (deletions, insertions, and/or replacements) that would
convert
%          s1 into s2 or vice-versa. Uses an efficient dynamic
programming
%          algorithm. Useful for gene sequence matching, among other
applications.
%
%          Example: d = EditDist('cow','house') returns a value of 4.
%          Example: s1 = 'now'; s2 = 'cow'; EditDist(s1,s2) returns a
value of 1.
%          Example from gene sequence matching:
%          EditDist('ATTTGCATTA','ATTGCTT') returns a value of 3.
%
%          If there are more than two inputs, the 3d, 4th, and 5th
inputs will be
%          interpreted as the costs of the three edit operations:
DELETION,
%          INSERTION, and REPLACEMENT respectively. The default is 1
for all
%          three operations. Note that if the cost of replacement is
at least twice
%          the respective costs of deletion and insertion,
replacements will never be
%          performed.
%
%          Example: EditDist('cow','house',1,1,1) returns a value of
4.
%          Example: EditDist('cow','house',1,2,1.5) returns a value
of 5.
```

```
%         Example: EditDist('cow','house',1,1,2) returns a value of
6.
%
%
%USAGE:   d = EditDist('string1','string2');
%
%         d = EditDist('string1,'string2',1.5,1,2);
%
%

%Written and tested in Matlab 5.3, Release 11.1 (should work with
earlier versions).
%Copyright 2000, Miguel A. Castro 6/4/2000
%talk2miguel@yahoo.com
%--------------------------------------------------------------------
-----------------------

%Determine the number of inputs. If 2 inputs, set default edit costs
to 1.
%Otherwise, make sure there are exactly 5 inputs, and set edit costs
accordingly.
if ~isempty(varargin)
   if length(varargin) ~= 3
      error('Usage is:
EditDist(''string1'',''string2'',DeleteCost,InsertCost,ReplaceCost)'
);
   end;
   DelCost = varargin{1};
   InsCost = varargin{2};
   ReplCost = varargin{3};
else
   DelCost = 1;
   InsCost = 1;
   ReplCost = 1;
end;

[m1,n1] = size(s1);
[m2,n2] = size(s2);

%Make sure input strings are horizontal.
if ~(ischar(s1) & ischar(s2) & m1 == 1 & m2 == 1)
   error('s1 and s2 must be horizontal strings.');
end;

%Initialize dynamic matrix D with appropriate size:
D = zeros(n1+1,n2+1);

%This is dynamic programming algorithm:
for i = 1:n1
   D(i+1,1) = D(i,1) + DelCost;
end;

for j = 1:n2
   D(1,j+1) = D(1,j) + InsCost;
end;

for i = 1:n1
   for j = 1:n2
      if s1(i) == s2(j)
         Repl = 0;
      else
```

```
         Repl = ReplCost;
      end;
      D(i+1,j+1) = min([D(i,j)+Repl D(i+1,j)+DelCost
D(i,j+1)+InsCost]);
   end;
end;

d = D(n1+1,n2+1);
```

APPENDIX B: Matlab Code for Longest Common Subsequence

```
function [D, dist, aLongestString] = LCS(X,Y)
%%%Calculates the longest common substring between to strings.
%%%Code written by David Cumin
%%%email: d.cumin@auckland.ac.nz
%%%INPUT
%%%X, Y - both are strings e.g. 'test' or 'stingtocompare'
%%%OUTPUT
%%%D is the substring over the length of the shortest string
%%%dist is the length of the substring
%%%aLongestString is a sting of length dist (only one of potentially
many)

%%%For example
%X = 'abcabc';
%Y = 'adcbac';
%[D dist str] = LCS(X,Y);
%%% results in:
%%% D = 0.6667
%%% dist = 4
%%% str = acbc
%%% this is seen for X: 'a-c-bc' and Y: 'a-cb-c'

%%%Make matrix
n =length(X);
m =length(Y);
L=zeros(n+1,m+1);
L(1,:)=0;
L(:,1)=0;
b = zeros(n+1,m+1);
b(:,1)=1;%%%Up
b(1,:)=2;%%%Left

for i = 2:n+1
    for j = 2:m+1
        if (X(i-1) == Y(j-1))
            L(i,j) = L(i-1,j-1) + 1;
            b(i,j) = 3;%%%Up and left
        else
            L(i,j) = L(i-1,j-1);
        end
        if(L(i-1,j) >= L(i,j))
            L(i,j) = L(i-1,j);
            b(i,j) = 1;%Up
        end
        if(L(i,j-1) >= L(i,j))
            L(i,j) = L(i,j-1);
            b(i,j) = 2;%Left
        end
    end
end
L(:,1) = [];
L(1,:) = [];
b(:,1) = [];
```

```matlab
b(1,:) = [];
dist = L(n,m);

D = (dist / min(m,n));
if(dist == 0)
    aLongestString = '';
else
    %%%now backtrack to find the longest subsequence
    i = n;
    j = m;
    p = dist;
    aLongestString = {};
    while(i>0 && j>0)
        if(b(i,j) == 3)
            aLongestString{p} = X(i);
            p = p-1;
            i = i-1;
            j = j-1;
        elseif(b(i,j) == 1)
            i = i-1;
        elseif(b(i,j) == 2)
            j = j-1;
        end
    end

    if ischar(aLongestString{1})
        aLongestString = char(aLongestString)';
    else
        aLongestString = cell2mat(aLongestString);
    end
end

end
```

APPENDIX C: Gönüllü Katılım Formu (In Turkish)

Bu çalışma, Doruk ÖZDEMİR tarafından yüksek lisans tezi için yürütülen akademik bir çalışmadır. Çalışmanın amacı, katılımcıların farklı durumlarda, verilen sorularını çözme sürelerini ve bu süreçteki göz hareketlerini incelemektir. Çalışmaya katılım tamamimiyle gönüllülük temelindedir. Ankette, sizden kimlik belirleyici hiçbir bilgi istenmemektedir. Cevaplarınız tamamıyla gizli tutulacak ve sadece araştırmacılar tarafından değerlendirilecektir; elde edilecek bilgiler bilimsel yayınlar ve sunumlar için kullanılacaktır.

Verilecek bulmacalar, kişisel rahatsızlık verecek sorular içermemektedir. Ancak, katılım sırasında sorulardan ya da herhangi başka bir nedenden ötürü kendinizi rahatsız hissederseniz deneyi yarıda bırakıp çıkma hakkına sahipsiniz. Böyle bir durumda deneyin yürütücüsüne, deneyi tamamlamayacağınızı söylemeniz yeterli olacaktır. Deney sonunda, bu çalışmayla ilgili sorularınız cevaplandırılacaktır. Bu çalışmaya katıldığınız için şimdiden teşekkür ederiz. Çalışma hakkında daha fazla bilgi almak için Doruk Özdemir'e ulaşabilirsiniz.

Bu çalışmaya tamamen gönüllü olarak katılıyorum ve istediğim zaman yarıda kesip çıkabileceğimi biliyorum. Verdiğim bilgilerin bilimsel amaçlı yayımlarda kullanılmasını Kabul ediyorum. (Formu doldurup imzaladıktan sonra uygulayıcıya geri veriniz).

Ad-Soyad   Tarih

İmza

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APPENDIX D: METU Ethics Committee

1956

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GÖNDEREN: Prof.Dr.Nazife Baykal
Enformatik Enstitüsü Müdür

KONU: Doruk Özdemir

Bilişsel Bilimler Anabilim Dalı Yüksek Lisans programı öğrencisi 1710102 no.lu Doruk Özdemir'in, 01 Aralık 2012 – 31 Ağustos 2013 tarihleri arasında "GÖZ İZLEME VE TEPKİ SÜRESİ METOTLARI KULLANILARAK BULMACA ÇÖZME SÜREÇLERİNİN ANLAŞILMASI" başlıklı araştırma çalışmasına ilişkin "ODTÜ Bilgi İşlem Daire Başkanlığı İnsan Bilgisayar Etkileşimi Araştırma ve Uygulama Laboratuvarı"nda uygulama yapmak için görevlendirme başvurusu incelenmiş, ilgili EABD Başkanlığı'nın görüşüne dayanarak adı geçen öğrencinin isteği doğrultusunda görevlendirilmesine Etik Komite onayı koşulu ile uygun görülmüştür.

Saygılarımla,

Ek: YKK
EABD

Etik Komite Onayı

Uygundur

Prof. Dr. Canan ÖZGEN

.../.../2012

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TEZ FOTOKOPİSİ İZİN FORMU

ENSTİTÜ

Fen Bilimleri Enstitüsü ☐

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YAZARIN

Soyadı : ÖZDEMİR
Adı : DORUK
Bölümü : BİLİŞSEL BİLİMLER

TEZİN ADI (İngilizce) : A CASE STUDY OF PROBLEM SOLVING IN EYE-TRACKING

TEZİN TÜRÜ : Yüksek Lisans ☑ Doktora ☐

1. Tezimin tamamından kaynak gösterilmek şartıyla fotokopi alınabilir. ☑
2. Tezimin içindekiler sayfası, özet, indeks sayfalarından ve/veya bir bölümünden kaynak gösterilmek şartıyla fotokopi alınabilir. ☐
3. Tezimden bir (1) yıl süreyle fotokopi alınamaz. ☐

TEZİN KÜTÜPHANEYE TESLİM TARİHİ : …………………….