NEURAL AND OCULAR CORRELATES OF VISUOSPATIAL PROBLEM SOLVING PROCESSES

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ABSTRACT

NEURAL AND OCULAR CORRELATES OF

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Current thesis analyzes the neural and ocular correlates of visuospatial problem solving processes by investigating three different two-dimensional problems which are constructed with regard to different problem features and problem spaces. Recent studies focused on visuospatial problem solving processes suggest that eye tracking and functional near-infrared spectroscopy methodologies can provide better understanding of fixation patterns and working memory demands respectively. Experimental protocol including various visuospatial problem tasks was applied to approximately 20 young adults. While completion times and accuracy percentage were calculated for behavioral results, fixation duration, the number of fixation and fixation rate were calculated for eye-tracking results and maximum oxygenation values (i.e. peak values) were calculated for fNIR results. During problem solvers engaged in visuospatial tasks, behaviors which were categorized as distance, similarity and orientation were observed from scan path analysis. Results revealed that different working memory load and fixation related patterns occurred for different visuospatial reasoning tasks.

Keywords: visuospatial problem solving, eye-tracking, fnir, prefrontal cortex

ÖZ

GÖRSEL-UZAMSAL PROBLEM ÇÖZME SÜREÇLERİNİN

NÖRAL VE OKÜLER İZDÜŞÜMLERİ

TÜRKMEN, Gamze

Yüksek Lisans, Bilişsel Bilimler

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Bu tez, görsel uzamsal problem çözme süreçlerinin prefrontal ve oküler izdüşümlerini farklı problem özelliklerine ve farklı problem alanlarına göre tasarlanmış iki boyutlu üç farklı problem türüyle anlamaya çalışmaktadır. Görsel-uzamsal problem çözme süreçleriyle ilişkili yakın zaman çalışmaları, göz izleme ve fonksiyonel near-infrared spektroskopi yöntemlerinin odaklanma paternlerinin ve işler bellek yüklerinin anlaşılmasında yararlı olduklarını öne sürmektedir. Tez çalışması kapsamında farklı görsel-uzamsal görevlerin bulunduğu bir deney protokolü yaklaşık 20 genç yetişkine uygulanmıştır. Analizler kapsamında davranışsal sonuçlar için tamamlama süresi ve doğruluk yüzdeleri hesaplanırken göz izleme sonuçları için odaklanma süresi, odaklanma sayısı ve odaklanma oranı ve fNIR sonuçları için maksimum oksijenleşme değerleri (örn. tepe nokta değerleri) hesaplanmıştır. Problem çözücülerin görsel uzamsal problemlerin çözümü sırasında modele uzaklık, modele benzerlik ve modelin konumu gibi bilgileri referans aldığı gözlemlenmiştir. Sonuçlar, farklı görsel-uzamsal görevler için farklı işler bellek yüklerinin ve odaklanma paternlerine sebep olduğunu göstermektedir.

Anahtar kelimeler: görsel-uzamsal problem çözme, göz izleme, fnir, prefrontal korteks

To my family

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CHAPTER 1

INTRODUCTION

We perceive and explore the outside world with our senses and reflect what is on our minds while viewing areas of interests (Ballard, Hayhoe, Pook & Rao, 1997; Just & Carpenter, 1980). Visuospatial shapes are featured in those areas of interests beyond any doubt. We think about visuospatial shapes while engaging in mathematical activities, in natural scenes, or imaging an umbrella which may be constructed with the J letter and horizontal D letter (Tversky, 2005). Constructing visuospatial shapes can be used in problem solving activities either internally or externally. So, the substantial question in cognitive science which is to understand the possible characteristics of a shape in reference to internal and external representations is to figure out how shapes are used during humans' visuospatial reasoning processes.

A considerable number of studies focus on ocular and neural correlates of visuospatial problem solving processes. For instance, recent studies in cognitive neuroscience have identified the critical role fulfilled by the prefrontal cortex in the management of visuospatial working memory and decision making during visuospatial tasks (Ayaz, Shewokis, Izzetoglu, Cakir, & Onaral, 2012; Honegger et al., 2011; Owen, McMillan, Laird, & Bullmore, 2005; Petrides, 2000; Ricciardi et al., 2006; Sato et al., 2013; Schon, Ross, Hasselmo, & Stern, 2013; Slotnick, 2005). In particular, visuospatial tasks that involve abstract thinking were found to recruit a fronto-parietal network of cortical areas, particularly in the right hemisphere (Jung & Haier, 2007).

Similarly, numerous eye tracking studies have focused on eye gaze patterns observed during different kinds of visuospatial reasoning tasks. For instance, increased difficulty of cognitive processes has been associated with increased number of fixation durations (Liversedge & Findlay, 2000). Additionally, different task types are known to elicit different eye movement patterns (Tatler, Wade, Kwan, Findlay, & Velichkovsky, 2010). As the seminal work by Yarbus (1967) indicated, gaze patterns may show key differences depending on the task at hand, even when subjects continue to attend to the same stimulus at the background. In addition to this, complex tasks that require comparisons between complex patterns (Just & Carpenter, 1976) reveal reciprocating saccades as in block-copying tasks during different stages of the task (Ballard, Hayhoe, Pook, & Rao, 1997; Hayhoe, Bensinger, & Ballard, 1998).

Understanding the nature of visuospatial reasoning processes are particularly important in the context of mathematical cognition (Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999). Solving geometrical problems often require complex visuospatial reasoning skills. Puzzles such as Tangrams that require solvers to produce larger shapes by arranging several smaller pieces are popularly used in elementary math education to help students develop geometry concepts such as translation, symmetry and area (C. P. Lin, Shao, Wong, Li, & Niramitranon, 2011). In particular, while working on a task like Tangram, the solver must (i) identify the relevant pieces, (ii) search the target model for familiar patterns; (iii) retrieve relevant facts from memory; (iv) make inferences about possible arrangements, and (v) enact the moves and reflect on the unfolding arrangement. Inferences can be reported by some nonverbal attempts during the visuospatial problem solving processes.

Studies aiming at finding neural correlates of mathematical cognition have been mostly focusing on arithmetical operations (Anderson, Betts, Ferris, & Fincham, 2011; Meiri et al., 2012; Rosenberg-Lee, Lovett, & Anderson, 2009). The syntactic, orderly nature of arithmetic tasks allow experimenters to easily control task complexity and linguistic factors, which make such tasks ideal candidates for neuroimaging studies. However, visuospatial reasoning tasks often have more degree of freedom in terms of different solution paths one can follow. Moreover, inferences made during visuospatial problem solving tasks are notoriously difficult to verbalize for the subjects, which make the use of think-aloud protocols methodologically challenging. So, there is a need for incorporating neuroimaging studies with eye tracking and activity measures (e.g. screen recording of time-stamped moves) to better make sense of brain activation patterns observed during visuospatial reasoning tasks.

Existing neuroimaging (Cabeza & Nyberg, 2000) studies of visuospatial reasoning processes primarily use modalities such as functional magnetic resonance imaging (fMRI), positron emission tomography (PET) and electroencephalography (EEG). Each imaging modality offers specific advantages and disadvantages for the monitoring of neural activity during such tasks. For instance, fMRI and PET are more restrictive as compared to EEG since such devices require subjects to be located in confined positions. However, the placement of EEG sensors and ensuring their conductivity during experiments require considerable expertise.

Recently functional near-infrared spectroscopy (fNIRS) emerged as a new brain imaging modality which offers compatible, user-friendly and convenient design especially suitable for HCI studies (Girouard, Hirshfield, Solovey, & Jacob, 2008). fNIRS monitors brain activity by monitoring optical changes that occur in the blood vessels located on the surface of the brain cortex due to neural activity (M. Izzetoglu et al., 2005). fNIRS provides a good balance of temporal and spatial resolution, which makes it suitable for conducting studies at more ecologically valid situations (M. Izzetoglu et al., 2005). The portability of fNIRS makes it an ideal candidate for conducting visuospatial reasoning tasks in synch with a desktop eye tracker.

Despite the vast interest in the cognitive science literature towards visuospatial reasoning, simultaneous investigation of neural and ocular correlates of such processes via synchronous recording of eye gaze and neuroimaging data is a relatively recent domain of investigation. These studies generally focus on identifying interrelationships among neural and ocular processes underlying visuospatial reasoning. This thesis study aims to contribute to this effort by simultaneously investigating neural and ocular patterns elicited during tangram and block copying paradigms, which require visual inspection, manipulation and arrangement of geometric objects. In particular, this thesis investigates the differences in problem solvers' strategies while they solve visuospatial tangram problems that differ in terms of the symmetry/asymmetry of the target model and the organization of the problem space (outline/no outline). In addition to tangram tasks, participants were also given visuospatial tasks such as block copying and mental rotation tasks, which are hypothesized to tap in neural and ocular resources differently as compared to tangram tasks. For this purpose, the differences among these tasks are investigated with eye tracking and fNIRS recordings. The measures include the number of fixation counts, fixation durations, and the number of transitions from eye tracking data; and the relative changes in the concentration of oxygenation and total hemoglobin levels from fNIRS data. These differences are analyzed and interpreted with regards to specific motor and working memory demands elicited by each type of visuospatial task.

1.1 Research Aims

Tangram problems require participants to engage in visuospatial reasoning with the given specific pieces. Before or during dynamic transformations of geometrical objects, making inferences from different possibilities with regard to complexity of the problems must be made to reach the given target model. The complexity of tangram problems is determined in reference to (i) minimum number of transformations required to fit the target model, (ii) workspace area condition (outlined or without outlined), (iii) problem construction (symmetric or antisymmetric).

For the tangram task, it was expected that the workspace in which the pieces are arranged would elicit more fixation counts in the outline condition in comparison to without outline condition, and that patterns of eye movements would reflect distance related behaviors (such as locating the piece relative to other piece after looking at its place on the target model); as well as orientation related behaviors (such as transforming the piece after looking at its shape on the target model).

There are three premises that form the foundation of the research questions in this study: (1) Participants' eye movements will focus on the distinct features of the problems to reveal information about the relationship between the initial and the goal states. (2) Tangram tasks are constructed from geometrical shapes and therefore participants will construct the model in the workspace area by considering the transformations and orientations of the current pieces. (3) Engaging with difficult tasks will expend more cognitive resources, which would elicit more activity in the prefrontal cortex associated with working memory and visual attention.

Although block copying tasks have been presented within a dynamic environment which allows participants to manipulate pieces by drag-and-drop actions as tangram tasks, they have limited number of blocks and do not require any rotation or transformation. However, engaging in tangrams require excessive amount of rotations and transformations to reach the goal state due to various geometrical objects which differ in reference to their shapes and orientations. In brief, while conditions in block-copying tasks are comprised of different colors assigned for limited blocks, target model constructions and number of individual blocks to copy within three different areas; conditions in tangram tasks include various geometrical objects (two little triangles, one medium triangle, two large triangles, one parallelogram and one square) in different orientations and degree of rotation within three different areas. These differences result in different strategies while solving the given problems. While block copying tasks require sequential order to copy the blocks with regard to given target model, in tangram tasks, participants tend to use heuristics. So, our first and second research questions were aimed towards investigating the neural and ocular implications of these differences.

Research question 1: Is there any significant difference in solvers' gaze patterns during solvers attempt to solve block copying and tangram tasks?

Hypothesis 1: While solvers need more back and forth saccades and longer fixation durations during the solution of the tangram tasks, they will follow a sequential order in the block-copying tasks.

Research question 2: Is there any significant difference in brain activation data measured during block copying and tangram tasks?

Hypothesis 2: Solvers will expend more cognitive resources during solving tangram problems due to various features and this difference will be observed especially at the right prefrontal cortex.

Additionally, geometry analogy and tangram tasks have similarities and dissimilarities. In geometry analogy tasks, solvers think of the possible parts of the given target model and all decisions are made mentally. However, as aforementioned, tangram tasks allow solvers to manipulate the pieces. Since target models of geometry analogy tasks are also constructed by different objects like the tangram tasks, pieces may have different degrees of rotation as they form the target shape. This requires solvers to mentally rotate the pieces and assess their fit during the solution. So, our third and fourth research questions aim to investigate the ocular and neural implications of these differences.

Research question 3: Is there any significant difference in solvers' gaze patterns during the solvers attempt to solve geometry analogy and tangram tasks?

Hypothesis 3: Solvers will do more reciprocating saccades between the model and relevant piece even for distinct features while engaging in geometry analogy tasks.

Research question 4: Is there any significant difference in brain activation data measured by block copying tasks and tangram tasks?

Hypothesis 4: Geometry analogy tasks will require mental transformation and rotation of pieces. So, solvers will have to store the relevant actions in working memory and this will result in higher working memory load during solving geometry analogy tasks compared to tangram solution process.

Finally, problem spaces and shapes of tangram tasks have organized in many different ways: outline vs. no outline, symmetric vs. antisymmetric. So, our fifth and sixth research questions aim to investigate the ocular and neural implications of these differences.

Research question 5: Is there any significant difference in solvers' gaze patterns with regard to problem space features (with outline or without outline, symmetric vs. antisymmetric) while solving tangram puzzles?

Hypothesis 5: Solvers will show distance and size related behaviors in no outline organization. Back and forth saccades between the target model and the constructed image will show differences. Since outline organization has a reference frame for the target model, solvers will not make any saccade related with understanding the sense of size.

Research question 6: Is there any significant difference in solvers' brain activity levels at the prefrontal cortex as measured with fNIRS with regard to problem space features (with or without outline, symmetric vs. antisymmetric) while solving tangram puzzles?

Hypothesis 6: In without outline organization, participants will expend more cognitive resources compared to the with outline organization.

1.2 Approaches and Significance

Eye-tracking and fNIRS technology were used in this research to understand the ocular and neural correlates of visuospatial problem solving. Studies in eye tracking and fNIRS technology about visuospatial problem solving with healthy (Ayaz et al., 2012; Epelboim & Suppes, 2001; Kaller, Rahm, Bolkenius, & Unterrainer, 2009; Nitschke, Ruh, Kappler, Stahl, & Kaller, 2012; Ruh, Rahm, Unterrainer, Weiller, & Kaller, 2012) and clinical (Cocchi et al., 2013; Franceschi et al., 2007; Jennekens-Schinkel, van der Velde, Sanders, & Lanser, 1989) subjects will provide a valuable perspective for this research in comparing results. Indeed, this thesis will contribute to methodological insights for future eye-tracking and fNIRS researches on the process of visuospatial problem solving.

Top-down processes will guide the study in concurrence with bottom-up processes. This combined approach under the visuospatial reasoning domain will provide understanding internal and external representations which significantly influence the aspects of problem solving.

1.3 Organization of the Thesis

Chapter 2 will include a literature review on visuospatial reasoning (section 2.1), neuroimaging and eye tracking studies on visuospatial problem solving (section 2.2 and 2.3), and a summary about the existing literature (section 2.4). Chapter 3 will consist of the used methodology throughout the thesis study. Chapter 4 will present the results of the study. Chapter 5 will discuss and provide a conclusion about the results. Finally, Chapter 6 will draw the limitations of the study and provide ideas about the possible future researches.

CHAPTER 2

LITERATURE REVIEW

2.1 What is Visuospatial Reasoning?

Bruner (1973) defined reasoning as going beyond the given information. The substantial point in the aforementioned sentence is primarily finding ways to how we can go beyond the given information rather than what is beyond the given information. To define "how" part, two ways can be tried. The first way is to transform the given information and the second way is to make inferences and judgments about the given information (Tversky, 2005).

Tversky (2005) stated visuospatial reasoning domain requires visuospatial information which is comprised of visual and spatial properties with regard to static and dynamic arrays. While shape, texture, color, location of a subject relative to one another in a static arrangement refer to visual properties, pathways or sequences of movements or relative change of direction (in mentally or physically) refer to spatial properties.

Representations and transformations are two important concepts in concern with reasoning. Representation can be a concept, an image, a thought or an engram which symbolize, reflect or replace the events, phenomenon, or objects in the mind; whereas transformations are limited by the captured representations which refer to forms of visuospatial inferences (Tversky, 2005).

Visuospatial reasoning can be approached by both top-down and bottom-up processes. Mental imagery (see Section 2.1.1) is an example for the bottom-up approach and more complex reasoning based on visuospatial information and diagrams (see Section 2.1.2) are examples for the top-down approach.

People can assign a different meaning to mental representations. For instance, the same figure of a natural environment can be designed or sketched in different ways by the people who deliver the message and create mental representations. Additionally, mental transformations which are shaped by the representations show visuospatial reasoning have also motor foundations beside perceptual foundations.

Eye tracking and neuroimaging studies are used to investigate neural and ocular correlates of visuospatial reasoning with regard to studying on mental representations and transformations. Following sections will mention these researches and the relevance with the current thesis study.

2.1.1 Mental Imagery

Imagery (internal representation) is one of the basic components of the human cognitive system and a substantial cognitive method for problem solving. Mental imagery, known as a bottom-up approach for visuospatial reasoning, studies have mostly focused on mental rotation of complex objects that Shepard and Metzler (1971) proposed.

Shepard and Metzler (1971) presented a set of three dimensional objects within different angles and asked participants for finding the identical shape to the given shape. The response times of the participants showed linear increase as the angle difference of the shapes increased. This behavioral data illustrated that the participants tried to take one or two reference frames to decide on how much degree and from which perspective they could rotate the three-dimensional objects.

Moreover, Kosslyn et al. conducted another experiment that supports the aforecited study. They wanted from participants to memorize a map of island which has different places located on the map like a well and a cave. Then, subjects were asked to imagine the two points they saw on the map. Results revealed that as the actual distance on the map increases, subject's mental scanning also increases (Denis & Kosslyn, 1999; Kosslyn, Ball, & Reiser, 1978). So, this finding moves the study of Shepard and Metzler one step beyond. However, these studies have mostly been designed aiming at measuring one difference between the tasks so that these studies can only show us how "a" mental transformation can be performed. To put in a different way, studies have been conducted in which some situations and tasks require applying several mental transformations. For instance, more than one transformation is needed to be applied for geometry analogy problems (Kosslyn, 1980; Tversky, 2005).

Novick and Tversky (1987) stated that the order of performing transformations affect the solution accuracy and performance time. The preferred order is performed not by in working memory, but considerations about general information, task specificity, and individual differences in analogy ability. Since analogies are performed in working memory, more difficult transformations may be performed at the first order to reduce the working memory load and facilitate the problem solving. However, Novick and Tversky (1987) found that geometrical shapes were not transformed with regard to difficulty.

2.1.2 Diagrammatic Reasoning

Spatial diagrams (external representation) play facilitative role in reasoning and problem solving process is a top-down approach for visuospatial reasoning. Diagrams are designed to provide inferences considering lower level constraints.

To deliver the right inferences, several researches have conducted studies on graph understanding (Kosslyn, 1989). Diagrams allow people make inferences and various mental transformations on visuospatial elements about the abstract ideas. So, the spatialization of the abstract ideas with diagrams will serve for increasing understandability of the current problem by making inferences (Tversky, 2011).

2.1.3 Problem Solving

Problem solving process includes three elements to reach an end-state: goal directedness, subgoal decomposition, and operator application. A problem space is constructed by different states of the problem and the states are known as initial state, goal state and the intermediate states between initial and the goal state. With an operator, current problem state can be transformed to another problem state (Kirsh, 2009).

Werheimer (1959) conducted a study to understand the problem solvers' behaviors towards the differences in problem appearance and he found that the similarities between problems constructed with different environments can be understood by the structural elements. In addition, in the research it is seen that experts have deeper understanding the problems than novices. This situation presents a plausible prediction for that the possible differences between representational structures are related with the expertise (Holyoak & Morrison, 2005).

Kirsh (2009) suggests that reorganization of the physical layout for the environment facilitate completing a cognitive task. Environmental structures used during problem solving process as a part of the problem feed the need for internal representation.

Moreover, epistemic activities facilitate problem solving process (Kirsh & Maglio, 1994). Tetris can be given as an example for this situation. It has different shaped zoids dropped from the top of the screen and they must be placed at the bottom of the screen by providing intertwining blocks. When a row is filled, it disappears. As the time progresses, the speed of the falling pieces increases. A player can rotate the falling pieces by a 90 degree. While a player is interacting with the game, they obviate the need by transforming the pieces so this action brings benefits by reducing the demands for internal memory.

2.2 Neuroimaging Studies in Visuospatial Problem Solving

2.2.1 Prefrontal Cortex and Working Memory

It is well established that many higher level cognitive processes such as planning (Owen et al., 2005), reasoning (Wood & Grafman, 2003) and problem solving (Allen, Strauss, Kemtes, & Goldstein, 2007; Anderson et al., 2011; C. L. Lin, Jung, Wu, Lin, & She, 2012; Rosenberg-Lee et al., 2009) recruit areas within the prefrontal cortex. As far as known areas of the prefrontal and parietal cortex have important roles for executive functions (Falcone, McKendrick, & Parasuraman, 2013; Honegger et al., 2011; Protopapa et al., 2011; Watson & Chatterjee, 2012).

Complexity of the executions is matched with the organization of the prefrontal functions. Prefrontal Cortex (PFC) corresponds to high-level interconnection areas which takes various inputs from all sensory systems and sends outputs to all motor and sensory systems (Wood & Grafman, 2003). PFC convers two regions lying on the lateral surfaces of the frontal lobe: dorsal regions 8, 46, and 9; known as DLPFC; and ventral regions 46, 45, and 12; known as VLPFC (see Figure 2.1).

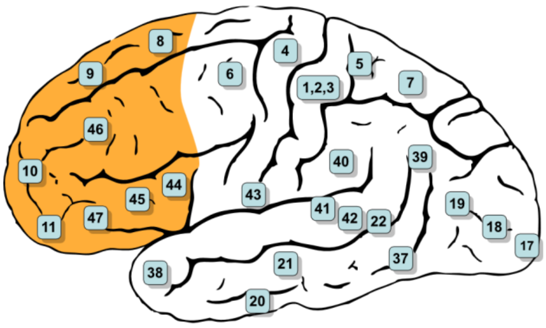


Figure 2.1 Colored areas demonstrate the assigned numbers of Broadman Areas in dorsolateral and ventral areas of prefrontal cortex. While regions 8, 46, and 9 are associated with DLPFC, regions 46, 45, and 12 are associated with VLPFC.

In addition to these, studies with nonhuman primates (Petrides, 2000) and humans (Kaller, Rahm, Spreer, Weiller, & Unterrainer, 2011; Owen et al., 2005; Tanji, Shima, & Mushiake, 2007) found that mid-dorsolateral prefrontal cortex (DLPFC) has a crucial role for planning activities. Also, functional neuroimaging studies conducted on healthy humans in reasoning suggest that deductive and inductive reasoning occur in both left and right prefrontal cortex with the specialized brain regions for each type of reasoning (Goel & Dolan, 2004).

Most recently researches have focused on visuospatial tasks to investigate the neural correlates of visuospatial problem solving. A recent study (Ayaz et al., 2012) focused on investigating a Tangram task which requires visuospatial reasoning. Findings showed that at right channels 9 and 12, significant difference found between control (which presents easier subtasks) and experimental conditions (which presents either animal or geometrical shapes). The author concluded that the right hemisphere is related with visuospatial reasoning.

Additionally, Ruh et al. (2012) focused on separable phases of problem solving. In the study, they used Tower of London task by acquiring fMRI data into two phases: tower configuration, search depth. The results showed that while solvers demonstrates greater activity in left lateralization of DLPFC, detection of search depth demonstrates greater activity in right lateralization of DLPFC. In other words, larger number of move alternative (measured in search depth phase) which refers to planning ahead recruited right DLPFC. They concluded that DLPC involve in planning activities. Similar results were found by Kaller et al. (2011). While Kaller et al. (2011) made a set of fMRI experiments focusing on Tower of London founds increased demand of the information resulted in stronger activation in the right lateralization of DLPFC.

On the other hand, Allen et al. (2007) made an experiment with right and left hemisphere patients focusing on Halstead Category test under the problem solving domain. Any significant difference was found between right and left hemisphere patients. So, the study concluded that problem solving may play a role bilaterally.

In addition to aforementioned studies, Linden et al. (2003) made a set of fMRI experiment focusing on visual discrimination on task. Participants were given single and multiple object conditions ad fronto-parietal activities of the participants were measured. Findings reported that working memory has greater activity on fronto-parietal region in the multiple object conditions. Also, as number of presented objects increase, the middle frontal gyri of both hemispheres also showed an increase.

Furthermore, a study investigated the fMRI data of a Working Memory task (Rypma, Berger, & D'Esposito, 2002). Participants engaged in a WM task and findings suggested that DLPFC activation increased with increasing memory load during the maintenance and retrieval periods. High-performance and low-performance subjects showed different activation patterns. So, study concluded that DLPFC activation may be affected by strategic organization and strategy-shifting processes.

Several studies conducted by electrophysiology, fMRI and PET also showed that several brain regions results in demands on working memory during processing of the visuospatial materials (Diwadkar, Carpenter, & Just, 2000; Lagreze, Hartmann, Anzinger, Schaub, & Deister, 1993; Manoach et al., 1997; Pessoa, Gutierrez, Bandettini, & Ungerleider, 2002; Smith et al., 1995; Wager & Smith, 2003). Furthermore, as far as known DLPFC is associated with working memory as than ever any other cognitive processes (Johnston & Everling, 2011).

The Working Principles of Working Memory

Working memory is the process of holding online information in temporal storage and controlling it as within a short period of time (Baddeley, 2003). According to Baddeley's working memory model (2003), it has three distinct subsystems: phonological loop, episodic buffer and visuo-spatial sketchpad. Phonological loop provides retaining phonological information within a brief time span; the integrated units of visual, spatial and verbal information is bound by episodic buffer and visuo-spatial sketchpad arranges and manipulates the visuo-spatial images. In addition, central executive function coordinates these subsystems and binds the information taken from them.

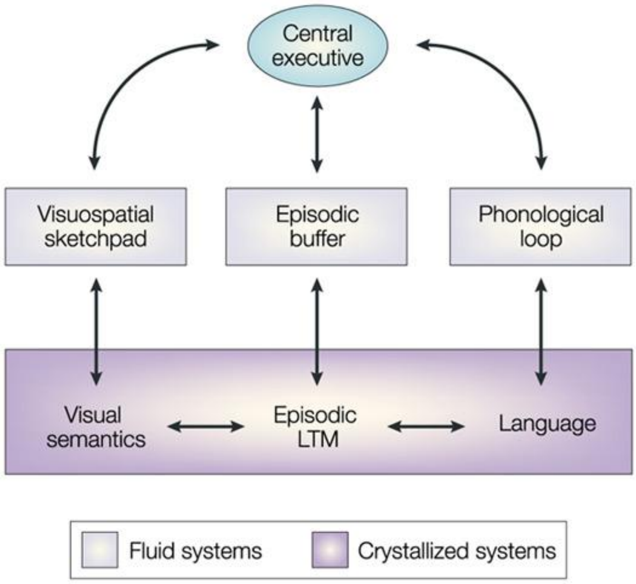


Figure 2.2 Multi Component Working Memory Model of Baddeley (2003)

Baddeley's answer to possible separated systems for the imagery and the verbal modalities defined visuospatial materials have similar executive functions with visuospatial sketchpad (Vega, Intons-Peterson, Johnson-Laird, Denis, & Marschark, 1996).

Visuospatial Working Memory

Visuospatial working memory (VSWM) is the process that maintains and allows manipulating a limited amount of visuospatial information. This ability is important to plan future behavior but because of limited capacity, the selection of relevant information is critical. Specialized visuospatial working memory system is supported by dual-task paradigms which include both visuospatial and verbal materials. While tracking numbers with regard to visual and spatial properties such as the relative position of the numbers in a square matrix interfere with the task, verbally tracking materials had less interference (Logie, Baddeley, Mane, Donchin, & Sheptak, 1989).

In addition to these, Kosslyn (1980) proposed a computational imagery model which supports specialized visuospatial working memory system which embeds a visual buffer that provides generating and refreshing the information from long-term memory.

The ability of visuospatial working memory provides detecting useful and unnecessary items and effective decision on using the detecting items. In addition, visuospatial working memory system provides to identify the object itself and the location of it. Although an object can be viewed from the various perspectives and number of angles, it still can be recognized as the perceived object (McAfoose & Baune, 2009).

Moreover, Ricciardi et al. (2006) mentioned that the posterior parietal, dorsolateral prefrontal cortex, and the anterior prefrontal cortex were activated during a spatial working memory task.

2.2.2 PFC Activation in Analogical Reasoning and Mental Rotation

Analogical reasoning is determined as the “core of the cognition” (Hofstadter, 1981). This type of reasoning features the relational processes. Neural correlates of analogical reasoning are supposed to localize at the rostrolateral prefrontal cortex (RLPFC) (Krawczyk, McClelland, & Donovan, 2011; Ripoll et al., 1996).

Watson and Chatterjee (2012) made a set of experiments to investigate the neural correlates of visuospatial analogical reasoning. Visuospatial analogy task includes three geometrical shapes above and two choices including three geometrical shapes below for which participant should look at the distinct feature and make relational reasoning between choices and the given model. Results revealed greater activation in both left and right RLPFC.

Furthermore, in mental rotation tasks, a geometric shape is presented to participant and then a set of possible choice is presented and participant is asked to determine which one is the same shape for rotated version (Lovett, Tomai, Forbus, & Usher, 2009). Cooper and Shepard (1984) showed that one or two corresponding parts of given task was identified by participants and then they made the rotations based on those corresponding parts. By looking at some distinct features such as edge of a rectangle, participants can determine quickly the rotational difference (Lovett et al., 2009).

A recent study (Schendan & Stem, 2007) illustrated that bilateral anterior ventrolateral prefrontal cortex (BA 47, BA 12) and posterior ventrolateral prefrontal cortex activated during mental rotation task. Haier, Karama, Leyba, and Jung (2009) studied with Tetris, a visuospatial problem solving game embeds geometrical figures and requires rotations, to find the relevant areas for visuospatial reasoning. Participants were subjected to Tetris during three months. And, brain activation was observed with fMRI. After three months, activation level in frontal areas showed decrease and thicker cortex was observed in practiced participants at primarily BAs 6 and 22/28. Especially the left BA 6 which is known as related with the frontal eye fields showed the most significant cortical thickness change. In brief, Haier et al. (2009) assured that after practice the cortical activation have not to be observed at the same place. This study provides to see the development in neural correlates of visuospatial problem solving.

Although aforecited study has been replicated for many times (Roth & Kosslyn, 1988; Shepard & Metzler, 1988), the associated brain regions for mental rotation remains the impenetrability.

Studies have been conducted with patients who have damage on different brain areas provide giving inside on the neural correlates of the cognitive processes underlying mental rotation. Kosslyn, Farah, Holtzman, and Gazzaniga (1985) found that activation patterns firing from mental rotation could not be observed at split-brain patients who have brain damage on the left-hemisphere. Additionally, patients who had damage on temporal and frontal regions of the brain had difficulties in using the advance information about the orientations of objects. However, these patients could perform mental rotation tasks. The reason could be given as these patients may have difficulty in finding appropriate strategy for the mental rotation task (Alivisatos, 1992). The results from beforementioned patient studies show that mental rotation is not a separated process and like other cognitive processes mental rotation recruit different brain regions and need to engage in various cognitive processes (Kosslyn & Ochsner, 1994).

Aforecited studies infer that the neural correlates of mental rotation are not based on one or two regions. For this reason, mental transformations have been evaluated in reference to different brain regions (Zacks, Rypma, Gabrieli, Tversky, & Glover, 1999). Spatial visualization and mental rotation have two main visual pathways: “what” or “ventral” pathway which correspond to identify the objects and “where” or “dorsal” which correspond to spatial pathway (Kosslyn, 2005).

Cohen et al. (1996) found that mental rotation tasks recruit areas in the left-inferior parietal cortex which is associated with the locating and tracking objects in the visual field. Also, frontal areas which are bound to parietal areas were activated in mental rotation task studies.

2.3 Eye Movement Researches

Eye gaze demonstrates two actions: saccades and fixations. Rayner (2009) defines a saccade as short rapid movements occur between two fixations. Saccades are not always directed to a special target and can include an exploratory purpose. In exploratory conditions, saccades do not explicit with the targets but they are generated internally. Each saccade follows a fixation and vice versa each fixation follows a saccade. Figure 2.3 illustrates a saccade sequences during scene viewing. These saccadic sequences are known as scan paths. Sequence of eye movements represented with scan paths play an important role in achieving visual memory of that image (Noton & Stark, 1971).

Fixations are stoppages correspond to action of encoding new information. Under normal circumstances, people are like blind during a saccade so that to see the desired information clearly, people will move the eyes to target stimulus (Rayner, 2009).

Fixations become longer while more effortful cognitive processing occurs. For instance, fixation duration increases as participants are provided with relatively more difficult geometrical problems (Epelboim & Suppes, 2001). Whereas, saccade duration increases with two effective factors: more difficult tasks, and a decreased processing capacity (Holmqvist et al., 2011).

2.3.1 Eye Movement Researches in Mental Imagery

Although Section 2.1.1 and 2.2.2 summarized the mental imagery studies focusing on behavioral and neural correlates of mental imagery mostly underlying mental rotation tasks, mentioning briefly from the eye movement researches will also shed light on the ocular correlates of mental imagery and provide to see the big picture of the study.

Mast and Kosslyn (2002) stated that eye movements are functionally involved in mental imagery processes and store the spatial layouts of each mental image to be prepared for arrangement of them when are necessary.

Furthermore, Irwin and Brockmole (2000) suggested that saccadic eye movements restrain mental rotation.

2.3.2 Eye Movement Researches in Problem Solving

Eye tracking methodologies have been widely accepted in studying various topics in problem solving. Eye movements can be investigated to reveal step-by-step problem solver’s cognition during a given task.

Time course of problem solving have been understood by using different techniques such as think-aloud protocols, observation, and verbal reports. However, these techniques can result in invalid data because of unawareness of participants’ own cognitive processes (Solomon, 1995). Whereas, eye movements provide researchers envisaging about the cognitive processes underlying problem solving (van Gog, Paas, van Merrienboer, & Witte, 2005).

There are two main hypotheses related with eye movements and problem solving processes: (1) Eye movements elucidate problem solving processes, and (2) eye movements have a potential in assisting to problem solving processes.

Many studies in mathematical problem solving reveal the relationship between eye movements and mental activities. For instance, Hess and Polt (1964) showed that pupil diameter increases when participants attempted to solve more difficult tasks. Furthermore, Yarbus (1967) associated saccadic eye movements with problem solving tasks. He stated that asking different questions on given images resulted in different scan paths which were comprised of saccades.

Task and Paradigms in Visuospatial Problem Solving

Problem solving tasks which require eye movement strategies, visuospatial planning, or visuospatial reasoning have been widely studied. Examples of studied tasks are chess, card sorting, Tower of Hanoi, and block-copying.

Chess is a most common task used in problem solving studies focusing on expertise. Eye tracking studies on chess (Charness & Reingold, 1992; Chase & Simon, 1973; Gobet & Simon, 1996) revealed that while expert players looked at bigger segments, novice players looked at individual pieces so that fewer fixations during play occurred for expert players.

Kaller et al. (2009) studied by eye-tracking methodology on Tower of London task to elicit the visuospatial problem solving processes and separating the process into dissociable phases. This problem requires mental rearrangement for a set of balls which are presented in a computer-based environment and make participants enter the solution to computer. Kaller et al. (2009) found that 57.1% of participants re-fixated to ultimate state and the final fixation duration before the arrangement of a ball is highly correlated with the complexity of the problem. So, this action is defined as a clear-cut separation between internalization and planning processes.

Gaze-shifting approaches were used for a variety of cognitively demanding tasks (Bensinger, Hayhoe, & Ballard, 1995; Hayhoe et al., 1998). Ballard, Hayhoe, and Pelz (1995) made participants copy meaningless blocks to workspace and discovered that for each copying participants looked twice at the given model. While the first look was related with "what" the color, the second look was defined as related with "where" the place. As the number of fixation increases, participants simplify the complexity of the problems. Ballard et al. (1995) concluded that participants used visual representation to increase visual working memory capacities.

Geometric reasoning studies and spatial reasoning problems also provide insight in terms of eye movement patterns during visuospatial problem solving (Cook, Mitchell, & Goldin-Meadow, 2008; Epelboim & Suppes, 1997). For instance, Epelboim and Suppes (2001) showed that solvers made repetitive scanning to understand individual pieces of diagrams in geometry analogy problems.

Difficult puzzles are often assigned to insight problems so great proportion of participants never find the solution. Participants who found the solution described the solution process as a miracle and "a sudden solution". During participants got into a tight corner, mean fixation duration increased significantly (Knoblich, Ohlsson, & Raney, 2001).

Table 2.1 Examples of eye-movement metrics and related cognitive processes adapted from (Holmqvist et al., 2011)

Eye-movement metrics	**Relevance**	**Reference**
Fixation-related		
Fixation duration	Decrease with more difficult tasks	(Tsai, Viirre, Strychacz, Chase, & Jung, 2007)
Fixation rate (fixation count / completion time)	Decrease with task difficulty	(Kristjansson & Nakayama, 2002)

Fixation count	Increase with task difficulty	(Ehmke & Wilson, 2007)
Saccade-related		
Saccade duration	Increase with task difficulty	(Vuori, Olkkonen, Pölönen, Siren, & Hakkinen, 2004)
Saccadic velocity	Increase with more difficult tasks	(Galley, 1993)
Scanpath-related		
Transition rate	In repetitive tasks, measuring the visual working memory demand	(Berséus, 2002)

2.4 Summary

Bottom-up and top-down cognitive processes such as mental imagery and diagrammatic reasoning draw upon visuospatial reasoning process. Studies conducted to figure out neural correlates of visuospatial reasoning suggest that fronto-parietal cortex is related with the visuospatial reasoning processes. Additionally, patterns in eye gaze are leaded by different visuospatial tasks underlying specific cognitive processes.

In the light of this information, conducted synchronized measurements have a potential in increasing existing knowledge about neural and ocular correlates. With an experimental study which involves various visuospatial reasoning tasks, the nature of visuospatial reasoning processes will be investigated.

The following chapter outlines the methodology used to categorize such patterns from eye movement and fNIR data collected as participants engaged in various visuospatial tasks.

CHAPTER 3

METHODS

In this chapter, firstly, the experimental setup will be introduced. Secondly, the experimental protocol and the data collection procedure including the functional near-infrared spectroscopy and eye-tracking data collection procedures will be described. Finally, analysis methods for the collection of data will be explained.

3.1 Contextual Environment

Thesis study was conducted at the Human-Computer Interaction Laboratory, Middle East Technical University (METU). The experimental protocol was approved by the Human Subjects Ethics Committee of METU.

A total of right-handed 17 voluntary participants (5 female, 12 male) took part in this study. Participants had no history of neurological or psychological disorders. They had normal or corrected to normal vision. Average of the sample size of participants' eye movement data was %85.76. They were all undergraduate and graduate students at METU. %56 of the participants was not familiar with the computer-based tangram tasks and they all stated themselves as familiar with geometrical shapes. Two participants' data were excluded from further data analysis due to lack of signal quality. The age distribution of participants (n=15, mean=27.27, *SD*=3.35) is shown at Figure 3.1.

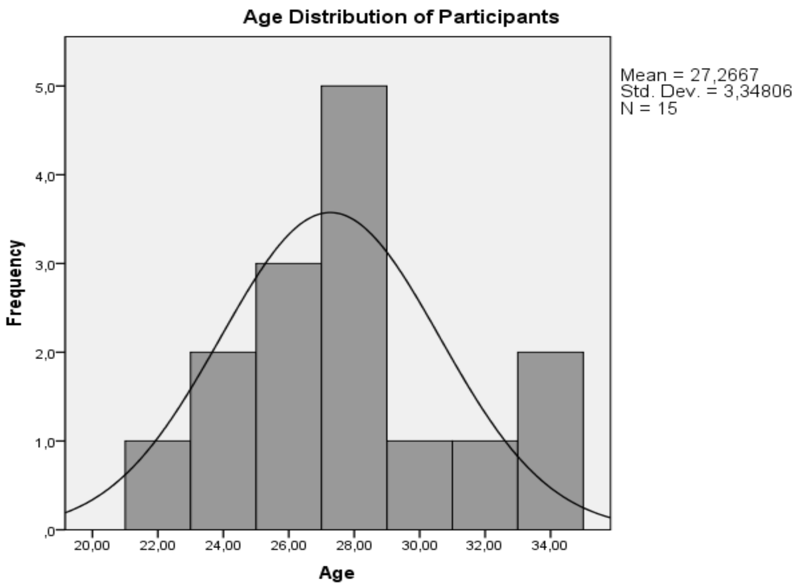


Figure 3.1 Age distribution of participants

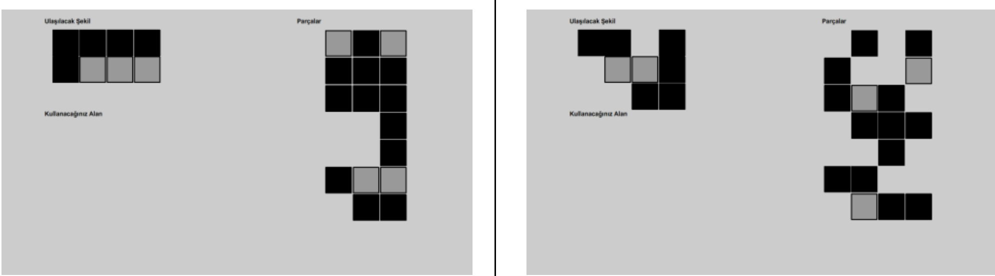
3.2 Experimental Design

During the experiment subjects were asked to complete a series of puzzles by using interactive computer-based software developed by the researcher. Participants used this software to control and manipulate basic two-dimensional shapes to construct a given target shape.

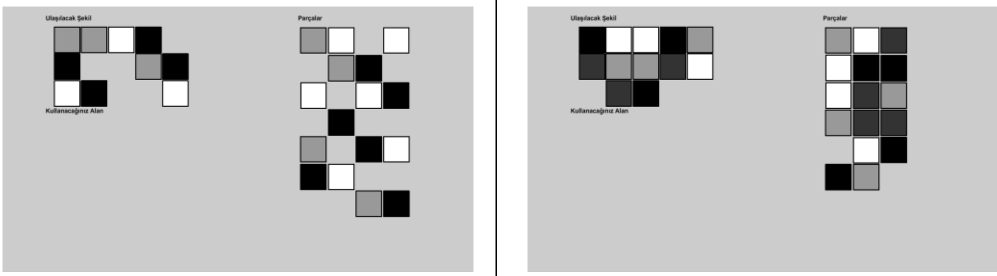
The protocol consists of two phases. The first phase is the training part which includes two tangram tasks. These tasks have the same target shape, but in one task the outline of the target is provided on the workspace, whereas in the other no outline is given. The aim of the training phase is to introduce basic controls and the puzzle environment to the participants. The second part consists of the main experimental protocol. In this part, there are three tasks: block-copying tasks, geometry analogy tasks and seven-piece Chinese tangram tasks.

3.2.1 Block-Copying Task

Four block-copying tasks adapted from a previous study (Ballard et al., 1997) were used in this study: task with black and grey blocks; tasks with black and grey blocks in different shapes; tasks with black, grey and white blocks; and tasks with black, grey, white and dark grey blocks. The color combinations and the size of the targets are varied in order to increase the complexity of the task. The screen of the block-copying tasks has three different areas. Target model is located at the left-upper side, the pieces to be used are located at the right-upper side and the workspace area is located under the target model. Figure 3.2 shows the appearance of a block copying task screen. Participants were asked to perform mouse movements to copy blocks on workspace area to construct target model. Participants have 65 seconds to complete the copying.



(a) (b)

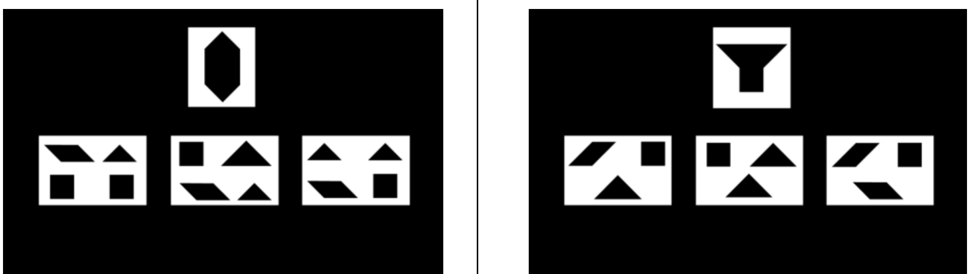


(c) (d)

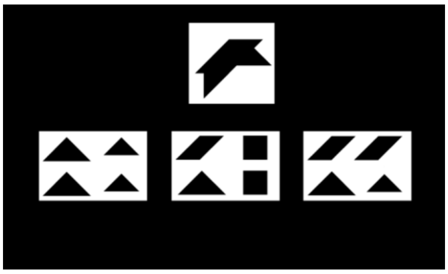
Figure 3.2 Block-copying Tasks. Upper left side of the screen shows the target model; whereas, right side of the screen demonstrates pieces and bottom left side of the screen presents the workspace area. Figure 3.2 (a) and (b) illustrate the first and second block-copying tasks used before tangram tasks two colors and basic target models with 8 pieces; while Figure 3.2 (c) illustrates the third block-copying task used before tangram tasks has three block colors and relatively a complex target model with 10 pieces. Finally, Figure 3.2 (d) illustrates the fourth block copying task used after tangram tasks has four block colors and relatively a complex target model with 12 pieces.

3.2.2 Geometry Analogy Task

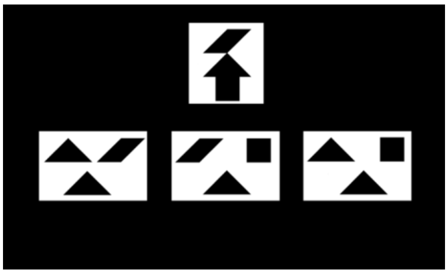
Four geometry analogy tasks (with multiple choice answers) were used in this study: four-piece hexagon, funnel, shape with triangles and arrow (see Figure 3.3 below). Participants were asked to imagine constructing the target model with the given set of pieces and make the appropriate choice among the three alternatives provided. Participants could not move or rotate any one of the pieces. They were asked to make a choice without performing any mouse movement and were allowed 120 seconds to complete the task.



(a) (b)



(c)



(d)

Figure 3.3 Geometry Analogy Tasks. Figure 3.3 (a) shows the first geometry analogy tasks which has a four-piece hexagon shape used before tangram tasks; whereas, Figure 3.3 (b) shows the second geometry analogy task which has a three-piece funnel shape used before tangram tasks. Figure 3.3 (c) shows the third geometry analogy task which has a four-piece triangles shape used after tangram tasks. Finally, Figure 3.3 (d) shows the fourth geometry analogy task which has a three-piece shape used after tangram tasks.

3.2.3 Chinese Tangram Task

Eight Chinese Tangram tasks were presented to the participants. The task environment has three areas as in block-coping tasks: target model, workspace area, and seven pieces (see Figure 3.4 below).

Participants can move the given piece by dragging them by pressing the left mouse button and rotate the selected piece by using the CTRL key. They can end the current task by pressing the ENTER key at any time. After completing each trial, participants move onto a new task by pressing the SPACE key. No additional controls were given to the participants. Participants were allowed 240 seconds during the main experiment and 100 seconds during the training part to complete each tangram task.

A total of ten tangram tasks (two for control condition and eight for experiment condition) were presented to the participants, where each puzzle belongs to a different condition. Four of the tangram tasks have symmetric targets and the rest of them have asymmetric targets (e.g. animal shapes). There are also contextual differences among tangram tasks. Four of the tangram tasks have an outline of the target in the workspace area, whereas the rest have no outline in the workspace area. Figure 3.4 shows the various cases for tangram tasks.

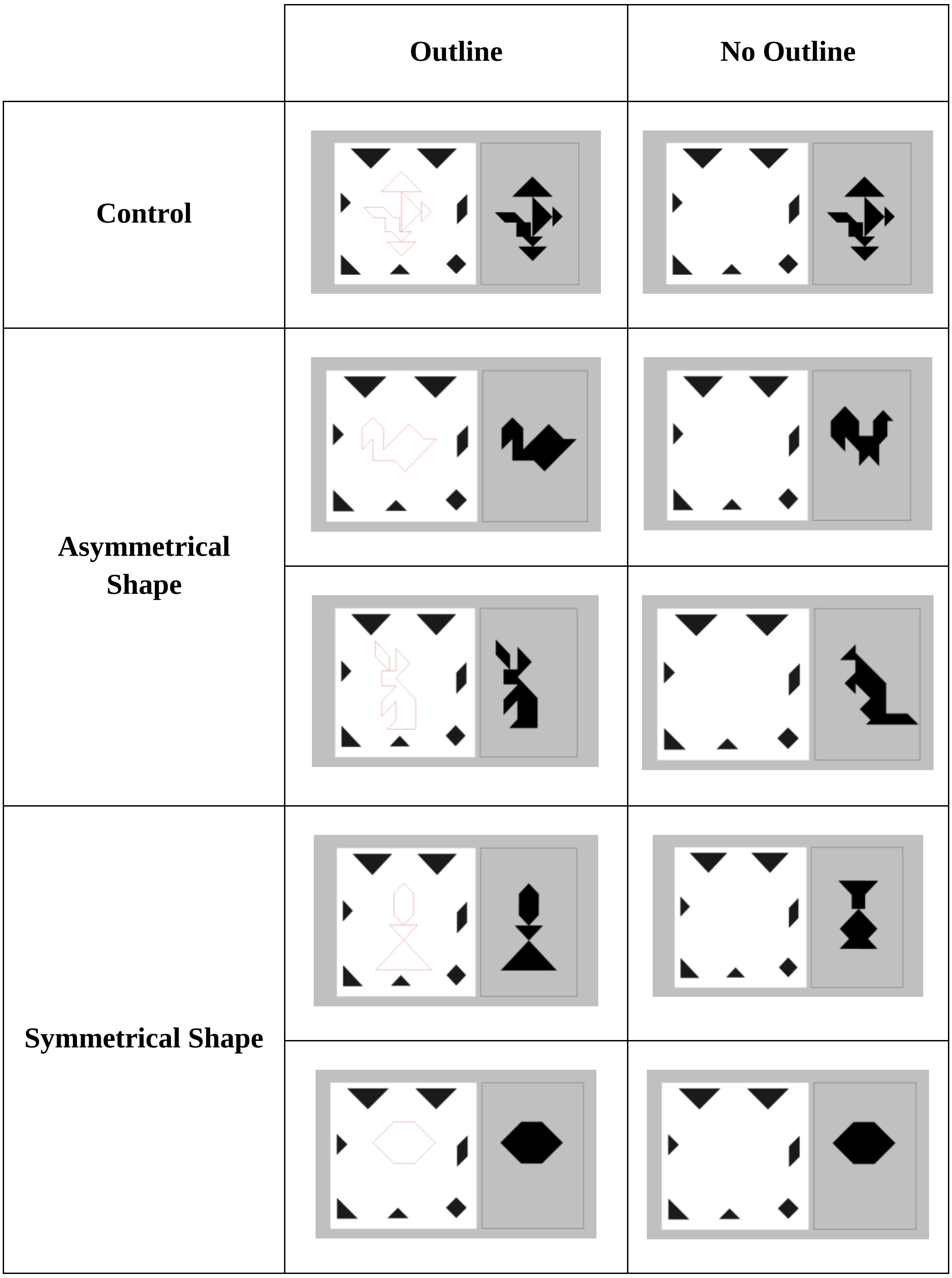


Figure 3.4 Conditions for seven piece tangram tasks. Matched tangram models presented within outline and no outline workspaces show similar characteristics regarding feature characteristics.

All stimuli were prepared by using the Macromedia Flash 8 application. Participants were not required to have any domain knowledge to solve these tangram tasks.

3.3 Experiment Procedure

Each participant was individually tested and the study was introduced to each participant at the beginning of each session. Before the experiment, participants were given a consent form approved by the Human Subjects Committee of METU. Before the experiment, participants were given a questionnaire to collect basic demographic data and to assess their previous knowledge of basic geometric shapes and experience with tangram puzzles.

3.3.1 Eye Tracking and fNIR Data Acquisition Procedure

After participants filled in the questionnaire, they sat in front of the eye tracker so that the distance between the monitor and the participants was approximately 60 cm. Then the fNIRS sensor is placed on the forehead (see Figure 3.5) and a 20 seconds long baseline was recorded while the participant's eyes were closed. Next, a calibration phase with 9 dots for the eye tracker was administered. Until 9 dots are successfully calibrated, the calibration process continued.

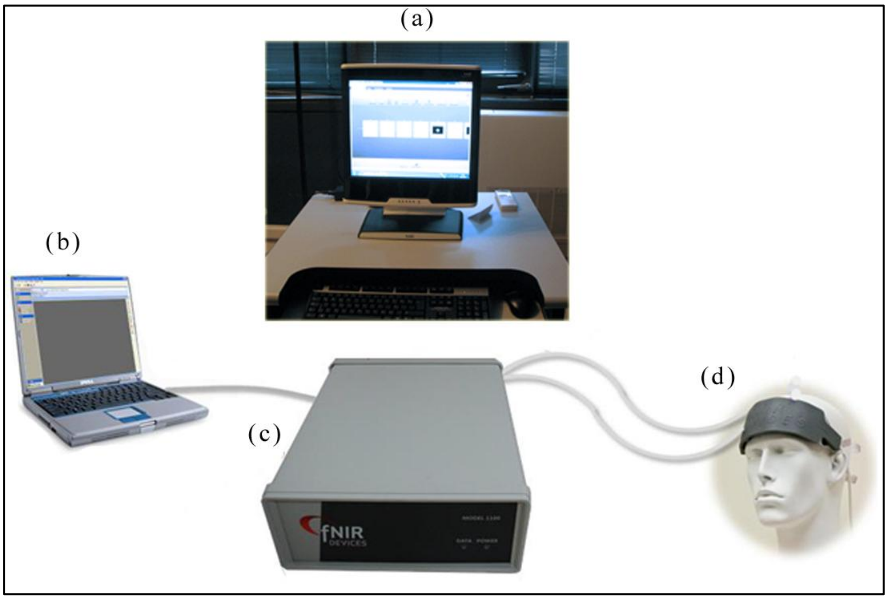


Figure 3.5 Demonstration of Tobii T120 Eye-tracker and fNIRS device. (a) shows the Tobii T120 eye-tracker; whereas (b), (c), and (d) illustrate the fNIRS data acquisition procedure. Figure 3.5 (b) represents a personal computer run COBI Studio, (d) fNIRS Sensors that are connected to (c) fNIRS device Imager 1000 device developed by the Optical Brain-Imaging Lab at Drexel University, manufactured and supplied by fNIRS Devices LLC (Potomac, MD; www.fnirdevices.com).

In order to stabilize the brain signals and eliminate random fixations on given tasks, a 10-seconds long rest period was included before each task. Participants were asked to look at a fixation cross located in the middle of the screen while they are resting in between experimental tasks.

Since participants were unfamiliar with the two-dimensional computerized tangram tasks and the experimental protocol, they were given a short training before they completed the main protocol. Information about basic controls was given before the participants attempted the training tasks, which include two asymmetric tangram problems within the environment one with an outline and the other without an outline.

The experiment together with the training phase took approximately 45 minutes in total. During the main experimental protocol, participants attempted 16 tasks: four block-copying tasks, four geometry analogy tasks, and eight tangram tasks. Participants began dealing with the tasks with three of the block copying tasks. Then, for two of the geometry analogy tasks, they selected the appropriate choice of pieces that could be used to construct the given geometric shape. Then, participants faced tangram tasks. After participants took tangram tasks, they solved two of the geometry analogy tasks. Finally they took the last block copying task (see Figure 3.7). All tasks were given to participants in the same order.

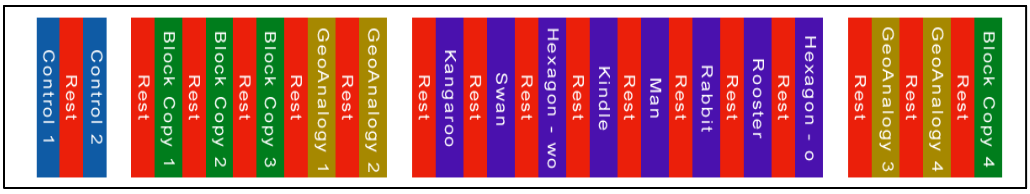


Figure 3.6 Task order in protocol. Participants were presented control tangrams for training at the beginning of the experiment. Then, three block-copying and two geometry analogy tasks were presented before participants are engaged with tangram problems, eight tangram problems in different problem spaces, and after tangram problems participants were presented two geometry analogy and one block-copying tasks.

3.3.2 Data Collection

In this study, various tools were used to collect data. Summary of the data collection procedure is indicated below:

1. Demographic Data Sheet and Questionnaire: Age, Sex, Level of Education, Department, Previous knowledge about geometric shapes and tangram tasks (see Appendix B)

2. Eye tracker: Eye movement metrics (number of fixations, fixation durations, fixation rates, mouse click counts, and transition rates)

3. fNIR: Brain data including oxygenated hemoglobin

Neuroimaging Data

Neuroimaging data were collected using the Functional Near-Infrared Spectroscopy (fNIRS) Imager 1000 device (see Figure 3.5).

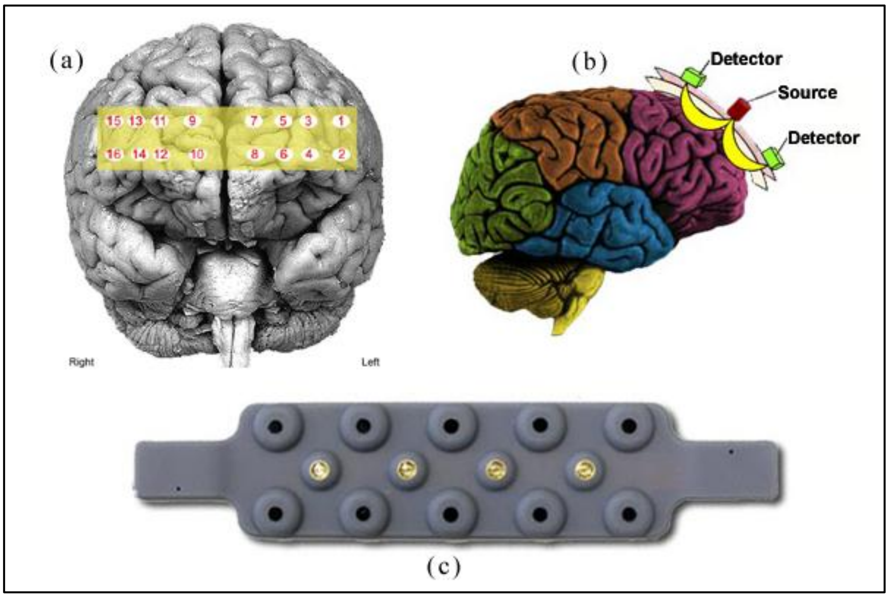


Figure 3.7 Demonstration of working principles and the correlates of fNIRS with prefrontal areas. (a) and (c) illustrate the related channels of fNIRS (b) shows the working principles of the fNIRS which uses light source to collect the reflected signals coming from the brain.

Executive function and working memory network can be monitored by the physical principles of light absorption. 4 light sources and 10 light sensors are placed in a rectangular band (see Figure 3.7 (c)). Signals were collected from sixteen channels because one light source placed at the middle of the four light sensors corresponds to four light sensors. Figure 3.7 (b) illustrates the working principles of fNIRS. When brain cells activated, they consume energy. When brain cells need energy, oxygen is required to metabolize glucose. Requisite oxygen is transported via oxygenated hemoglobin. Oxy-hemoglobin and deoxy-hemoglobin absorb infrared light and blood color is change in reference to infrared spectroscopy and photons which are not absorbed by infrared light provide observation of hemodynamic response. To be more specific, oxygenation level corresponds to observation of the difference between oxy- and deoxy-hemoglobin concentration changes (Izzetoglu, 2008).

3.3.3 Preprocessing of Eye-Tracking and fNIR Data

Tobii IV-T fixation filter algorithm was applied to figure out fixations from the raw data. Each task is defined as a segment for each participant.

fnirSoft was used to preprocessing of fNIR Data. Two filters were applied on the raw data to eliminate saturated channels and artifacts due to head motion and cardiac effects. Sliding window motion artifact filter with window size 10, upper threshold 25 and lower threshold 3 was employed to eliminate the effects of head movement (Ayaz et al., 2010). Low pass, finite impulse response filter was applied to eliminate noise due to respiration and hearth beat.

3.4 Behavioral and Eye-Tracking Statistical Analysis

Eye tracking data was analyzed by Tobii Studio (v3.1.3). This software offered a platform for recording eye movements, exporting eye gaze data, and visualizing of the recorded eye movements as gaze plots, heat maps, and bee swarms. Area of interests (AOIs) can be defined by Tobii Studio analysis tool and the measures such as number of fixations, duration of fixations, and total visit duration can be calculated by this software.

Since block copying and tangram tasks involve active manipulation and arrangement of objects in the workspace, it is challenging to define meaningful AOIs at the level of objects. For that reason, broader AOIs that correspond to the target shape and the workspace were used to estimate fixation counts and durations that occurred during problem solving.

In the case of analogy tasks, static AOIs are used since the task does not include dynamic changes to the visual scene. However, the complexity of part whole relationships among the target and tangram pieces, 4 AOIs were defined that cover the target and the 3 choices presented to the participants.

Statistical Package for Social Sciences (SPSS) was used for fNIR data and eye tracking raw data.

3.4.1 Eye tracking analysis of the Block Copying Tasks

For each block-copying task; completion times, fixation counts, and fixation durations were calculated and one-way repeated-measures ANOVA was conducted to investigate the differences between completion times and mouse click counts among block-copying tasks. Variables were analyzed with SPSS.

In addition to previous analysis, three areas of interests (AOI) were specified to figure out *number of fixations*, *fixation durations* (millisecond), *fixation rates*, and *transition rates*. Fixation rates were calculated based on fixation counts and completion times (fixation count/completion time of the task). AOIs were drawn over different areas; workspace area, target model area, and pieces area.

3x4 two-way repeated-measures ANOVA with repeated measures was conducted in order to investigate the differences of fixation durations and fixation counts among three areas in block-copying tasks; workspace area, target model area, pieces area.

3.4.2 Eye tracking analysis of the Geometry Analogy Tasks

For each geometry analogy task; accuracy and response times were calculated and one-way repeated-measures ANOVA was conducted to investigate the differences between response times among geometry analogy tasks.

In addition to previous analysis, four AOIs were specified to figure out *number of fixations*, *fixation durations, and fixation rates*. AOIs were drawn among four different areas; target model area, and answers areas (first-second-third).

3.4.3 Eye tracking analysis of the Chinese Tangram Tasks

For each tangram task, completion time, fixation count on workspace areas, fixation durations on workspace areas, fixation rates, and mouse click counts was calculated and one-way repeated-measures ANOVA was conducted to investigate the differences between completion times among tangram tasks for normally distributed data.

Another analysis to investigate the differences between with outline and without outline versions was conducted with a 2x6 repeated-measures ANOVA.

3.4.4 Overall Eye-tracking analysis among various tasks

One-way repeated measures ANOVA was performed to analyze fixation durations on target scene among three types of task.

3.5 fNIR Statistical Analysis

Maximum Oxygenation Values (i.e. peak values) were analyzed in SPSS with one-way repeated-measures ANOVA for normally distributed data and Friedman's ANOVA for nonnormal distributed data.

3.6 Scanpath Analysis

For each task grouping among block-copying, geometry analogy, and tangram tasks were analyzed separately by the Tobi Studio. The general scan path of the participants was formed by analyzing the order of the transitions between the target model, workspace area and the pieces for block-copying and tangram tasks and between the target model and the answers for the geometry analogy tasks.

CHAPTER 4

RESULTS

The goal of this thesis study was to explore the course of ocular and neural events that occur while people solve different kinds of visuospatial problems. Eye tracking and brain activation data were analyzed to investigate the following questions:

(1) Is there any significant difference in solvers' gaze patterns during solvers attempt to solve block copying and tangram tasks?

(2) Is there any significant difference in brain activity levels measured during block copying and tangram tasks?

(3) Is there any significant difference in solvers' gaze patterns during the solvers attempt to solve geometry analogy and tangram tasks?

(4) Is there any significant difference in brain activity levels measured by block copying tasks and tangram tasks?

(5) Is there any significant difference in solvers' gaze patterns with regard to problem space features (with outline or without outline, symmetric vs. antisymmetric) while solving tangram puzzles?

(6) Is there any significant difference in solvers' brain activity levels at the prefrontal cortex as measured with fNIRS with regard to problem space features (with or without outline, symmetric vs. antisymmetric) while solving tangram puzzles?

Three major components of results were categorized: (a) a behavioral analysis of task performance (accuracy, and completion time); (b) eye tracking data that directly focus on the research questions (1), (2), and (3); and (c) brain activation data that directly focus on the research question (4).

In brief, results of the analysis of training part and main experiment part are mentioned. Eye tracking data, oxygenated hemoglobin (OxyHb) and total hemoglobin (HbT) concentration changes for block-copying tasks, geometry analogy tasks, and tangram tasks are presented. Finally, scan paths for tangram tasks are examined.

4.1 Behavioral Results

4.1.1 Accuracy and Completion Times

Block-Copying Tasks

Average completion times of block-copying tasks were calculated. Figure 4.1 below shows the distribution of completion times of all participants throughout solving four block-copying tasks. Results show that average completion time for block-copying tasks 1 is 44.2406 sec (n=16, SD=13.667); for block-copying task 2 is 37.3575 (n=16, SD=11.985) sec; for block-copying task 3 is 43.2025 sec (n=16, SD=8.147); and for block copying task 4 is 47.0013 sec (n=16, SD=11.492).

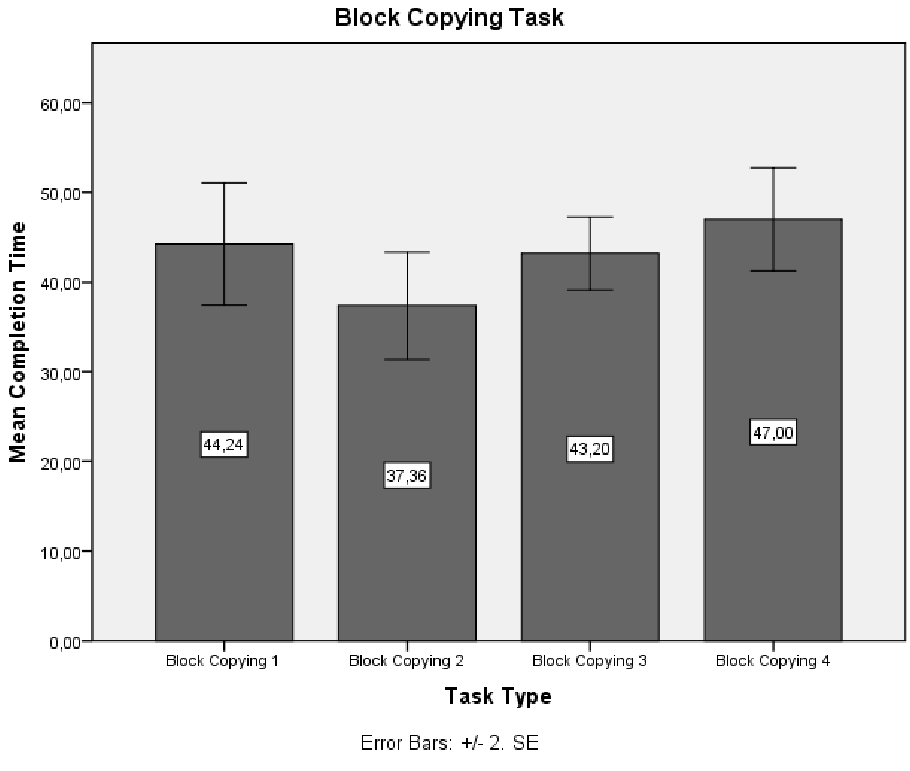


Figure 4.1 Distribution of completion times (sec) among Block-Copying Tasks

According to Mauchly's Test of Sphericity results, D(5)=.658, p>.05. So, sphericity assumption is satisfied to conduct one-way repeated-measures ANOVA. A one-way repeated-measures ANOVA was performed to measure the mean completion times among four block copying tasks. The results show that mean completion time of block copying tasks was significantly affected by the type of block copying tasks, F(3, 45)= 4.048, MSE=65,106, p<.05.

Although Bonferroni correction was applied for further analysis, any significant difference found between pairs after Bonferroni correction. So, paired-samples t-test was conducted to find whether there is a significant difference between the completion times of block copying tasks (see Table 4.1). The results showed that there is a significant difference between BC 1 vs. BC 2, BC 2 vs. BC 3, and BC 2 vs. BC 4 with respect to values t(15)=2.555, p=.022; t(15)=-2.499, p=.025; t(15)=-2.693, p=.017. Although expected result was that the first block copying task is significantly different than other block copying tasks due to basic features, the initial view and identification of the task environment increased the completion time of the first block copying task.

Table 4.1 Paried-Samples T-Test between Block Copying Task Pairs

Measure	N	Mean	Std. Dev.	df	t	*p
BC 1	16	44.241	13.667	15	2.555	.022
BC 2	16	37.358	11.985			
BC 1	16	44.241	13.667	15	.385	.706
BC 3	16	43.202	8.147			
BC 1	16	44.241	13.667	15	-.893	.386
BC 4	16	47.001	11.492			
BC 2	16	37.358	11.985	15	-2.499	.025
BC 3	16	43.202	8.147			
BC 2	16	37.358	11.985	15	-2.693	.017
BC 4	16	47.001	11.492			
BC 3	16	43.202	8.147	15	-1.498	.155
BC 4	16	47.001	11.492			

*p<.05

Geometry Analogy Tasks

Accuracy and response times for geometry analogy tasks were calculated. Figure 4.2 below shows the distribution of responses of all participants throughout solving geometry analogy tasks including four-piece hexagon task, funnel task, triangles task and arrow task. Results show that 7 participants selected the correct answer for the hexagon question and the average completion time based on correct answers for this question is 25.784 sec; 8 participants gave accurate answer for funnel question and the average completion time based on correct answers for this question is 28.398 sec; 8 participants gave accurate answer for triangles question and the average completion time based on correct answers for this question is 31.818 sec and 8 participants gave accurate answer for arrow question and the average completion time for this question is 12.351. Also, two participants for hexagon and one participant for triangles task cannot make any attempt before the time is out.

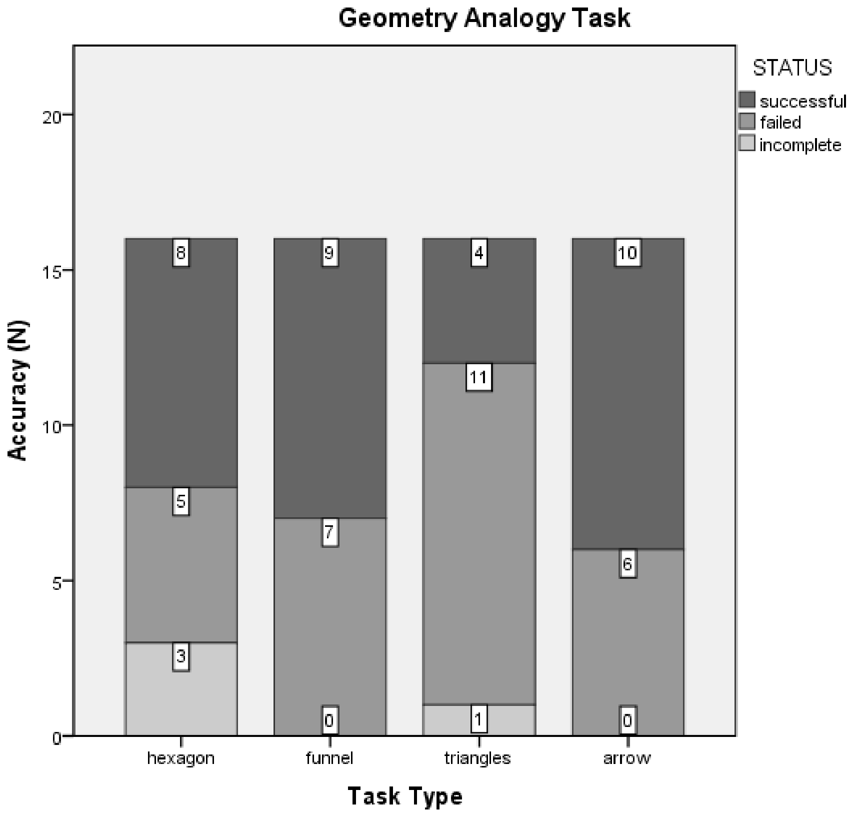


Figure 4.2 Distribution of answers among Geometry Analogy Tasks

Behavioral analysis includes average completion times for geometry analogy tasks. Figure 4.3 below shows the distribution of completion times of all participants throughout solving geometry analogy tasks. Results show that average completion time for hexagon task is 41.651 sec (n=16, SD=40.137); for funnel task is 22.454 (n=16, SD=15.150) sec; for triangles task is 38.658 sec (n=16, SD=28.042); and for arrow task is 12.150 sec (n=16, SD=9.852).

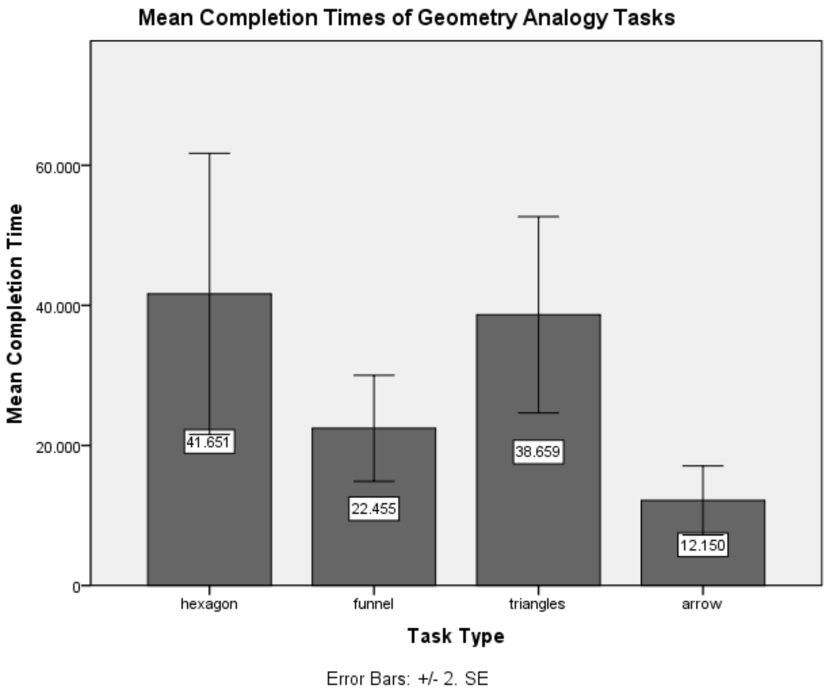


Figure 4.3 Distribution of completion times among Geometry Analogy Tasks

A one-way repeated-measures ANOVA was performed to measure the mean completion time among four geometry analogy tasks in reference to both successful and unsuccessful participants. According to Mauchly's Test of Sphericity results, sphericity is violated $D(5)=.414$, $p<.05$. Greenhouse-Geisser correction was used for nonsphericity (Geisser & Greenhouse, 1958). The results show that mean completion time of geometry analogy tasks was significantly affected by the type of geometry analogy tasks, $F(3, 45)= 4.886$, $p<.05$.

Paired-samples t-test was conducted to find whether there is a significant difference between the completion times of geometry analogy tasks (see Table 4.2). The results showed that there is a significant difference between Hexagon vs. Arrow, and Triangles vs. Arrow with respect to values $t(15)=2.362$, $p=.032$; $t(15)=-4.097$, $p=.001$.

Table 4.2 Paried-Samples T-Test between Geometry Analogy Task Pairs

Measure	N	Mean	Std. Dev.	df	t	*p
Hexagon	16	41.651	40.137	15	2.362	.032
Arrow	16	15.086	13.849			
Triangles	16	38.665	13.667	15	4.097	.001
Arrow	16	15.086	8.147			

*p<.05

Chinese Tangram Tasks

Number of successful and failed players and mean completion times for successful players were calculated. Figure 4.4 below shows the distribution of completion times of all participants throughout solving tangram tasks. Results show that average completion time for training 1 is 85.058 sec; for training 2 is 75.430 sec; for kangaroo is 155.291 sec; for swan is 101.342 sec; for hexagon (no outline) is 103.209 sec; for kindle is 109.033 sec; for man is 136.077 sec; for rabbit is 93.092 sec; for rooster is 170.509 sec; and for hexagon (outline) is 119.689 sec.

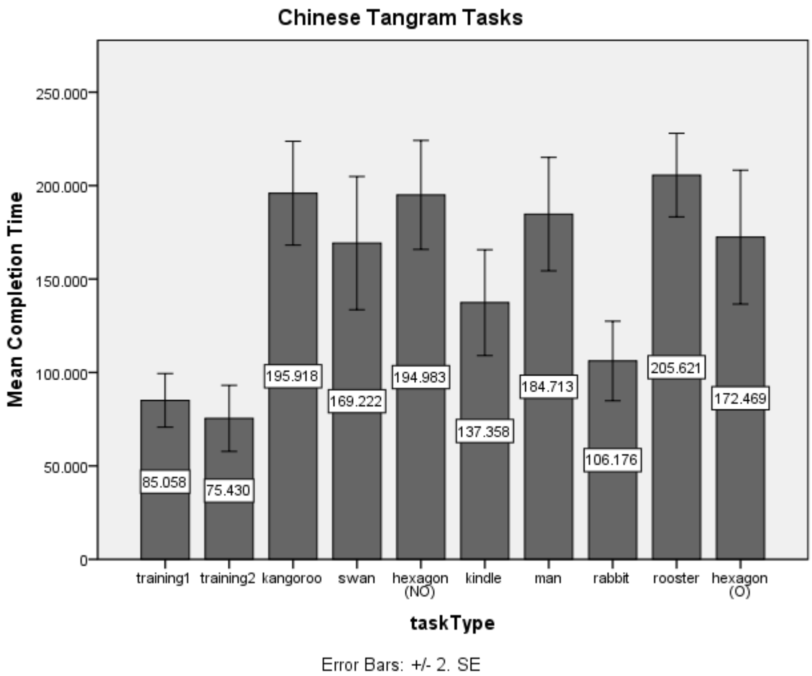


Figure 4.4 Average Completion Times of Tangram Tasks (Successful Players)

In Figure 4.5 below shows the accuracy (%) of successful participants throughout solving tangram tasks. Results show that the percentage of participants who succeeded in tangram tasks. Training 1 and training 2 tasks were completed with %100 accuracy; kangaroo task was completed with %18,8 accuracy; swan was completed with %31,3 accuracy; hexagon NO (no outline) was completed with %18,8 accuracy; kindle was completed with %68,8 accuracy; man was completed with %43,8 accuracy; rabbit was completed with %87,5 accuracy; rooster was completed with %25 accuracy; hexagon O (outline) was completed with %50 accuracy.

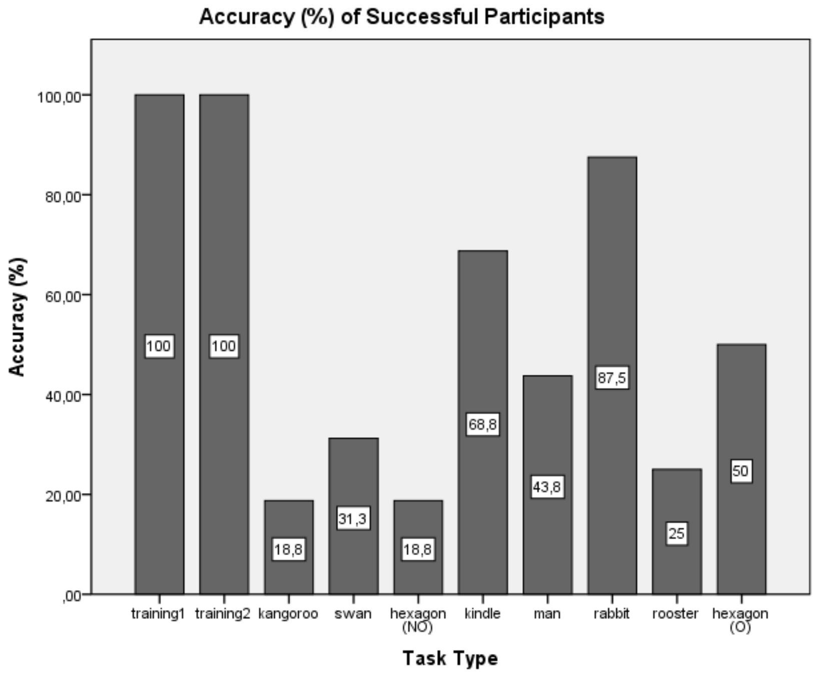


Figure 4.5 Accuracy value based on percentage of successful players

According to Mauchly's Test of Sphericity results, D(44)=.017, p>.05. So, sphericity assumption is satisfied to conduct one-way repeated-measures ANOVA. A one-way repeated-measures ANOVA was performed to measure the mean completion times among all four geometry analogy tasks. The results show that mean completion time of tangram tasks was significantly affected by the type of tangram tasks, F(9, 135)= 16.612, MSE=2.257e9, p<.001. Bonferroni correction was applied to see differences between pairs.

Table 4.3 Bonferroni Comparison for Completion Times over Tangram Tasks

Comparisons	Mean CT Difference (n)	Std. Error	95% CI Lower Bound	95% CI Upper Bound
Control 1 vs. Control 2	9.628	11.057	-34.831	-54.087
Control 1 vs. Kangaroo	-110.860*	14.860	-170.613	-51.106
Control 1 vs. Swan	-84.164*	14.506	-142.488	-25.839
Control 1 vs. Hexagon (NO)	-109.925*	12.343	-159.557	-60.294
Control 1 vs. Kindle	-52.300*	12.865	-104.030	-570.045
Control 1 vs. Man	-99.654*	15.639	-162.537	-36.772
Control 1 vs. Rabbit	-21.118	10.599	-63.734	21.499
Control 1 vs. Rooster	-121.563*	14.577	-179.176	-61.949
Control 1 vs. Hexagon (O)	-84.411*	15.458	-149.564	-25.258

* p < 0.05

Table 4.3 shows that completion times of the subjects had significantly less mean value to be complete the tangram task for the first control condition than they were for kangaroo, swan, hexagon (NO), kindle, man, rooster, and hexagon (O). In addition, (not illustrated at Table 4.2) the second control tangram had significantly less mean value to be completed than it had kangaroo, swan, hexagon (NO), man, rooster, and hexagon (O) tasks. Also, kangaroo task had significantly greater completion times to be completed by all subjects than the first and second control tasks and the rabbit task.

4.2 Eye Tracking Results

4.2.1 Eye Tracking Results of Block Copying Tasks

Fixation Duration

The mean value of fixation duration on the target model was 260 msec (n=16, SD=35) for the first block copying task; 300 msec (n=16, SD=57) for the second block copying task; 280 msec (n=16, SD=60) for the third block copying task; and 280 msec (n=16, SD=30) for the fourth block copying task.

A 4x3 two-way repeated-measures ANOVA was performed to test the effect of task type, AOI type, and their interaction on fixation duration. The results show that fixation durations were not significantly affected by the type of block copying tasks, $F(3, 45)= 1.867$, $p>.05$. Also, there is not a significant main effect for the interaction between task type, $F(6,90)=1.086$, $p>.05$. Whereas, there is a main effect for the type of areas for entire block copying tasks, $F(2,30)=111.824$, $p<.0001$.

Table 4.4 Bonferroni Comparison for Fixation Duration among AOIs

Comparisons	Mean FD Difference (sec)	Std. Error	95% CI Lower Bound	95% CI Upper Bound
Model vs. Piece	-0.056*	0.010	-0.082	-0.030
Model vs. Workspace	-0.400*	0.034	-0.493	-0.308
Piece vs. Workspace	-0.344*	0.035	-0.439	-0.249

* $p < 0.05$

Table 4.4 shows that average fixation duration values of the subjects were significantly lower on the target model area than it was on the piece and workspace areas. Also, average fixation duration of the subjects was significantly lower on the piece area than it was on the workspace area.

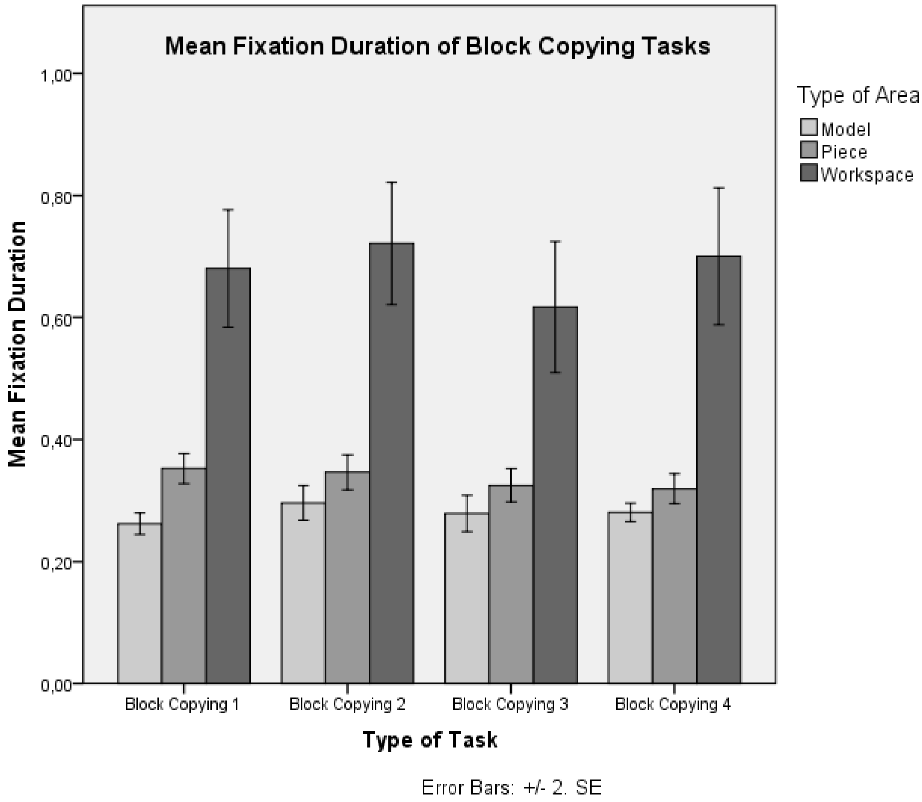


Figure 4.6 Mean Fixation Duration of Block Copying Tasks

Fixation Count

The mean value of fixation count on target model in block copying tasks was 22.75 (n=16, SD=11.62) on the first block copying task; 32.63 (n=16, SD=7.98) on the second block copying task; 21.75 (n=16, SD=8.67) on the third block copying task; and 28.25 (n=16, SD=11.87) on the fourth block copying task.

A 4x3 two-way repeated-measures ANOVA was performed to test the effect of task types, type of areas, and their interaction on mean fixation counts. The results show that fixation counts were significantly affected by the type of block copying tasks, $F(3, 45)= 1.867$, $p>.05$; the type of area, $F(2,30)=30.106$, $p<.0001$; and the interaction Type of Task (4) X Type of Area (3), $F(6,90)=3.365$, $p<.05$.

Table 4.5 Bonferroni Comparison for Fixation Count of Block Copying Task

Comparisons	Mean FC Difference (n)	Std. Error	95% CI Lower Bound	95% CI Upper Bound
BC 1 vs. BC 2	-9.875*	0.33	-19.142	-.608
BC 2 vs. BC 4	-10.875*	2.059	-17.128	-4.622

* p < 0.05

Table 4.5 shows that average fixation count of the subjects had significantly less number of fixations for the first block copying task than it was on the second task. Also, less number of fixations on the second block copying task than it was on the fourth task.

Table 4.6 Bonferroni Comparison for Fixation Count among AOIs

Comparisons	Mean FC Difference (n)	Std. Error	95% CI Lower Bound	95% CI Upper Bound
Model vs. Piece	3.406	1.339	-.200	7.012
Model vs. Workspace	-11.688*	2.353	-18.026	-5.349
Piece vs. Workspace	-15.094*	2.272	-21.213	-8.975

* $p < 0.05$

Table 4.6 shows that fixation count of the subjects had significantly less mean value on the target model and piece areas than it was on the workspace area.

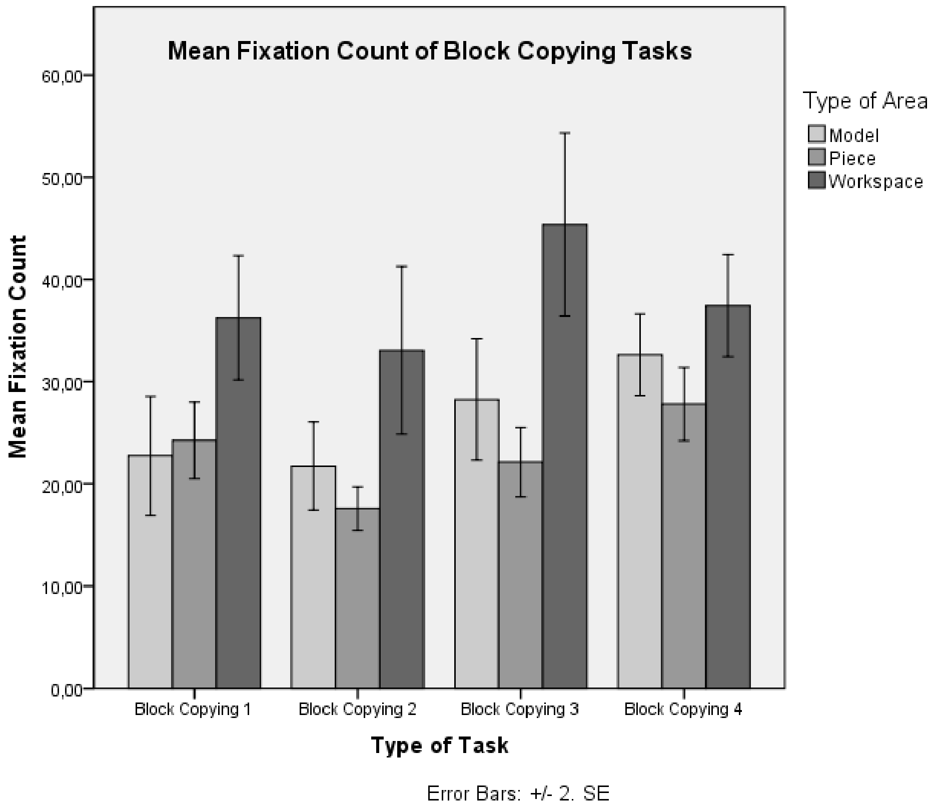


Figure 4.7 Mean Fixation Count of Block Copying Tasks

Fixation Rate

The mean value of fixation rate for each area of interest of block copying tasks was .83 s^{-1} for workspace area (n=16, SD=.174), .54 s^{-1} for target model area (n=16, SD=.317), .57 s^{-1} for pieces area (n=16, SD=.147) for the first block-copying task; .87 s^{-1} for workspace area (n=16, SD=.264), .58 s^{-1} for target model area (n=16, SD=.127), .51 s^{-1} for pieces area (n=16, SD=.180) for the second block-copying task; 1.06 s^{-1} for workspace area (n=16, SD=.471), .64 s^{-1} for target model area (n=16, SD=.229), .51 s^{-1} for pieces area (n=16, SD=.156) for the third block-copying task; and .81 s^{-1} for workspace area (n=16, SD=.172), .71 s^{-1} for target model area (n=16, SD=.151), .61 s^{-1} for pieces area (n=16, SD=.166) for the fourth block-copying task.

A 4x3 two-way repeated-measures ANOVA was performed to measure the mean fixation rate regarding type of tasks, type of areas, and the interaction (Type of Task (4) X Type of Area (3)). Greenhouse-Geisser correction was used for nonsphericity (Geisser & Greenhouse, 1958). The results show that although fixation rates were not significantly affected by the type of block copying tasks, $F(3,45)=2.360$, $p>.05$, type of areas $F(2,30)=2.107$, $p<.05$; and the interaction (Type of Task (4) X Type of Area (3)) $F(6,90)=3.431$, $p<.05$ had significantly effect on fixation rates.

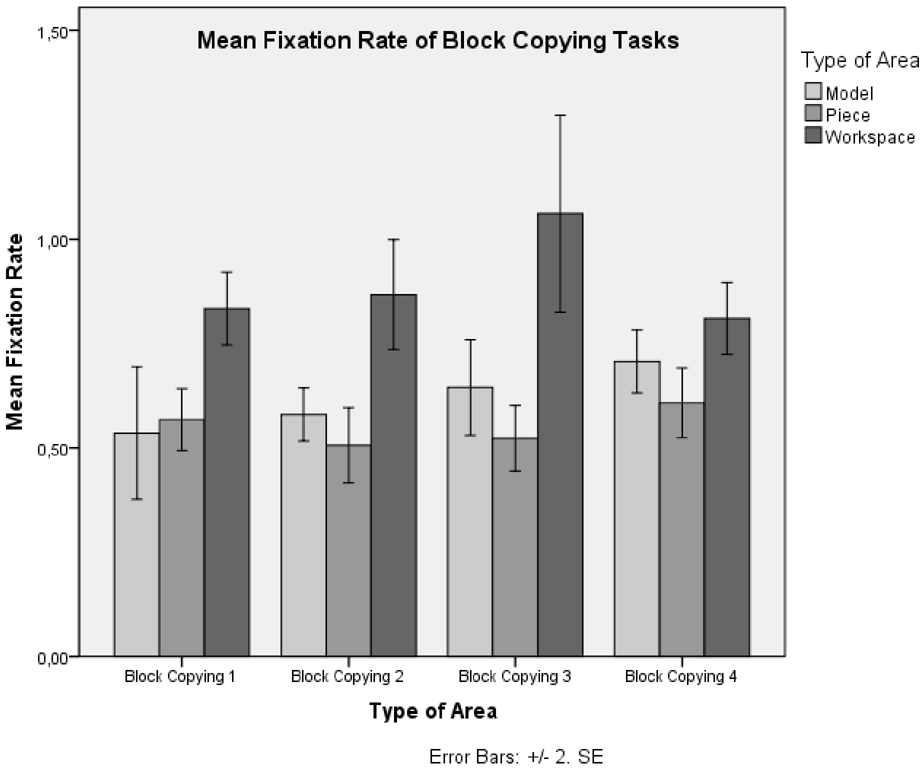


Figure 4.8 Mean Fixation Rate of Block Copying Tasks

Figure 4.8 shows average fixation rate values of Block Copying Tasks over three AOIs. It is seen that there is an increase trend until the fourth block copying task during fixations drop on the workspace area.

Transition Rate between Areas of Interests

The mean value of transition rate between workspace and pieces was .36 s^{-1} for the first block copying task (n=16, SDE=.111); .26 s^{-1} for the second block copying task (n=16, SDE=.123); .23 s^{-1} for the third block-copying task (n=16, SDE=.113); .27 s^{-1} for the fourth block-copying task (n=16, SDE=093). Also, the mean value of transition rate between workspace and model was .30 s^{-1} for the first block copying task (n=16, SDE=.153); .51 s^{-1} for the second block copying task (n=16, SDE=.118); .59 s^{-1} for the third block-copying task (n=16, SDE=.200); .46 s^{-1} for the fourth block-copying task (n=16, SDE=.121). Finally, the mean value of transition rate between model and pieces was .22 s^{-1} for the first block copying task (n=16, SDE=.076); .29 s^{-1} for the second block copying task (n=16, SDE=.109); .31 s^{-1} for the third block-copying task (n=16, SDE=.138); .31 s^{-1} for the fourth block-copying task (n=16, SDE=.111).

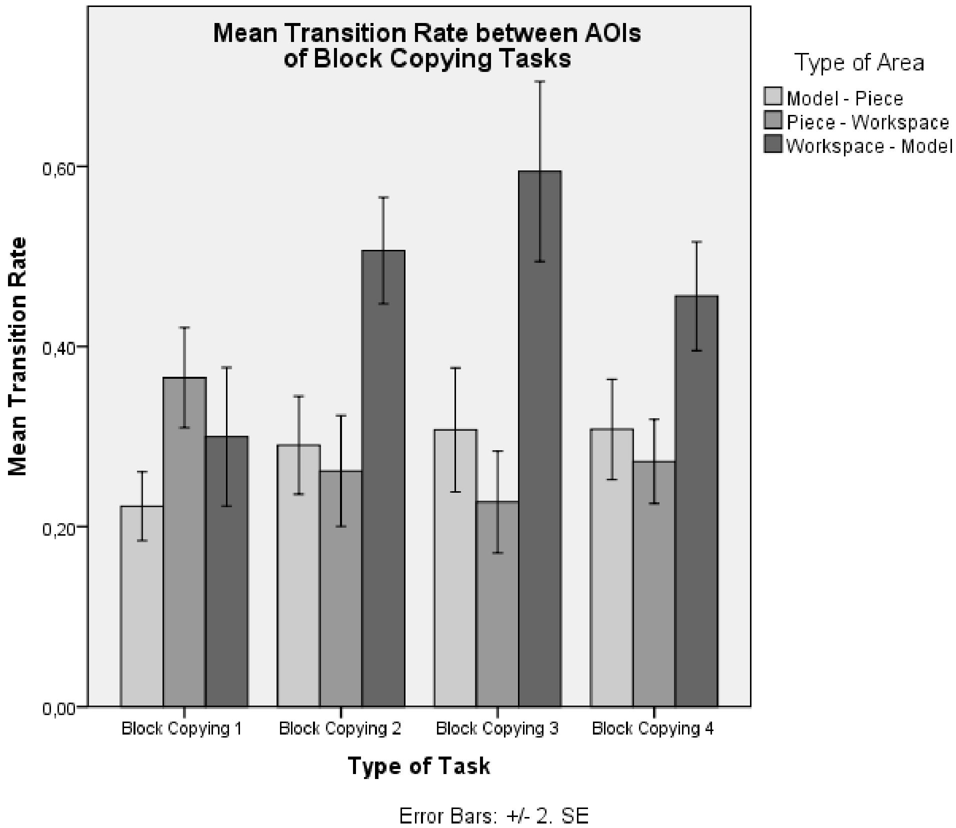


Figure 4.9 Average transition rates between three areas of interests for block copying tasks. PW stands for the transition rate between pieces and workspace; MW stands for the transition rate between model and workspace; and MP stands for the transition rate between model and pieces.

A one-way repeated measures ANOVA was performed separately to compare the mean transition rates among block copying tasks. The results show that mean transition rates differed regarding type of transitions; F(2,30)=8.074, p<.05 for the first block copying task; F(2,30)=.24.817, p<.001 for the second block copying task; F(2,30)=22.964, p<.001 for the third block copying task; and F(2,30)=14.551, p<.001 for the fourth block copying task. Table 4.8 shows the Bonferroni corrections for transition rate DV among block copying tasks.

A 4x3 two-way repeated-measures ANOVA was performed to compare the mean transition rates regarding type of tasks, type of transitions and the interaction (Type of Task (4) X Type of Transition (3)). The results show that transition rates were significantly affected by the type of block copying tasks, F(3,45)=5.549, p<.05. There are also significant main effects for the interaction Type of Task 4) X Type of Transition (3), F(6,90)=15.213, p<.05; and for the type of transition, F(2,30)=22.657, MSE=.031, p<.05.

Table 4.7 Bonferroni Comparison for Transition Rates over Type of Transitions

Comparisons		Mean TR Difference (n)	Std. Error	95% CI Lower Bound	95% CI Upper Bound
BC 1	MW vs. PW	-.065	.041	-.175	.044
	MW vs. MP	.077	.032	-.009	.163
BC 2	MW vs. PW	.244*	.040	.137	.352
	MW vs. MP	.216*	.036	.119	.313
BC 3	MW vs. PW	.367*	.065	.192	.541
	MW vs. MP	.287*	.057	.133	.441
BC 4	MW vs. PW	.184*	.033	.093	.274
	MW vs. MP	.148*	.037	.047	.248

* p < 0.05

Table 4.7 shows that the average transition rate between model and workspace (MW) were significantly higher than mean transition rate between pieces and workspace (PW) and model and pieces areas (MP) for the second, third and fourth block copying tasks.

Transition areas especially model to piece show linear increase as the complexity of the task increases. However, average transition rates (Figure 4.9) shows that at the fourth block copying task, problem solvers' transition rates between workspace and the model show decrease. This finding is also consistent with the previous fixation rate analysis. Results show that problem solvers had to make .31 transitions per second to copy the blocks between the model and the workspace. Although transition rate between the model and the workspace have always greater value, it has a decrease trend in reference to previous block copying tasks. This may be caused by the increasing demands of task properties.

4.2.2 Eye Tracking Results of Geometry Analogy Tasks

Fixation Duration

The mean value of fixation duration on target model for the geometry analogy task was 364.4 msec (n=16, SD=106.39) on the first block copying task; 439.4 msec (n=16, SD=100.83) on the second block copying task; 504.4 msec (n=16, SD=221.87) on the third block copying task; and 325 msec (n=16, SD=108.32) on the fourth block copying task.

A one-way repeated measures ANOVA was performed to test if there is a significant difference between the mean fixation duration values over the target models AOI for each geometry analogy tasks. Greenhouse-Geisser method was used to correct for sphericity (Geisser & Greenhouse, 1958). The results show that mean fixation duration significantly differed across geometry analogy tasks; $F(3,42)=6.043$, $p<.05$. Bonferroni corrected pair-wise comparisons were performed for further analysis. Table 4.9 shows the results of the Bonferroni comparisons for each pair of geometry analogy tasks.

Table 4.8 Bonferroni Comparison for FD of Target Models of Geometry Analogy Tasks

Comparisons	Mean FD Difference (sec)	Std. Error	95% CI Lower Bound	95% CI Upper Bound
Hexagon vs. Funnel	-.087*	.023	-.158	-.015
Hexagon vs. Triangles	-.117	.047	-.263	-.028
Hexagon vs. Arrow	.033	.036	-.076	-.142
Funnel vs. Triangles	-.031	.052	-.189	-.128
Funnel vs. Arrow	.120*	.022	-.053	.187
Triangles vs. Arrow	.151	.053	-.012	.313

* $p < 0.05$

Table 4.8 shows that mean fixation duration of the subjects was significantly lower on on the target model for the hexagon and arrow tasks than they were on the funnel task.

A 4x4 two-way repeated-measures ANOVA was performed to test effect of task type, AOI type, and their interaction on fixation duration. Greenhouse-Geisser correction was used for nonsphericity (Geisser & Greenhouse, 1958). The results show that fixation durations were significantly affected by the type of geometry analogy tasks, $F(3,45)=5.768$, $p<.05$. There are also significant main effects for the interaction between task type and AOI type, $F(9,135)=5.202$, $p<.05$; and for the type of areas, F(3,45)=35.401, p<.001. Bonferroni correction was applied for further analysis. Table 4.10 shows the Bonferroni comparison within geometry analogy tasks.

Table 4.9 Bonferroni Comparison for Fixation Duration of Geometry Analogy Tasks

Comparisons	Mean FD Difference (sec)	Std. Error	95% CI Lower Bound	95% CI Upper Bound
Hexagon vs. Funnel	.000	.010	-.031	.031
Hexagon vs. Triangles	-.010	.013	-.050	.030
Hexagon vs. Arrow	.043*	.023	-.005	.082
Funnel vs. Triangles	-.010	.016	-.058	.039
Funnel vs. Arrow	.044*	.013	.003	.085
Triangles vs. Arrow	.053*	.017	-.106	-.001

* p < 0.05

Table 4.9 shows that average fixation duration values of the subjects were significantly lower duration on the arrow task than they were for the hexagon, funnel task, and triangles task.

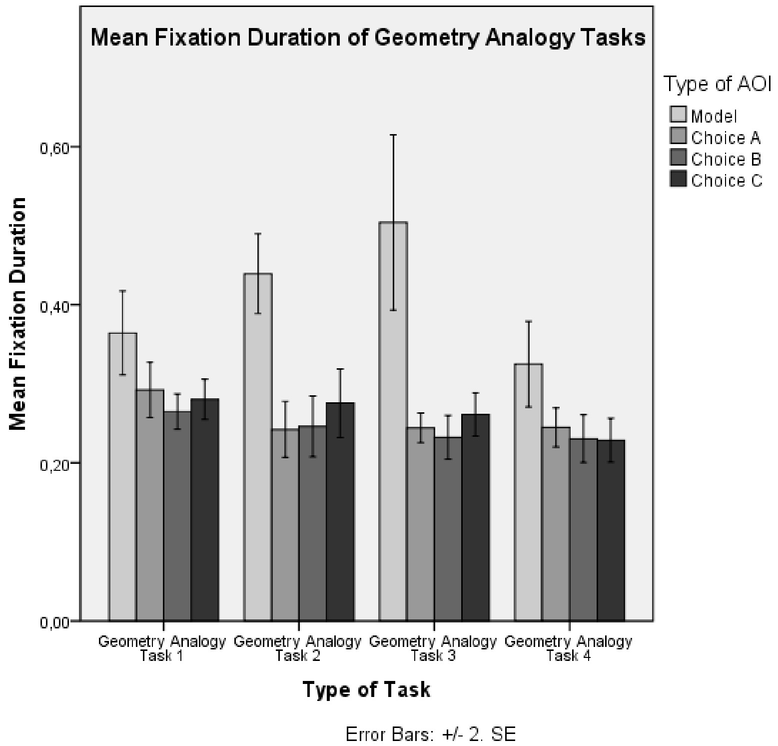


Figure 4.10 Mean Fixation Durations of Geometry Analogy Tasks

Fixation Count

A 4x4 two-way repeated-measures ANOVA was performed to test the mean fixation count regarding type of tasks, type of areas, and the interaction between type of task and AOI types. The results show that fixation counts were significantly affected by the type of geometry analogy tasks, $F(3, 45)= 1.867$, $p>.05$; the type of area, $F(2,30)=30.106$, $p<.0001$; and the interaction between type of task and AOI types, $F(6,90)=3.365$, $p<.05$.

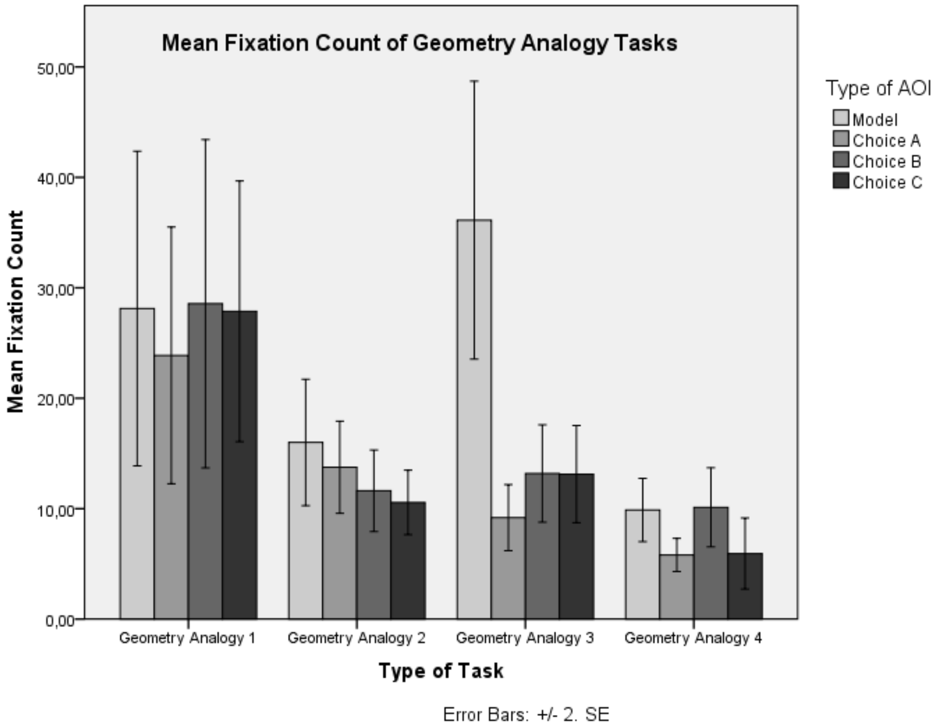


Figure 4.11 Mean Fixation Count of Geometry Analogy Tasks

Fixation Rate

The mean value of fixation rate for each area of interest of geometry analogy tasks was 1.14 s^{-1} for target model area (n=16, SD=.576), .31 s^{-1} for choice a (n=16, SD=.223), .47 s^{-1} for choice b (n=16, SD=.354), .46 s^{-1} for choice c (n=16, SD=.255) for triangles task; 1.00 s^{-1} for target model area (n=16, SD=.552), .73 s^{-1} for choice a (n=16, SD=.581), 1.04 s^{-1} for choice b (n=16, SD=.782), .67 s^{-1} for choice c (n=16, SD=.570) for arrow task; .73 s^{-1} for target model area (n=16, SD=.287), .59 s^{-1} for choice a (n=16, SD=.236), .70 s^{-1} for choice b (n=16, SD=.257), .91 s^{-1} for choice c (n=16, SD=.869) for hexagon task; and .73 s^{-1} for target model area (n=16, SD=.231), .69 s^{-1} for choice a (n=16, SD=.400), .58 s^{-1} for choice b (n=16, SD=.342), .59 s^{-1} for choice c (n=16, SD=.375) for funnel task.

4x4 two-way repeated-measures ANOVA was performed to test the mean fixation count regarding type of tasks, type of areas, and the interaction (Type of Task (4) X Type of Area (4)). The results show that although fixation rates were not significantly affected by the type of geometry analogy tasks, $F(3,45)=1.707$, $p>.05$, type of areas $F(3,45)=7.582$, $p<.05$; and the interaction (Type of Task (4) X Type of Area (4)) $F(9,135)=4.779$, $p<.05$ had significantly effect on fixation rates.

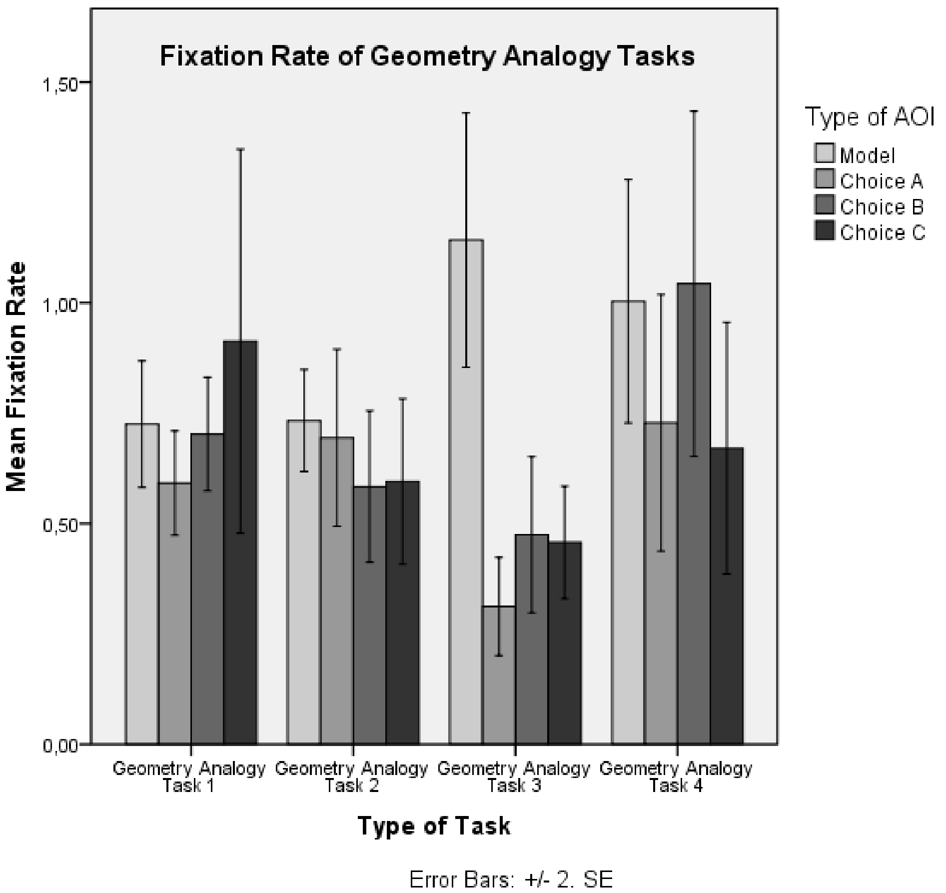


Figure 4.12 Fixation Rates of Geometry Analogy Tasks

4.2.3 Eye Tracking Results of Chinese Tangram Tasks

Fixation Durations

Fixation durations of all tangram tasks (control and experimental conditions) were entered (N=15) into one-way repeated measure ANOVA with *target models* as a within-subject factor. Mauchly's test suggested that the sphericity assumption was satisfied, $D(44)=.001$, $p>.05$. The results show that task type has a significant effect on mean fixation durations observed for each tangram task, $F(9,99)=13.214$, $p<.0001$.

Fixation durations of all tangram tasks (control and experimental conditions) were entered (N=15) into one-way repeated measures ANOVA with *workspaces* as a within-subject factor. Greenhouse-Geisser correction method was used to correct for sphericity. The results show that $F(9,126)=16.669$, $p<.0001$.

Table 4.10 Bonferroni Comparison for Fixation Duration DV (Model and Workspace)

	Comparisons	Mean FD Difference (sec)	Std. Error	95% CI Lower Bound	95% CI Upper Bound
Model	Control 1 vs. Swan	-.176*	.031	-.312	-.040
	Control 2 vs. Kangaroo	-.067*	.011	-.117	-.018
	Control 2 vs. Swan	-.192*	.024	-.295	-.088
	Control 2 vs. Man	-.093*	.018	-.172	-.015
	Control 2 vs. Rooster	-.148*	.022	-.245	-.050
	Kangaroo vs. Swan	-.124*	.024	-.228	-.021
	Kangaroo vs. Rooster	-.080*	.017	-.153	-.007
	Swan vs. Hexagon(NO)	.149*	.029	.01	.277
	Swan vs. Kindle	.156*	.025	.047	.264
	Swan vs. Rabbit	.161*	.031	.027	.295
	Swan vs. Hexagon(O)	.184*	.031	.047	.322
	Hexagon (NO) vs. Rooster	-.105*	.019	-.099	.169
	Kindle vs. Rooster	-.112*	.018	-.191	-.032
	Rooster vs. Hexagon (O)	.140*	.031	.003	.277
Workspace	Control 1 vs. Kangaroo	.127*	.025	.023	.230
	Control 1 vs. Swan	.282*	.044	.101	.463
	Control 1 vs. Rooster	.149*	.028	.036	.263
	Control 2 vs. Swan	.289*	.054	.070	.509
	Control 2 vs. Rooster	.157*	.034	.017	.296
	Kangaroo vs. Swan	.155*	.029	.036	.275
	Swan vs. Hexagon (NO)	-.196*	.036	-.342	-.050
	Swan vs. Kindle	-.199*	.034	-.336	-.061
	Swan vs. Man	-.178*	.033	-.311	-.045
	Swan vs. Rabbit	-.215*	.038	-.371	-.059
	Swan vs. Rooster	-.133*	.030	-.254	-.011
	Swan vs. Hexagon (O)	-.237*	.043	-.411	-.063
	Kindle vs. Rooster	.066*	.013	-.140	.064
	Rooster vs. Hexagon (O)	-.104*	.018	-.178	-.030

Table 4.10 shows fixation durations on the target model of the tasks had significantly shorter mean value on the first control condition than it was on swan task; shorter mean value on the second control condition than it was on kangaroo, swan, man and rooster tasks; shorter mean value on kangaroo than it was on swan and rooster tasks; greater mean value on swan than it was on control 1, control 2, kangaroo, hexagon (NO), kindle, rabbit, hexagon (O) tasks; shorter mean value on hexagon (NO) than it was on swan and rooster task; shorter mean value on kindle than it was on swan and rooster tasks; greater mean value on rooster than it was on control 2, kangaroo, hexagon (NO), kindle, and hexagon (O) tasks. Whereas, fixation durations on the workspace of the tasks had significantly greater mean value on the first control task than it was on kangaroo, swan, rooster tasks; greater value on the second control task than it was on swan, and rooster tasks; greater mean value on kangaroo task than it was on swan task; shorter mean value on swan task than it was on control 1, control 2, kangaroo, hexagon (NO), kindle, man, rabbit, rooster, and hexagon (O) tasks; greater mean value on hexagon (NO) than it was on swan task; greater mean value on kindle, than it was on swan and rooster tasks; greater mean value on man than it was on swan task; greater mean value on rabbit than it was on swan task; shorter mean value on rooster task than it was on control 1, control 2, swan, kindle, and hexagon (O) tasks; and greater mean value on hexagon (O) task than it was on swan and rooster tasks.

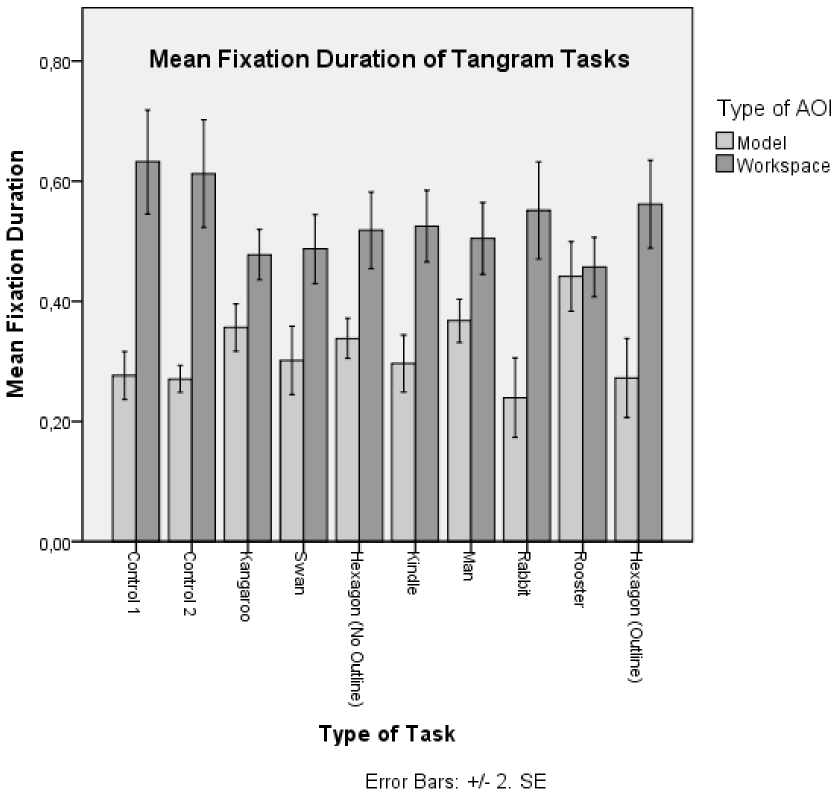


Figure 4.13 Mean Fixation Durations over AOIs among Tangram Tasks

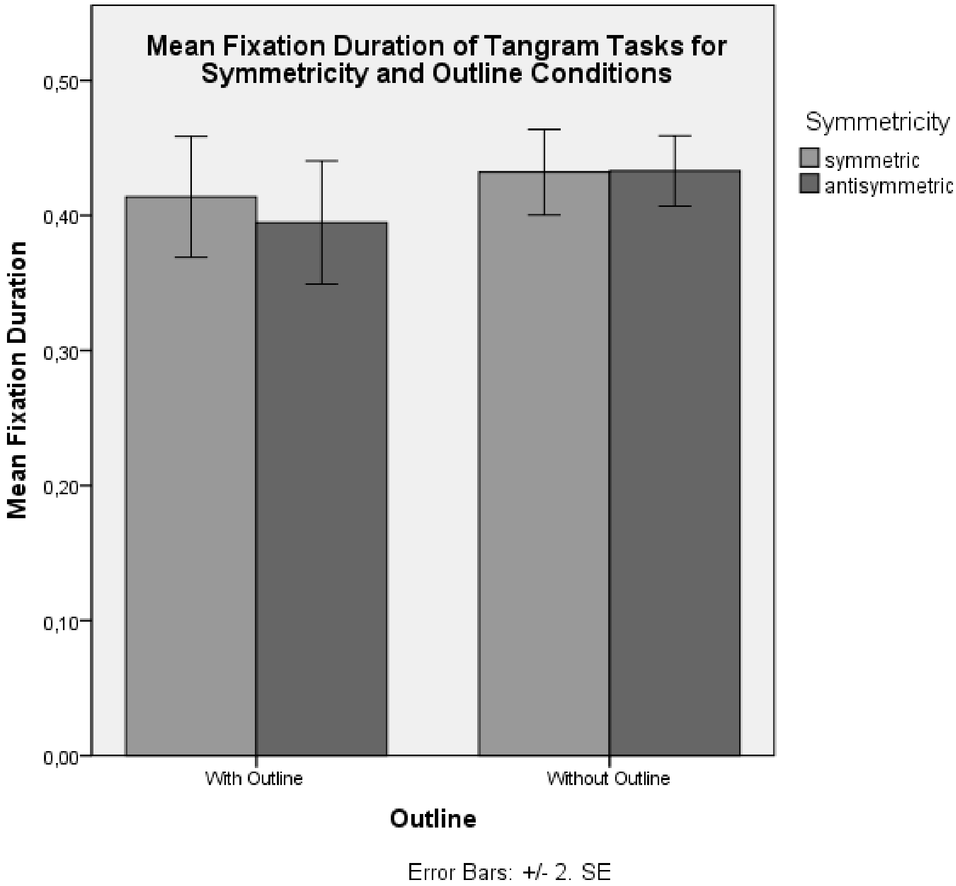


Figure 4.14 Mean Fixation Durations over Tangram Tasks (O vs. NO)

Fixation Count

Fixation counts of all tangram tasks (control and experimental conditions) were entered (N=12) into one-way repeated measure ANOVA with *target models* as a within-subject factor. Greenhouse-Geisser method was used to correct for nonsphericity. The results show that there is a significant difference between the type of types considering fixation counts F(9,99)=26.033, p<.0001.

In addition, fixation counts of all tangram tasks (control and experimental conditions) were entered (N=12) into two-way 10x2 repeated measures ANOVA with the AOI types as a within-subject factor. Sphericity assumption was satisfied for the interaction Type of Task (10) X Type of Area (2), D(44)=.000, p>.05. The results show that there is a main effect for the interaction Type of Task (10) X Type of Area (2), F(9,99)=28.013, p<.0001.

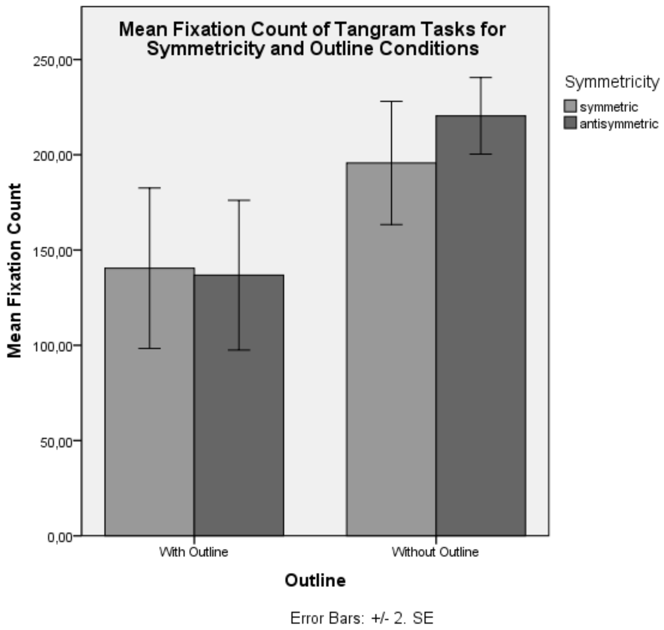


Figure 4.15 Mean Fixation Count of Tangram Tasks for Symmetricity and Outline Conditions

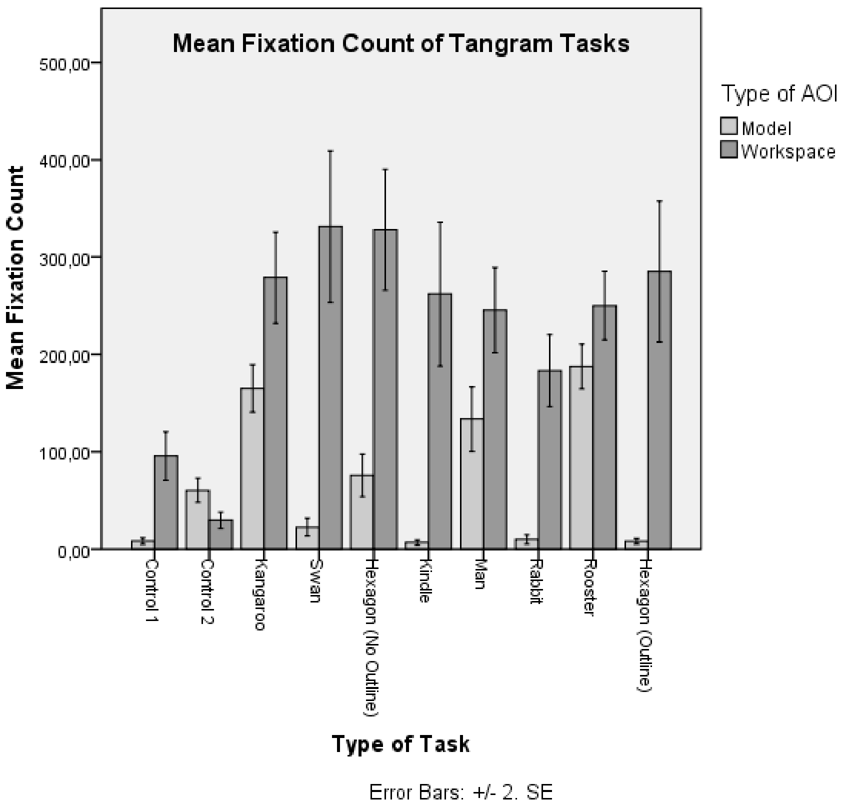


Figure 4.16 Mean Fixation Count of Tangram Tasks

Fixation Rate

A 10x2 two-way repeated-measures ANOVA was performed to measure the mean fixation rate regarding types of task, types of AOI, and the interaction. Greenhouse-Geisser correction was used for sphericity (Geisser & Greenhouse, 1958). The results show fixation rates were significantly affected by the types of tangram task, $F(1,798, 26,976)=239.698$, $p<.001$; types of AOI, $F(1, 15)=49.524$, $p<.001$; and the interaction $F(1,25, 18,748)=85.388$, $p<.001$.

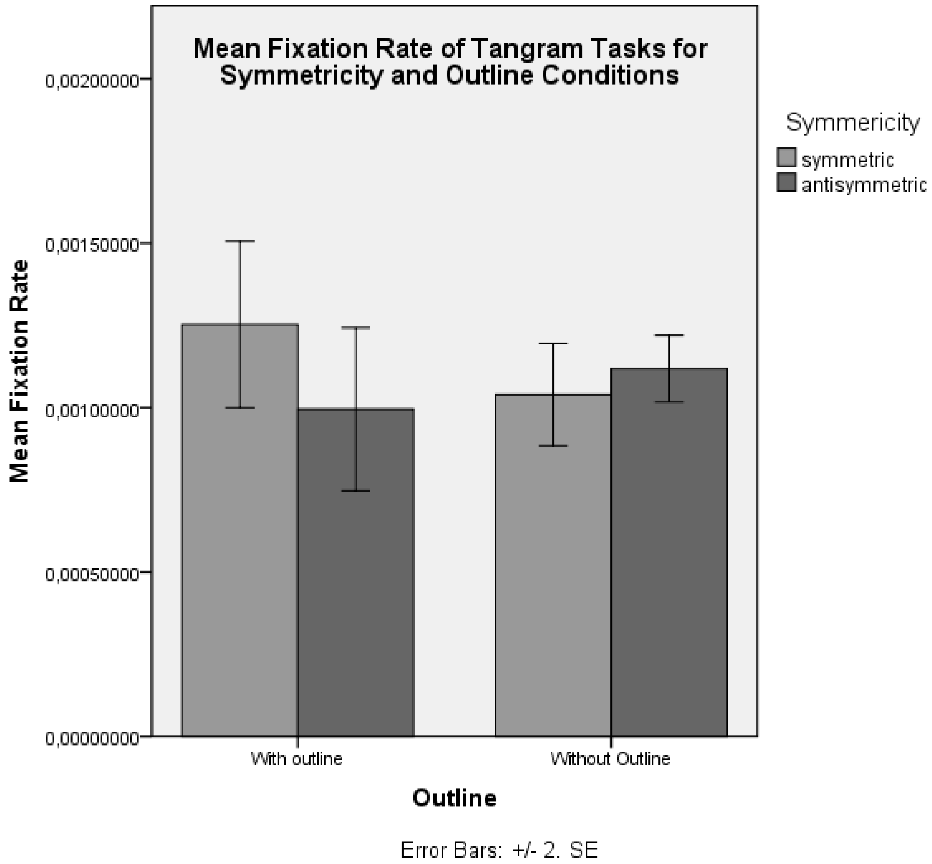


Figure 4.17 Average Fixation Rates of Tangram Tasks (O vs. NO)

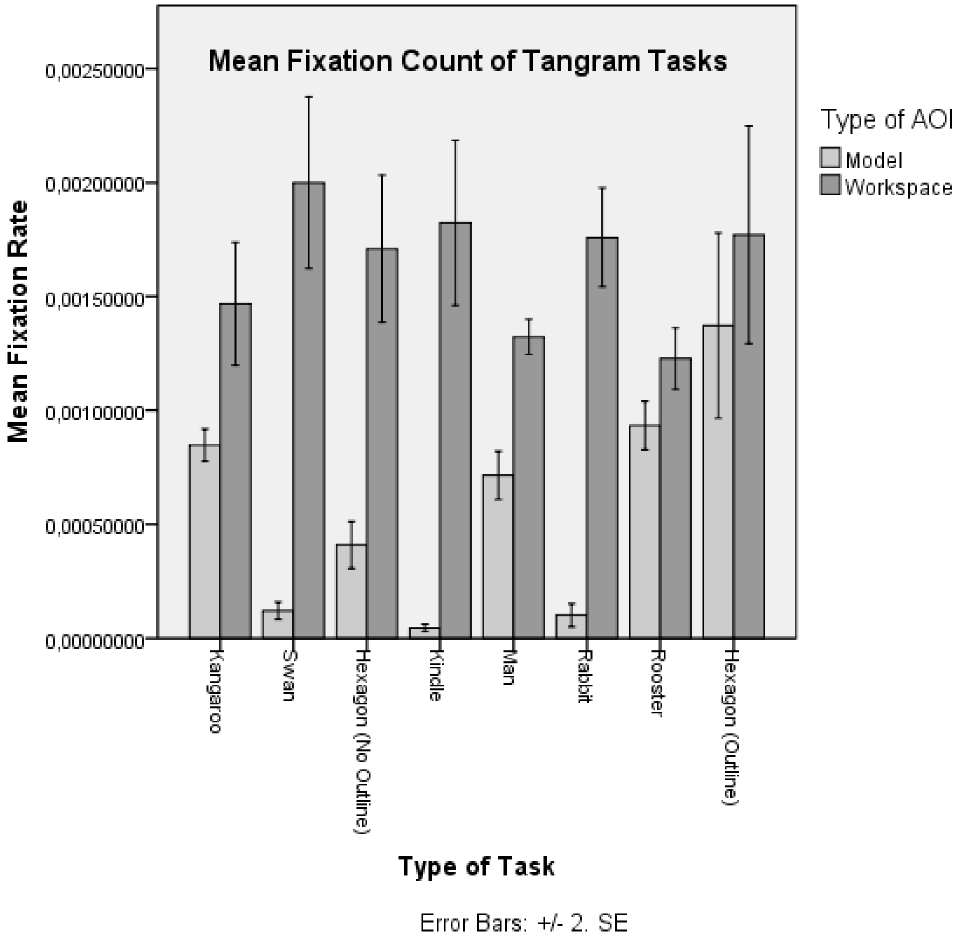


Figure 4.18 Average Fixation Rates of Tangram Tasks

4.2.4 Overall Eye-Tracking Results

A one-way repeated-measures ANOVA was performed to analyze mean fixation durations on target models of three types of task (block copying, geometry analogy, and tangram task). Statistics were Greenhouse-Geisser corrected for sphericity (Geisser & Greenhouse, 1958). The results show that fixation duration over target model was significantly affected by different visuospatial tasks; $F(1.430,21.452)=20.912$, $p<.0001$.

Bonferroni corrected pair-wise comparisons were performed for further analysis. Table 4.10 shows the result of the Bonferroni comparison for fixation duration among three task types.

Table 4.11 Bonferroni Comparison for Fixation Duration among Types of Task

Comparisons	Mean FD Difference (sec)	Std. Error	95% CI Lower Bound	95% CI Upper Bound
BC vs. GA	-.129*	.025	-.197	-.061
BC vs. Tangram	-.047*	.014	-.085	-.009
GA vs. Tangram	.082*	.019	-.029	-.134

* $p < 0.05$

Table 4.10 shows that mean fixation duration of the subjects was significantly lower on the target model for the block copying than they were on the tangram and geometry analogy tasks. Also, mean fixation duration of the subjects was significantly lower on the tangram task than they were on the geometry analogy task.

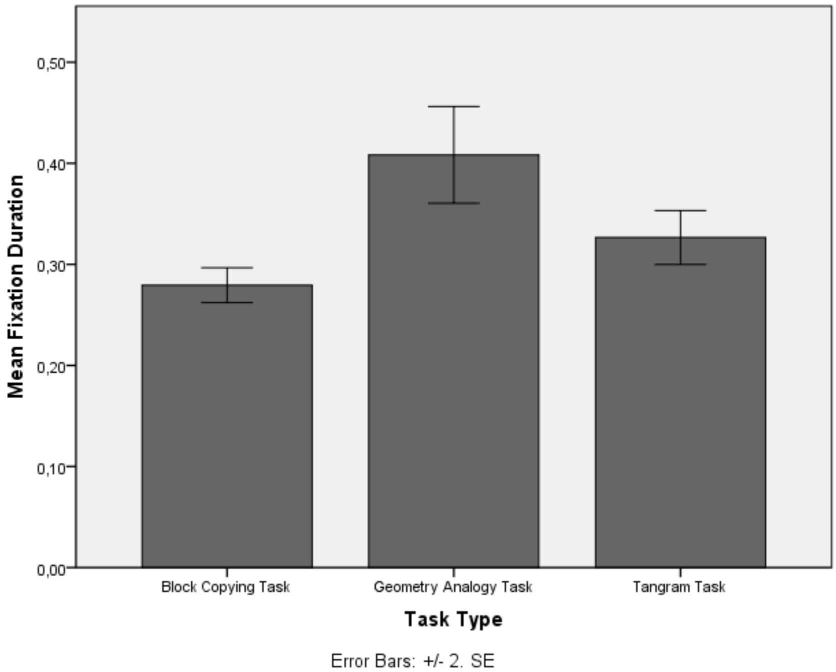


Figure 4.19 Average Fixation Duration over Three Types of Task

4.3 fNIR Results

After preprocessing the brain data, it is seen that 3rd, 5th, 7th, 9th, 11th, 13th, and 15th voxels were reliable to be used for further analysis. Remaining voxels needed to be eliminated due to low signal quality or signal saturation.

4.3.1 fNIR Results of Block Copying Tasks

Maximum (i.e. peak) oxygenation values observed while subjects attempted each block copying task were used for statistical comparisons. Acquired data were evaluated for normality and homogeneity (Krus & Blackman, 1988) assumptions. According to results, mean maximum oxygenation values of the most of block copying tasks were not distributed normally, and did not verify the homogeneity of variance assumption. Maximum oxygenation levels for 3rd (n=14), 5th (n=14), 7th (n=12), 9th (n=12), 11th (n=13), 13th (n=13) and 15th voxel (n=14) were entered separately into Friedman's ANOVA Test (Field, 2000) with task types to determine whether maximum oxygenation levels showed significantly differential ranks within four block copying tasks. Results of that analysis indicated that maximum oxygenation values were not significantly affected by types of block copying tasks $\chi^2(3) = 3.686$, $p>.05$ for 3rd voxel; $\chi^2(3) = 2.723$, $p>.05$ for 5th voxel; $\chi^2(3) = 2.800$, $p>.05$ for 7th voxel; $\chi^2(3) = .120$, $p>.05$ for 9th voxel; $\chi^2(3) = .580$, $p>.05$ for 11th voxel; $\chi^2(3) = .785$, $p>.05$ for 13th voxel; $\chi^2(3) = 2.314$, $p>.05$ for 15th voxel.

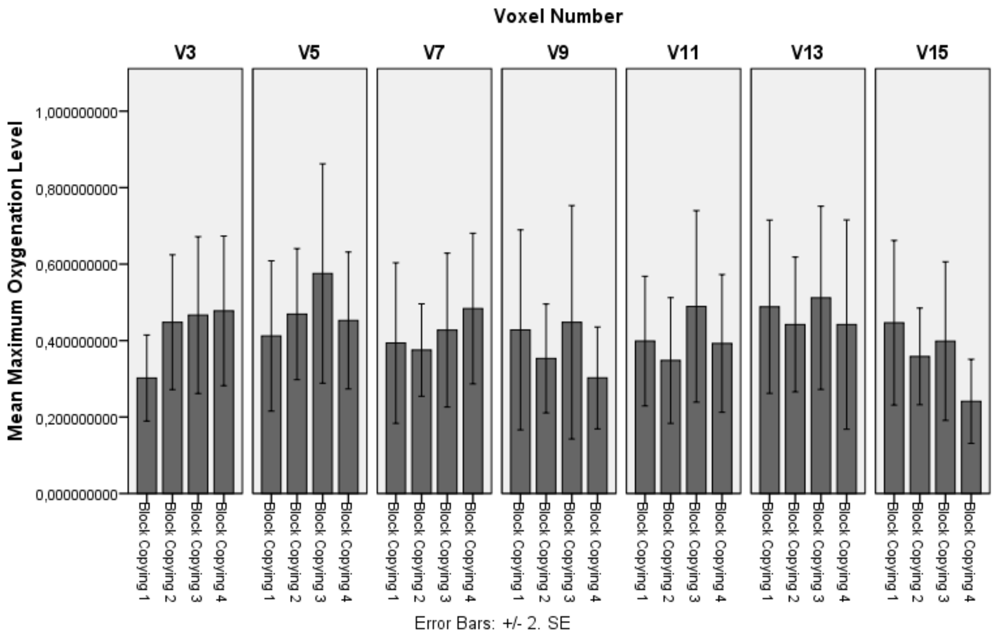


Figure 4.20 Mean Maximum Oxygenation Level of Block Copying Tasks

4.3.2 fNIR Results of Geometry Analogy Tasks

Maximum (i.e. peak) oxygenation values observed while subjects attempted each block copying task were used for statistical comparisons. Acquired data were evaluated for normality and homogeneity (Krus & Blackman, 1988) assumptions. According to results, mean maximum oxygenation values of geometry analogy tasks were not distributed normally, and did not verify the homogeneity of variance assumption. Maximum oxygenation levels for 3rd (n=14), 5th (n=14), 7th (n=12), 9th (n=11), 11th (n=13), 13th (n=13) and 15th voxel (n=14) were entered separately into

Friedman's ANOVA Test (Field, 2000) with task types to determine whether maximum oxygenation levels showed significantly differential ranks within four geometry analogy tasks. Results of that analysis indicated that maximum oxygenation values were significantly affected by types of geometry analogy tasks $\chi^2(3) = 8.743$, $p<.05$ for 3rd voxel. However, the rest of results showed that maximum oxygenation values were not significantly affected by the types of geometry analogy tasks $\chi^2(3) = .600$, $p>.05$ for 5th voxel; $\chi^2(3) = 2.700$, $p>.05$ for 7th voxel; $\chi^2(3) = 1.473$, $p>.05$ for 9th voxel; $\chi^2(3) = 6.877$, $p>.05$ for 11th voxel; $\chi^2(3) = 5.500$, $p>.05$ for 13th voxel; $\chi^2(3) = 7.286$, $p>.05$ for 15th voxel. Wilcoxon tests were used to follow up this finding. A Bonferroni correction was applied for 3rd voxel and so all effects are reported at a .0125 level of significance. It appeared that maximum oxygenation level significantly differentiated between triangles and arrow tasks, $T = 7$, $r = .540$ for 3rd voxel.

Table 4.12 Comparison between geometry analogy task mean maximum oxygenation levels (n=14) for 3rd voxel

	Comparisons	Mean Max Oxy Difference	Wilcoxon signed ranks test (two tailed)
V3	Hexagon vs. Funnel	1.060	Z = .722, p= .470
	Hexagon vs. Triangles	1.357	Z = .910, p=.363
	Hexagon vs. Arrow	1.421	Z = 1.726, p=.084
	Funnel vs. Triangles	1.865	Z = 1.915, p = .056
	Funnel vs. Arrow	2.116	Z = 1.789, p= .074
	Triangles vs. Arrow	1.838*	Z = 2.856, p = .004*

*: significant at p<.0125

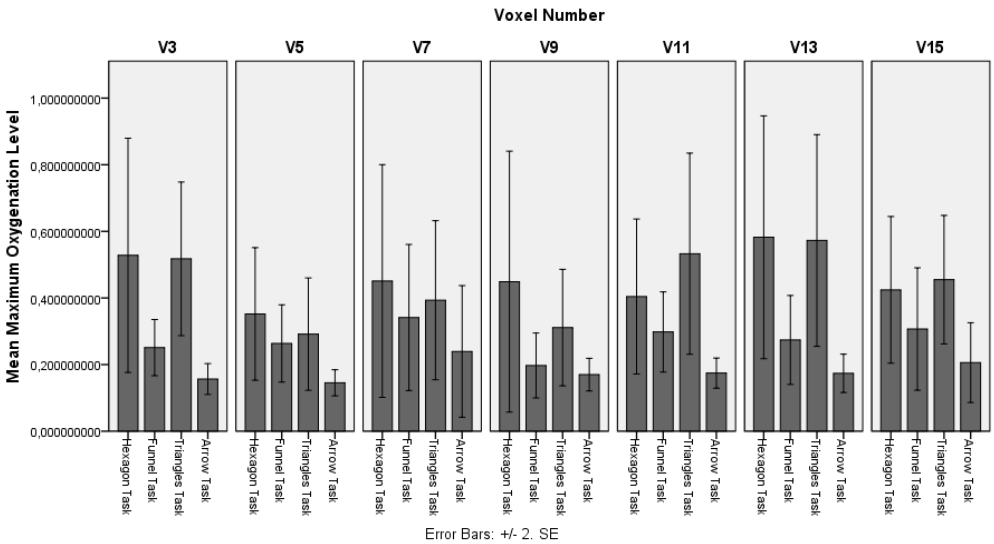


Figure 4.21 Mean Maximum Oxygenation Levels of Geometry Analogy Tasks

4.3.3 fNIR Results of Chinese Tangram Tasks

Maximum (i.e. peak) oxygenation values observed while subjects attempted each block copying task were used for statistical comparisons. Acquired data were evaluated for normality and homogeneity (Krus & Blackman, 1988) assumptions. According to results, tangram tasks were not distributed normally, and did not verify the homogeneity of variance assumption. Maximum oxygenation levels for 3rd (n=14), 5th (n=13), 7th (n=12), 9th (n=10), 11th (n=11), 13th (n=11) and 15th voxel (n=12) were entered separately into Friedman's ANOVA Test (Field, 2000) with task types to determine whether maximum oxygenation levels showed significantly differential ranks within ten tangram tasks (two control tasks and eight experimental tasks). Results of that analysis indicated that maximum oxygenation values were significantly affected by types of tangram tasks $\chi^2(9) = 18.065$, p<.05 for 9th voxel and $\chi^2(9) = 20.157$, p<.05 for 13th voxel. Wilcoxon tests were used to follow up this finding. A Bonferroni correction was applied for 9th and 13th voxels and so all effects are reported at a .005 level of significance. It appeared that maximum oxygenation level significantly differentiated between kangaroo and first control tangram tasks $T = 40$, $r = .597$ for 9th voxel and between kangaroo and first control tangram tasks $T = 75$, $r = .326$ and between rooster and first control tangram tasks $T = 52$, $r = .592$ for 13th voxel.

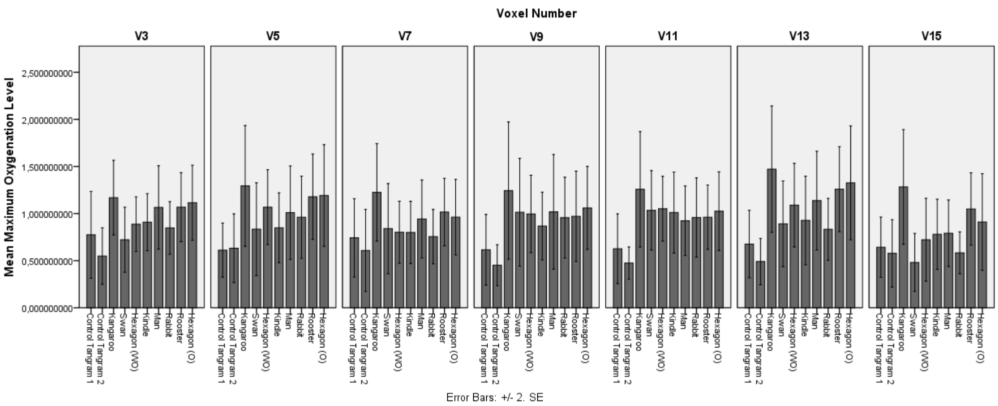


Figure 4.22 Mean Maximum Oxygenation Levels of Chinese Tangram Tasks

Furthermore, maximum oxygenation levels for 3rd (n=14), 5th (n=13), 7th (n=12), 9th (n=10), 11th (n=11), 13th (n=11) and 15th voxel (n=12) were entered separately into one-way repeated measures ANOVA (Field, 2000) in regard with different features which are comprised of symmetric and with outline tangram tasks (Hexagon (O) and Kindle), symmetric and without outline tangram tasks (Hexagon (WO) and Man), antisymmetric and with outline tangram tasks (Swan and Rabbit); and antisymmetric and without outline tasks (Kangaroo and Rooster) to determine whether maximum oxygenation levels showed significantly differential ranks within mentioned task features. Results of that analysis indicated that maximum oxygenation values were significantly affected by features of tangram tasks $F(2.202,26.423)=4.104$, p<.05 for 15th voxel. Wilcoxon tests were used to follow up this finding. A Bonferroni corrected pair-wise comparisons were performed for further analysis and all effects are reported at a .05 level of significance. It appeared that mean maximum oxygenation level significantly differentiated between antisymmetric outline tangram tasks and antisymmetric without outline tangram tasks, p<.05 (Table 4.14).

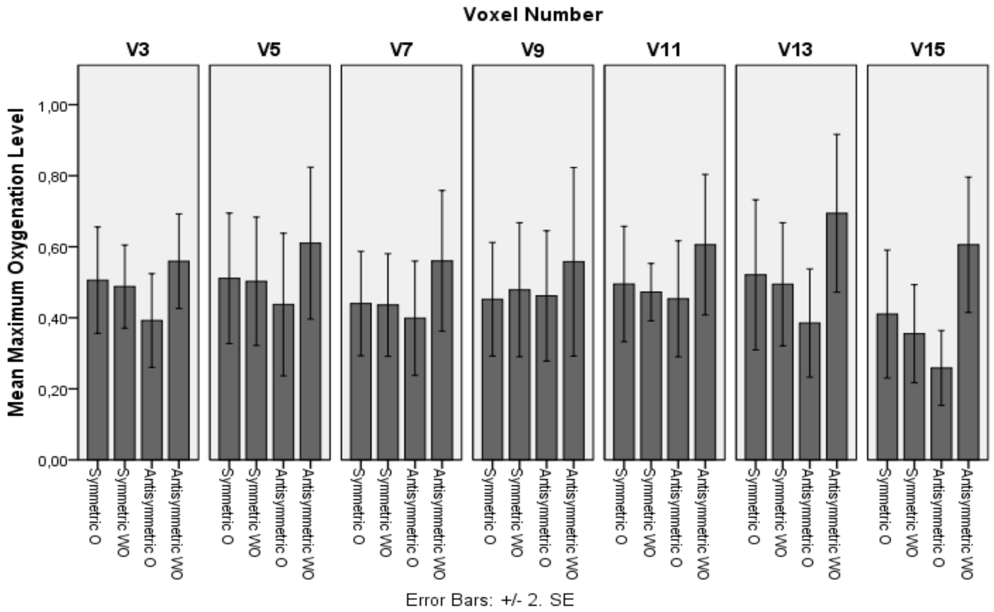


Figure 4.23 Mean Maximum Oxygenation Level of Chinese Tangrams (Symmetric Outline, Symmetric Without Outline, Antisymmetric Outline and Antisymmetric Without Outline)

Table 4.13 Bonferroni comparisons for Tangram Task Features

	Comparisons	Mean Maximum Oxy Difference	Std. Error	95% CI Lower Bound	95% CI Upper Bound
V15	Symmetric O vs. Asymmetric O	.303	.136	-.127	.733
	Symmetric O vs. Asymmetric WO	-.391	.233	-1.126	.344
	Symmetric O vs. Symmetric WO	.110	.230	-.616	.836
	Asymmetric O vs. Asymmetric WO	-.694*	.220	-1.386	-.001
	Asymmetric O vs. Symmetric WO	-.193	.136	-.622	.236
	Asymmetric WO vs. Symmetric WO	-.501	.239	-.253	1.254

*p<.05

4.3.4 Overall fNIR Results

Maximum (i.e. peak) oxygenation values observed while subjects attempted each visuospatial task were used for statistical comparisons. Acquired data were evaluated for normality and homogeneity (Krus & Blackman, 1988) assumptions. According to results, mean maximum oxygenation values of visuospatial tasks were distributed normally, and verified the homogeneity of variance assumption. Statistics were Greenhouse-Geisser corrected for sphericity (Geisser & Greenhouse, 1958). Maximum oxygenation levels for 3rd (n=14), 5th (n=13), 7th (n=12), 9th (n=10), 11th (n=11), 13th (n=11) and 15th voxel (n=12) were entered separately into one-way repeated measures ANOVA (Field, 2000) with various types of visuospatial tasks to determine whether maximum oxygenation levels showed significant difference. Results of that analysis indicated that maximum oxygenation values were significantly affected by types of visuospatial tasks $F(4,52)=8.688$, $p<.05$ for 3rd voxel, $F(4,36)= 6.179$, $p<.05$ for 5th voxel, $F(4,44)=5.716$, $p<.05$ for 7th voxel, $F(1.570, 10.993)=6.233$, $p<.05$ for 9th voxel, $F(4,36)=14.906$, $p<.05$ for 11th voxel, $F(2.060,18.540)=9.109$, $p<.05$ for 13th voxel, and $F(4,44)=6.408$, $p<.05$ for 15th voxel. Bonferroni corrected pair-wise comparisons were performed for further analysis. Table 4.15 shows the results of the Bonferroni comparisons for each pair of given visuospatial tasks. It appeared that mean maximum oxygenation level significantly differentiated between various visuospatial tasks, $p<.05$.

Table 4.14 Bonferroni comparisons for various visuospatial tasks

	Comparisons	Mean Maximum Oxy Difference	Std. Error	95% CI Lower Bound	95% CI Upper Bound
V3	Outline vs. Control	.237	.191	-.177	.650
	Outline vs. Without O	-.149	.167	-.509	.211
	Outline vs. GA	.535*	.140	.232	.838
	Outline vs. BC	.475*	.113	.230	.719
	Control vs. Without O	-.385*	.157	-.724	-.047
	Control vs. GA	.289	.143	-.011	.608
	Control vs. BC	.238	.151	-.089	.564
	Without O vs. GA	.684*	.133	.396	.971
	Without O vs. BC	.623*	.107	.391	.856
	GA vs. BC	-.060	.082	-.237	.116
V5	Outline vs. Control	.211	.275	-.411	.833
	Outline vs. Without O	-.230	.194	-.668	.208
	Outline vs. GA	.542*	.197	.096	.988
	Outline vs. BC	.341	.159	-.019	.702
	Control vs. Without O	-.441*	.166	-.817	-.065
	Control vs. GA	.331*	.135	.025	.637
	Control vs. BC	.130	.170	-.255	.515
	Without O vs. GA	.772*	.120	.501	1.043
	Without O vs. BC	.571*	.127	.284	.859
	GA vs. BC	-.200*	.084	-.391	-.009
V7	Outline vs. Control	.164	.235	-.353	.680
	Outline vs. Without O	-.157	.197	-.591	.277

	Outline vs. GA	.483*	.146	.162	.804
	Outline vs. BC	.419*	.123	.148	.690
	Control vs. Without O	-.321	.185	-.728	.085
	Control vs. GA	.319	.148	-.006	.644
	Control vs. BC	.255	.174	-.128	.638
	Without O vs. GA	.640*	.133	.346	.934
	Without O vs. BC	.576*	.132	.285	.867
	GA vs. BC	-.064	.081	-.242	.115
V9	Outline vs. Control	.393	.226	-.142	.927
	Outline vs. Without O	-.091	.250	-.681	.499
	Outline vs. GA	.521*	.207	.032	1.011
	Outline vs. BC	.431*	.164	.044	.819
	Control vs. Without O	-.483*	.061	-.627	-.340
	Control vs. GA	.129	.089	-.082	.339
	Control vs. BC	.039	.086	-.165	.242
	Without O vs. GA	.612*	.137	.288	.936
	Without O vs. BC	.522*	.131	.211	.832
	GA vs. BC	-.090	.084	-.288	.108
V11	Outline vs. Control	.382	.184	-.034	.798
	Outline vs. Without O	-.174	.140	-.491	.142
	Outline vs. GA	.582*	.166	.207	.958
	Outline vs. BC	.503*	.124	.222	.785
	Control vs. Without O	-.556*	.079	-.734	-.378
	Control vs. GA	.200*	.084	.011	.390
	Control vs. BC	.121	.095	-.094	.337
	Without O vs. GA	.756-	.106	.516	.996
	Without O vs. BC	.677*	.096	.461	.894
	GA vs. BC	-.079	.080	-.260	.102
V13	Outline vs. Control	.474*	.207	.005	.944
	Outline vs. Without O	-.138	.220	-.636	.360
	Outline vs. GA	.577*	.201	.121	1.033
	Outline vs. BC	.500*	.159	.140	.861
	Control vs. Without O	-.613*	.099	-.836	-.389
	Control vs. GA	.103	.085	-.090	.295
	Control vs. BC	.026	.081	-.158	.209
	Without O vs. GA	.715*	.164	.345	1.086
	Without O vs. BC	.639	.128	.350	.927
	GA vs. BC	-.077	.103	-.311	.157
V15	Outline vs. Control	.079	.195	-.351	.508
	Outline vs. Without O	-.273	.169	-.645	.100
	Outline vs. GA	.340*	.153	.004	.676
	Outline vs. BC	.303*	.127	.022	.583
	Control vs. Without O	-.351*	.153	-.689	-.014
	Control vs. GA	.262	.132	-.029	.552
	Control vs. BC	.224	.102	-.001	.449
	Without O vs. GA	.613*	.131	.326	.900
	Without O vs. BC	.575*	.116	.320	.831
	GA vs. BC	-.038	.072	-.195	.120

*p<.05

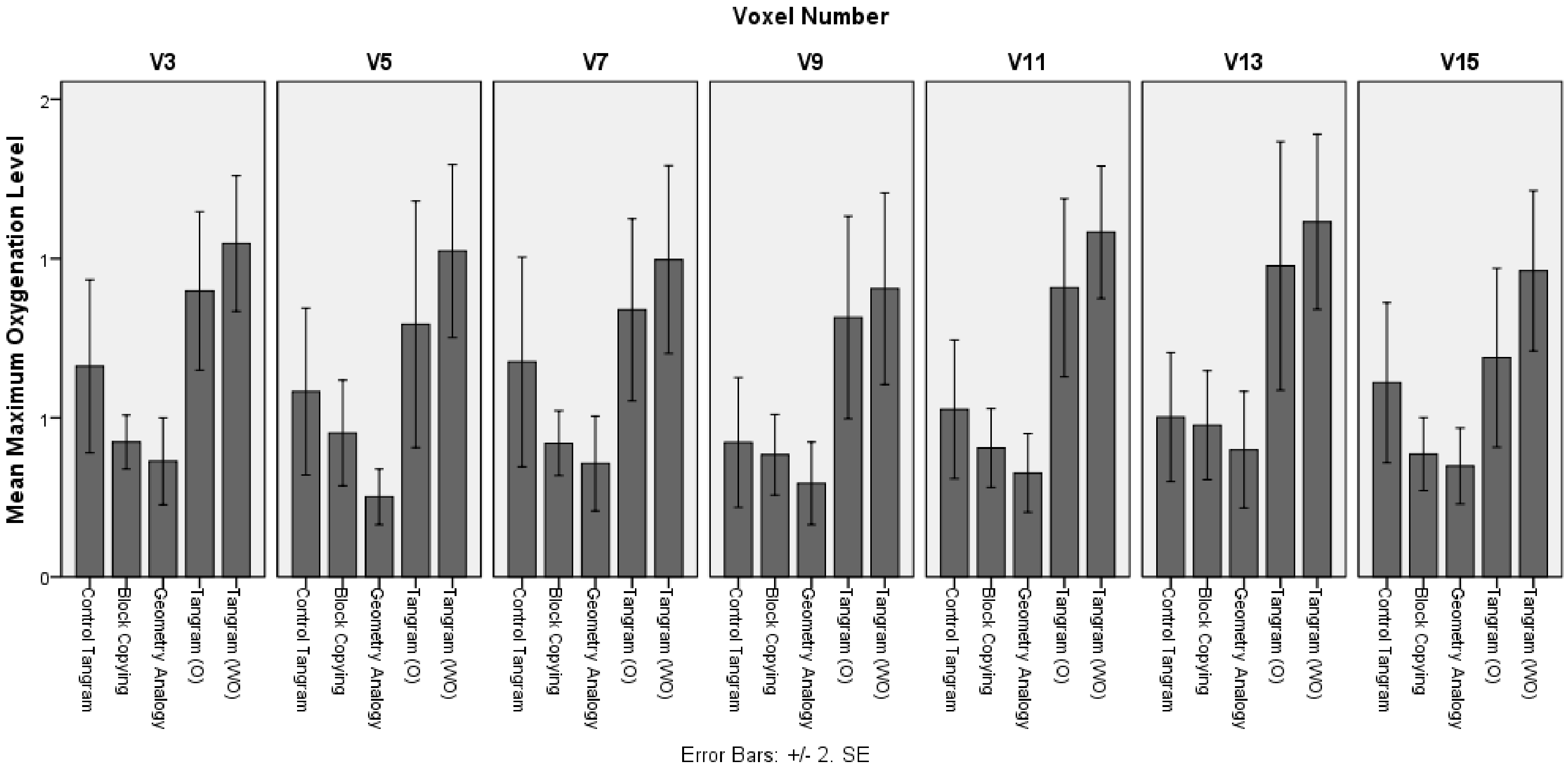


Figure 4.24 Mean Maximum Oxygenation Level Change over Types of Tasks

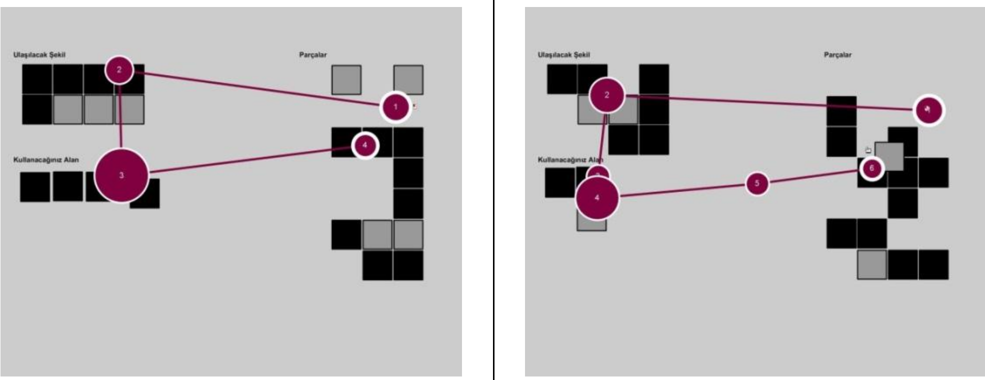
4.4 Scan Patterns

The scan patterns of all tasks were analyzed according to task types (block-copying, geometry analogy, and tangram). For tangram problems, problem space (outline and no outline) and problem feature (symmetric, asymmetric) were taken into account. Each task was analyzed individually. Circles in represented gaze plots illustrate the fixation points and lines between those fixations correspond to saccades. As the diameter of the circle increases, the time of looking that point increases also. The goal of these micro level case analyses is to qualitatively describe some of the gaze patterns observed during each task type in an effort to aid the interpretation of the statistical results presented in previous subsections.

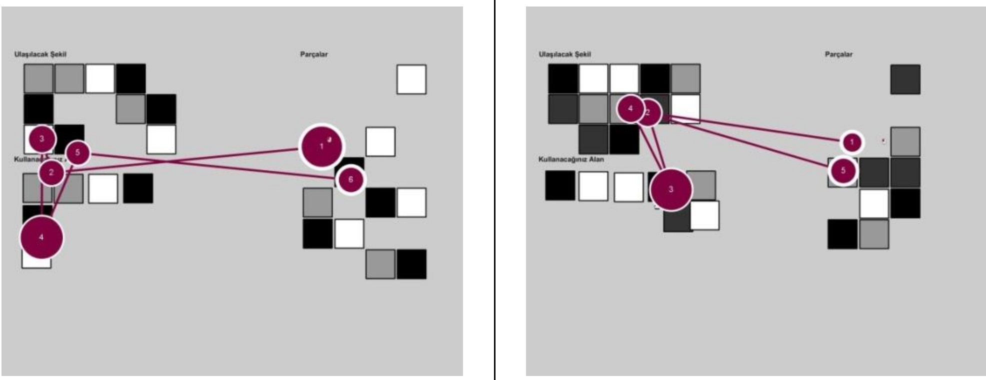
Block Copying Task

Acquired scan patterns during the completion period of block copying tasks show that participants show different saccadic movements as the number and the color of the block copying tasks increase. These saccadic movements are consistent with the findings of block-copying paradigm experiments and were categorized into four behaviors: (1) model-pickup-model-drop, (2) model-pickup-drop, (3) pickup-model-drop, (4) pickup-drop (Ballard et al., 1997). Figure 4.25 illustrates overall the gaze patterns of the block copying tasks.

Figure 4.25 (a) and (b) show that participants followed piece–pickup–model–workspace–drop sequence while copying two-colored block pieces to the workspace without considering the model design. After participants dropped the block to workspace, they looked to pieces area to construct same pattern for other block. In addition, Figure 4.25 (c) and (d) show that participants illustrated the same gaze patterns with an addition. After participants dropped the block to workspace, they looked back to the model before they moved the cursor to pieces area.



(a) (b)



(c) (d)

Figure 4.25 Gaze patterns during block copying tasks (a) Block copying task 1 consists of two different colored eight blocks and has a basic design, (b) Block copying task 2 consists of two different colored eight blocks with a different basic design, (c) Block copying task 3 consists of three different colored ten blocks with a basic design, (d) Block copying task 4 consists of four different colored twelve blocks with a complex design.

Geometry Analogy Task

Geometry Analogy Tasks requires to select the correct pieces to construct the given model. This selection process requires eye movement rather than hand movement. Indeed, the selection is made mentally. Since pieces are expected to be rotated and transformed mentally, many successive fixations were made during the problem solving process.

Geometry Analogy Task: Hexagon

Hexagon is a symmetric and four-piece geometry analogy task. Gaze patterns of participants during geometry analogy problem solving process were categorized into three different strategies: (1) gaze patterns between the model and the choices, (2) gaze patterns between the choices, (3) gaze patterns between the pieces in within choices.

Figure 4.26 illustrates a set of gaze patterns sampled from a participant while he was attempting the four-piece hexagon problem. After participants began to solve the problem by looking at the model, they tended to look at the choices (4.26 a). Then, individual pieces were investigated and re-fixations occurred between the model and the pieces (Figure 4.26 b-c-d). Then, fixation points dropped on the pieces within a choice (Figure 4.26 c-d). The crucial point is that sharp points of the pieces, the edge and the possible joint points of the hexagon were seemed to be investigated during the transitions between the pieces and the model. Indeed, participants looked at the above or below parts of the hexagon which may be corresponding to candidate locations for placing the triangles given in the choices.

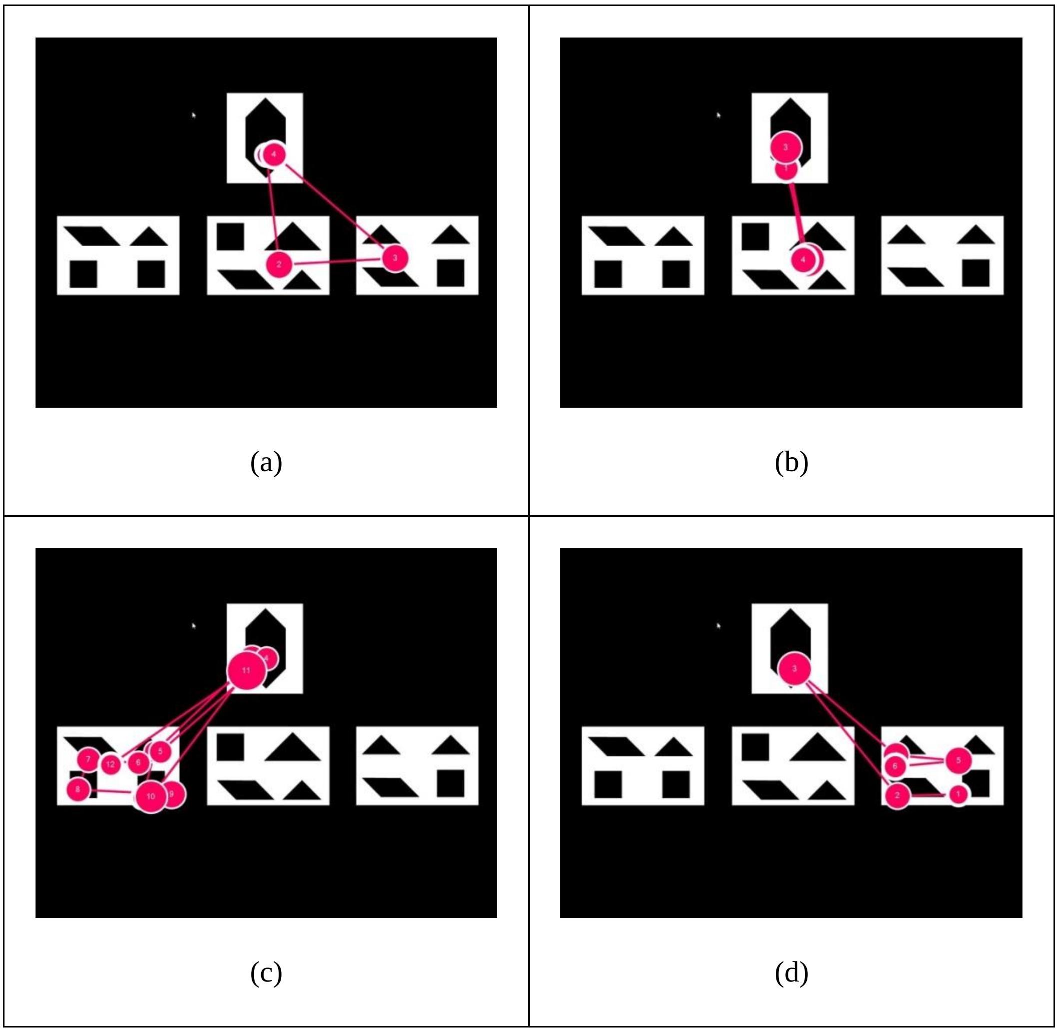


Figure 4.26 Gaze patterns of participants for four-piece hexagon task

Geometry Analogy Task: Funnel

Figure 4.27 illustrates a sample of gaze patterns during participants attempted to solve the funnel task. Gaze patterns revealed nearly the same strategies as the previous task (hexagon): (1) transitions between the choices and the model, (2) transitions between the pieces within a choice, (3) transitions between the choices. Participants looked at the details and the edges of the model. Re-fixations occurred after that participants made successive fixations on the model (see Figure 4.27). In other words, the funnel task has not incurred as many transitions between the pieces and the model as the hexagon task (Figure 4.27 c-d).

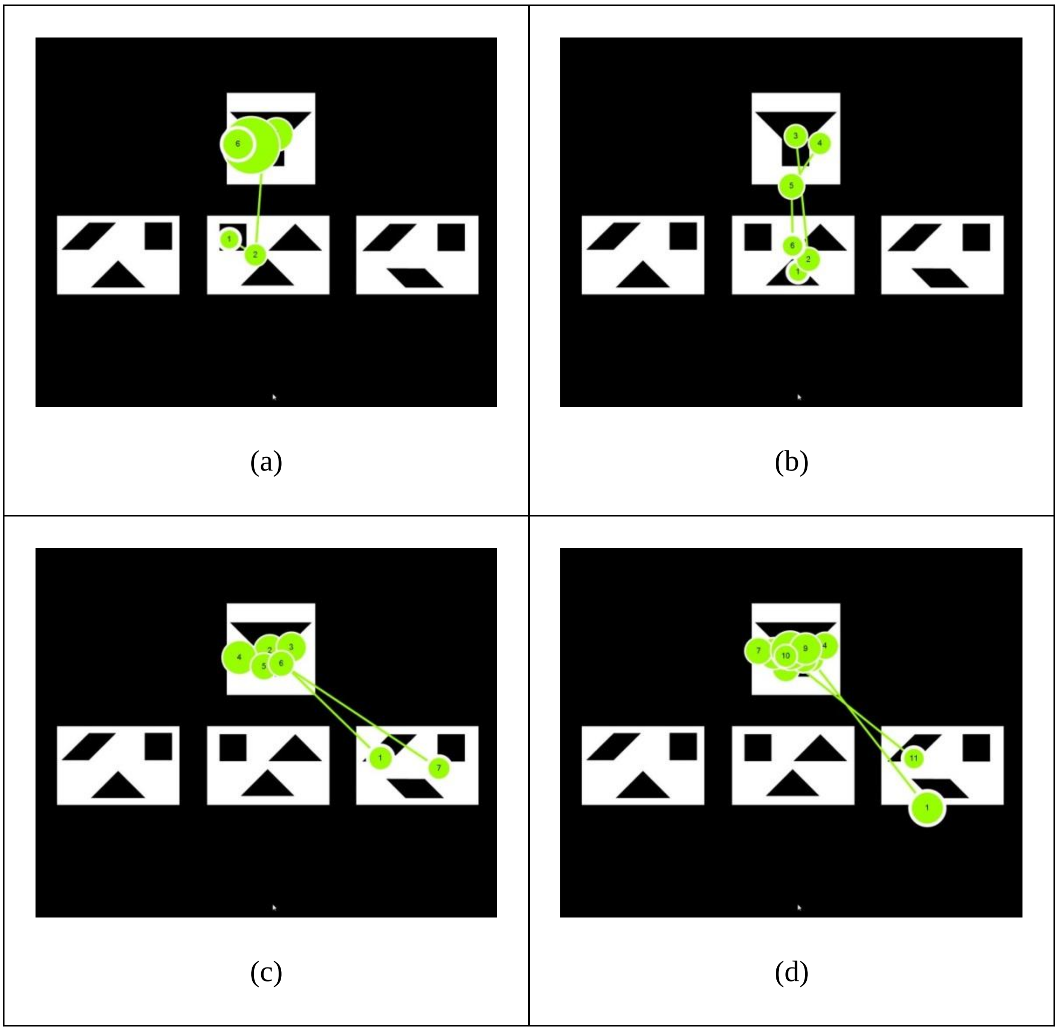


Figure 4.27 Gaze patterns of participants for funnel task

Geometry Analogy Task: Triangles

Figure 4.28 illustrates a sample of gaze patterns during participants attempted to solve triangles. Gaze patterns revealed nearly the same strategies as the previous tasks which are conducted before the tangram tasks (hexagon and funnel). However, participants made more transitions between piece and the model than between choices. Participants' gaze points show that after they fixated on the pieces they went back to the model and investigated the sharp and the possible joint points of the model (Figure 4.28 d).

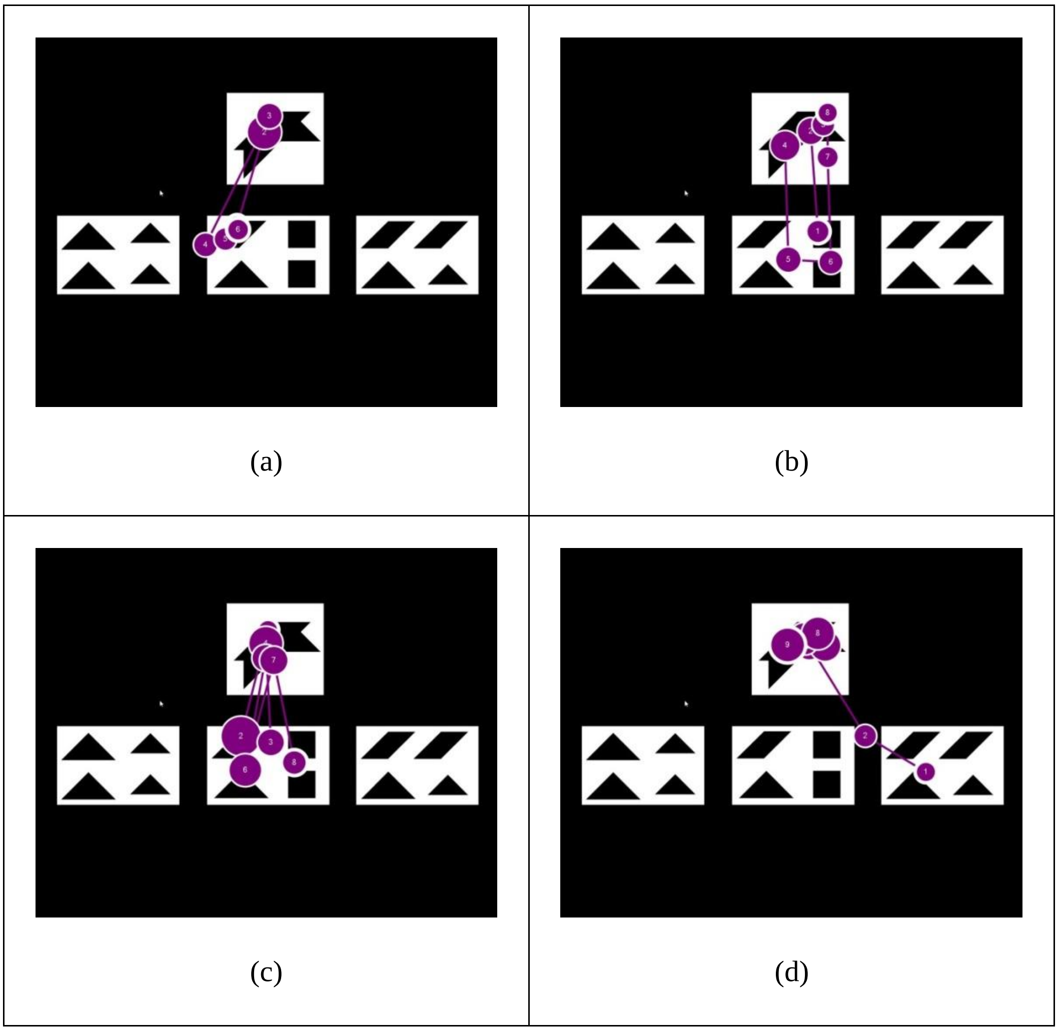
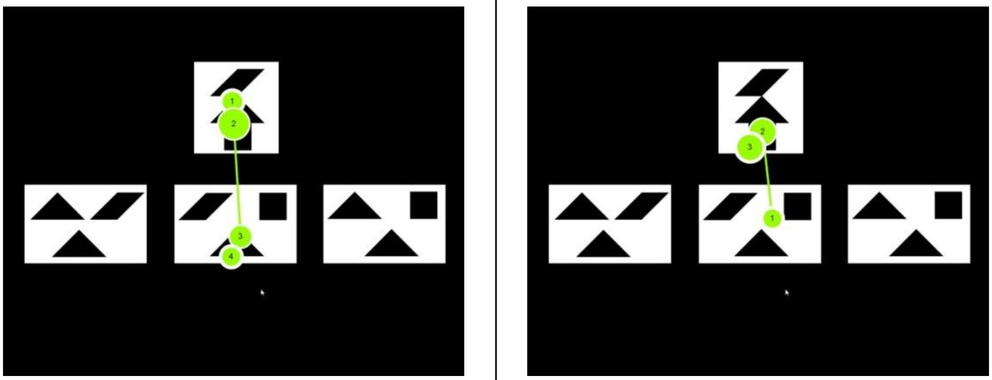


Figure 4.28 Gaze patterns of participants for triangles task

Geometry Analogy Task: Arrow

Figure 4.29 illustrates a sample of gaze patterns during participants attempted to solve arrow task. Arrow task requires three pieces to construct the given model. Also, participants do not need to rotate the pieces to construct the given model. Participants did not make look back eye movements (Figure 4.29 a-b).



(a) (b)

Figure 4.29 Gaze patterns of participants for arrow task

Tangram Task

Tangram Tasks has two control and eight experimental tasks which consist of outline and symmetry conditions.

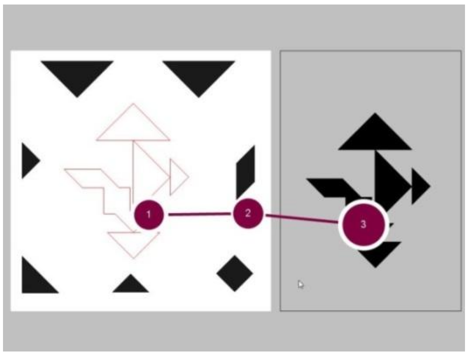
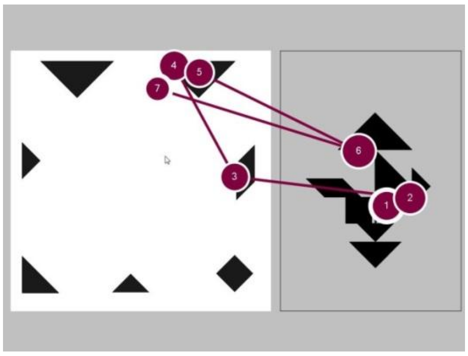
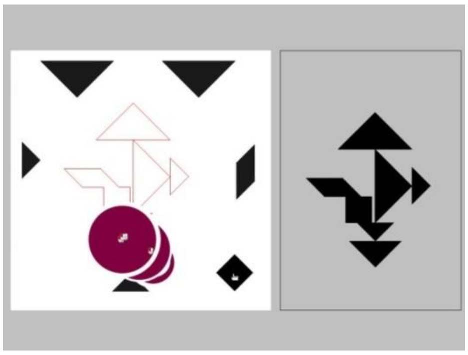
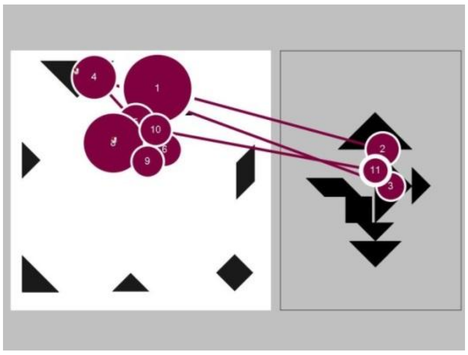
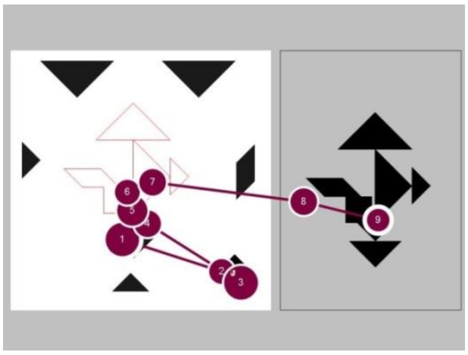
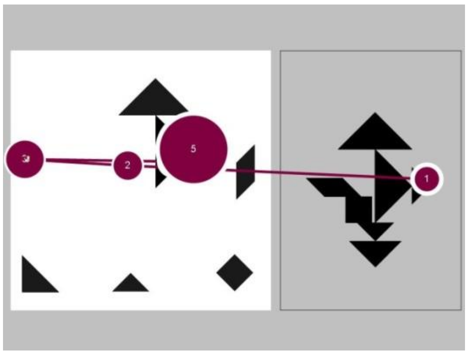
Tangram Task: Controls

Control tasks have the same constructed model (an asymmetric one) with outline and without outline conditions. Control tasks do not require many orientations and transformations. The joint points of the task are visible.

Even participants were given the same task, difference in problem space revealed different problem solving strategies. Figure 4.30 illustrates sample gaze patterns of participants in terms of outline and without outline conditions.

For the outline condition, gaze points of participants (1) went between the outline and the model. After the first mouse movement, (2) participants looked at the edges of the outline.

For without outline condition, gaze points of the participants (1) went between the pieces and the model. After participants located one or two pieces at the workspace area, (2) the fixation points of the participants dropped on the pieces at the workspace, pieces and the model. After participants moved all the pieces to the workspace, (3) the fixation points begin to cluster more on the unfolding construction on the workspace.

Outline Condition	**No Outline Condition**
 (a1)	 (a2)
00:56,000	02:15,515
 (b1)	 (b2)
01:04,727	02:18,181
 (c1)	 (c2)
01:09,333	02:26,666

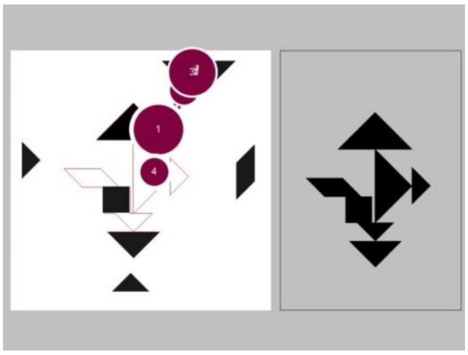
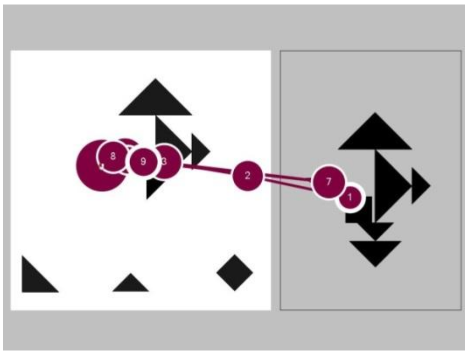
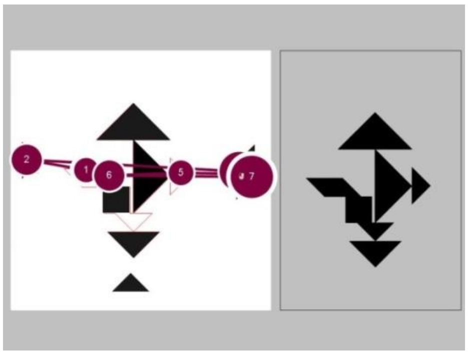
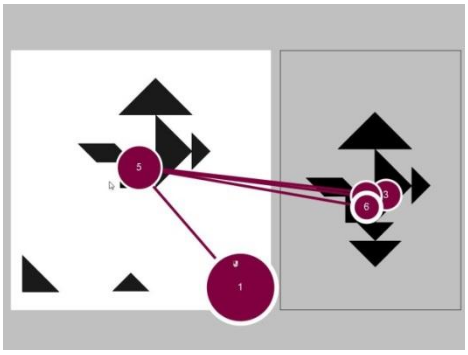
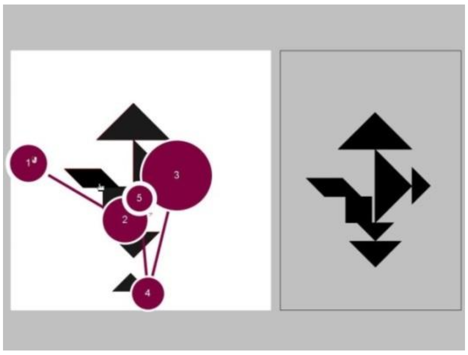
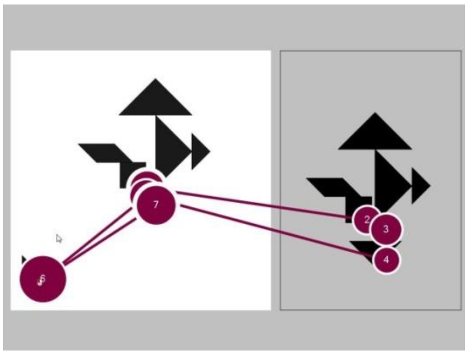
 (d1)	 (d2)
01:23,393	02:30,787
 (e1)	 (e2)
01:30,424	02:39,515
 (f1)	 (f2)
01:39,393	02:51,393

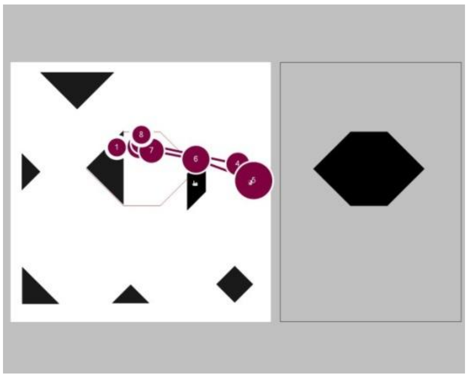
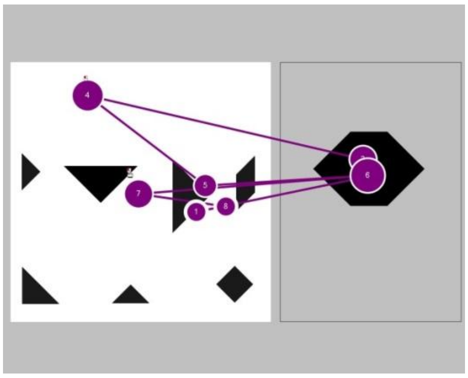
Figure 4.30 Gaze patterns of the control tasks (O vs. NO). (a1) and (a2) show the fixation points revealed at initial thinking time. In outline version (a1), participants'

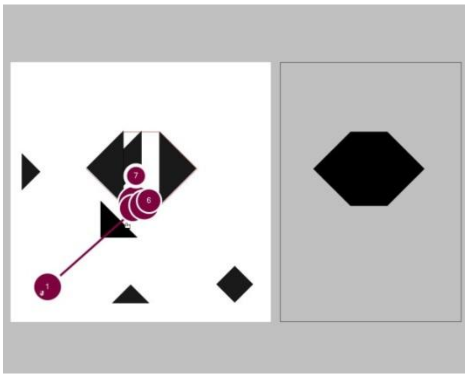
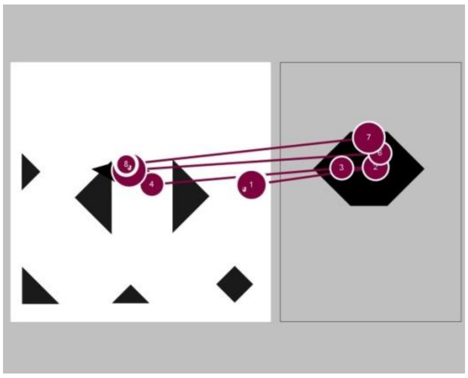
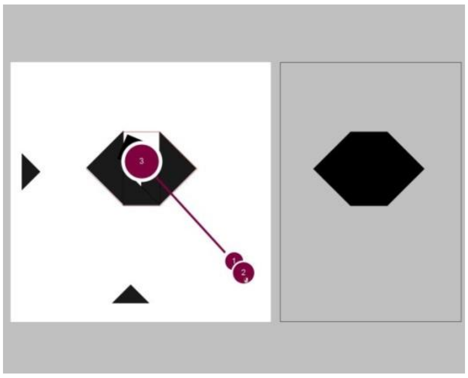
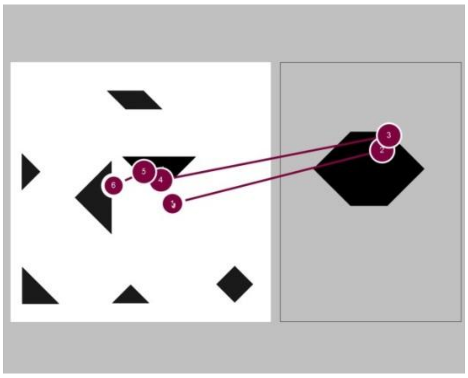
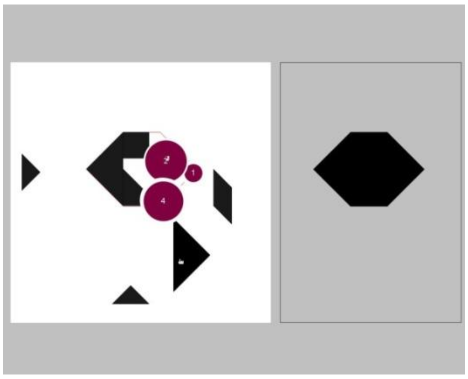
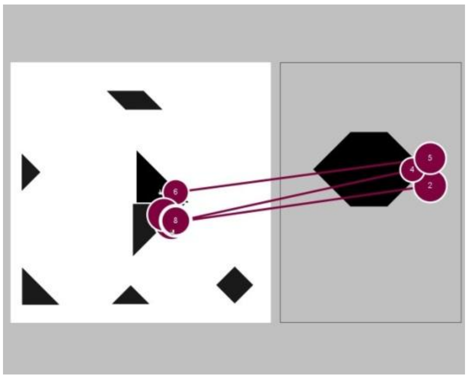
gaze behaviors went between the outline, the pieces and the model; whereas, in no outline version (a2) went between the pieces and the model (participants did not tend to look at the workspace). In outline version, overall gaze patterns indicate the transitions between the pieces and the model; however, in no outline version, gaze patterns indicate the transitions between the pieces, constructed image and the target model. For both versions, joint points were important to construct the given image.

Tangram Task: Hexagons

The following sequence of tangram solving actions was observed at the beginning of the hexagon (symmetric, with and without outline) tangram problem solving activity. First column of each figure represents the problem solving process of outline version and second column of each figure represents the problem solving process of no outline version. Participants began with focusing on the edges and sharp points of the hexagon (Figure 4.31- a1).

In both versions, participants looked at the edges of the outlines and began with placing the big triangle to peak side of the hexagon (a1-a2). Gaze patterns of participants did not make any transition between the constructed image and the target model in outline version (a1). However, in no outline version (a2), participants looked back the target model during the rotation and transformation of the pieces. In outline version, participants were not expected to imagine the sense of size. However, in no outline version, participants made saccades and fixations to construct the target model at the workspace within actual sizes (See Figure 4.31). After participants located the pieces in a string which cannot construct the target model, they tried a different variation for the solution (b1-c1-d1).

Outline	**No Outline**
 (a1)	 (a2)

 (b1)	 (b2)
 (c1)	 (c2)
 (d1)	 (d2)

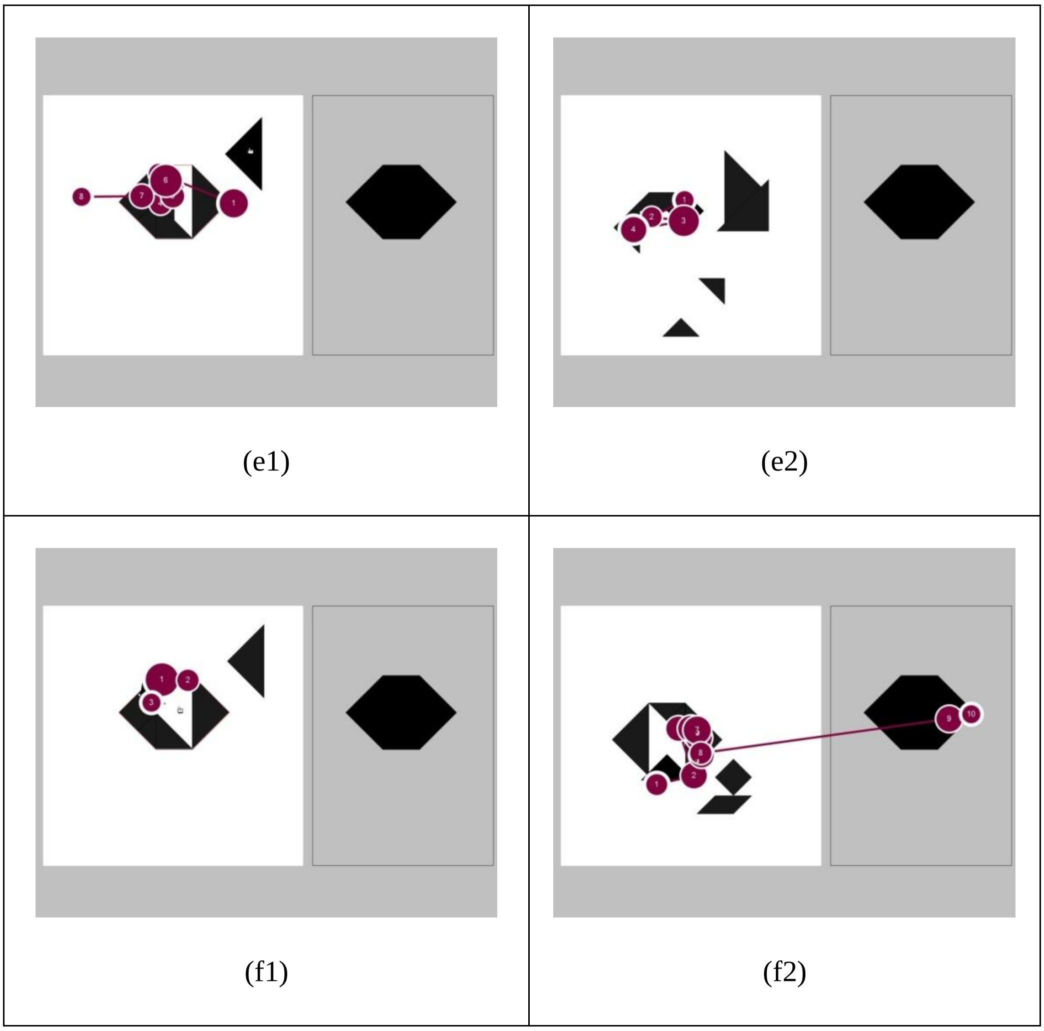


Figure 4.31 Gaze patterns of the hexagon tasks (O vs. NO)

Tangram Tasks: Swan, Kindle and Rabbit

Swan, kindle and rabbit tasks all have outline within their problem spaces. Figure 4.32 illustrates an example gaze patterns during outlined problem tasks. All tasks have detailed features which can make participants begin with those features. Figure 4.32 (a1), (a2) and (a3) showed gaze patterns of a participant during the swan task. Participant located the pieces to head of the swan which do not require any rotation (a1). Then, remaining pieces were put on the white areas (a2) and (a3).

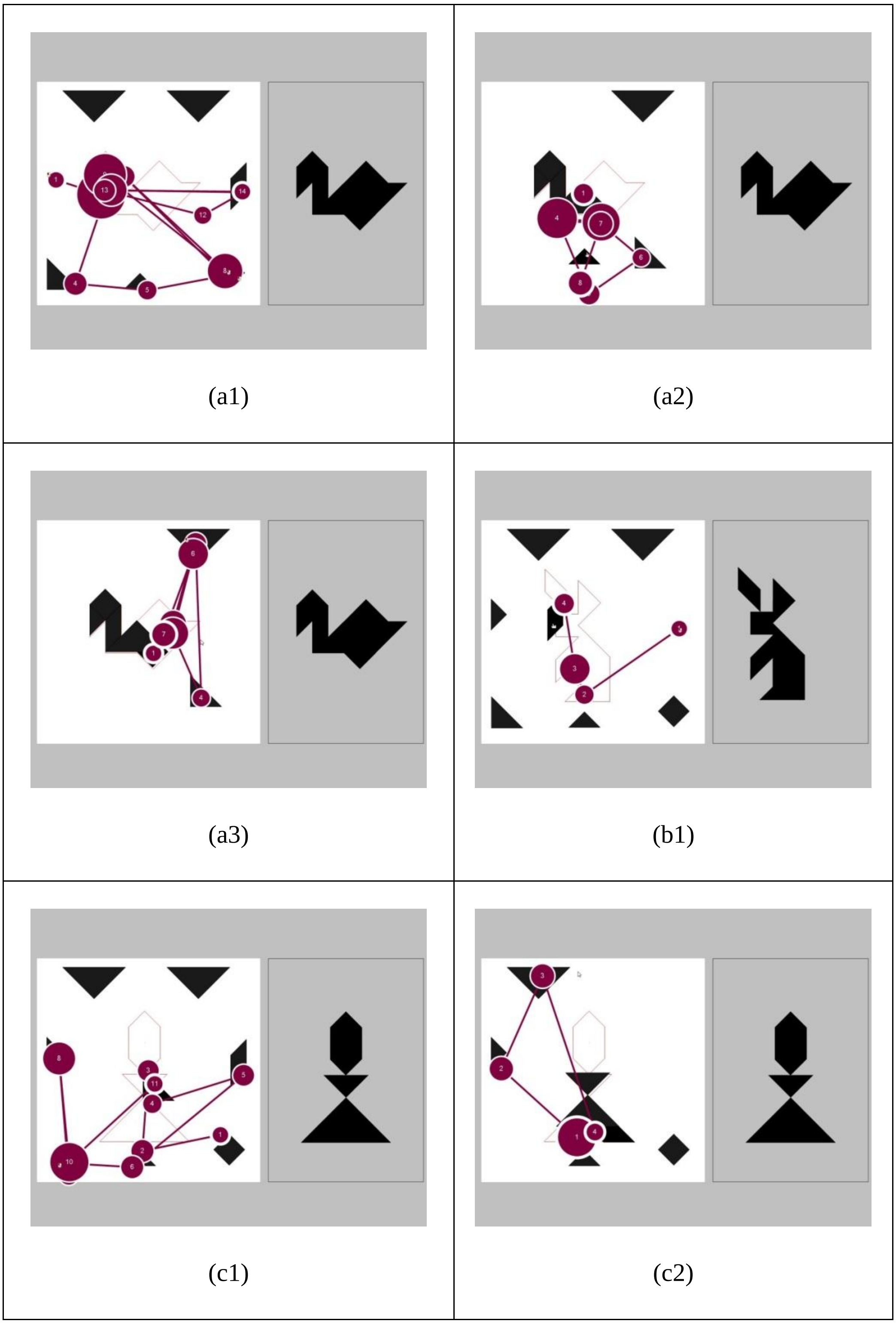


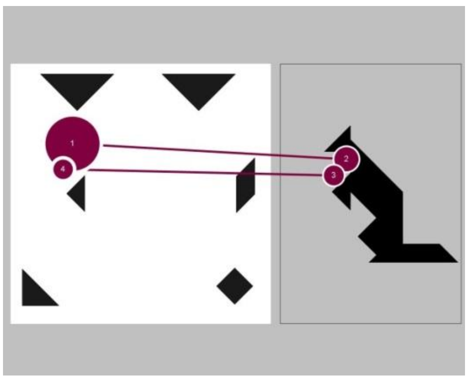
Figure 4.32 Gaze patterns of the swan, kindle and rabbit tasks (Outline)

Tangram Tasks: Kangaroo, Man, Rooster

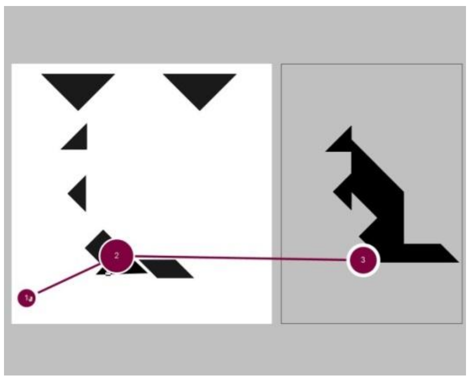
Kangaroo, man and rooster tasks have no outlines on problem space. So, transition between the target model, the pieces, and the constructed image had greater values.

Participants looked at the distinct features which can be separated from other features. To illustrate, kangaroo task has some detailed features (hand, head and feet). Participants looked at the little triangles and then, looked at the related part of the target model (a1) and rotated the little triangle and looked back to the head of the kangaroo. This movement is defined as *resemblance step*. (a2) illustrated another distinct feature. Participants looked at the medium triangle, square and the parallelogram, and then looked at the related part of the target model. 3rd fixation point of the figure (a2) showed that while participants located the medium triangle, they looked at the part which was considered as corresponding to feet. Similarly (b1) and (c1) has fixation patterns which correspond to detailed features, especially associated with edges and sharp points of the target model. (b1) illustrated an action for the man task. Participants looked at the target model and saw a piece, and then they located the square piece on the workspace. Also (c1) illustrated the similar portrait for rabbit task. Participants looked at the target model, and then located the square under the previously located piece.

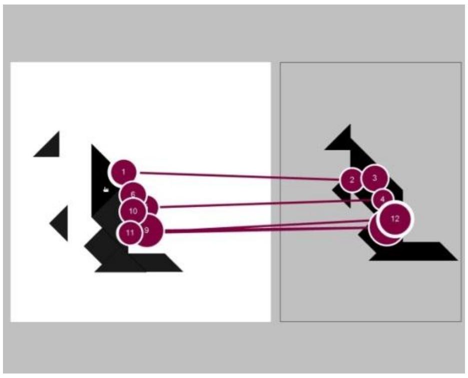
In addition to focusing on distinct features, in failure status during placing the pieces, gaze patterns showed that participants looked at the target model, separated pieces and the constructed image. Figures (a3), (a4) and (a5) illustrated this event for the kangaroo task. (a3) shows that participant looked at the constructed and the target model investigating their edges and sharp points. Then, participant looked at the possible head position (constructed with little triangle) and the target model (a4). Finally, participant changed the orientation of big triangles (a5). Figures (b1) and (c2) illustrated the similar patterns for the man and the rooster tasks. (see Figure 4.33)



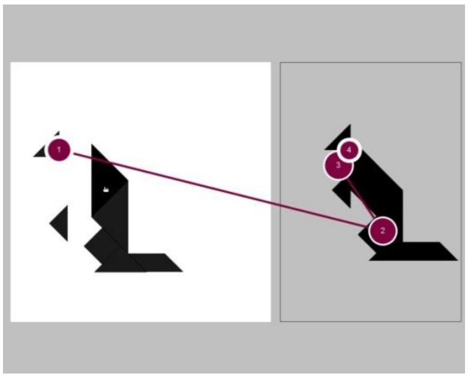
(a1)



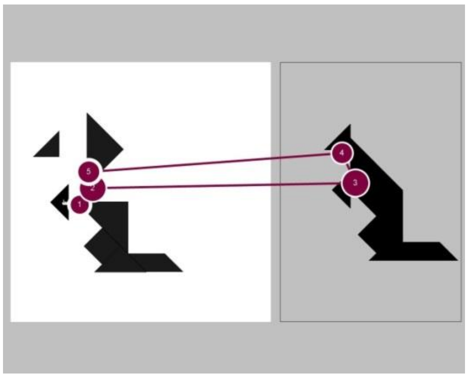
(a2)



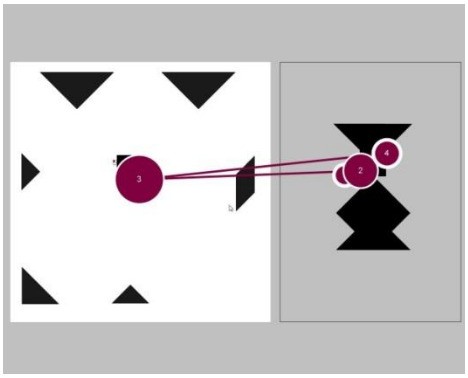
(a3)



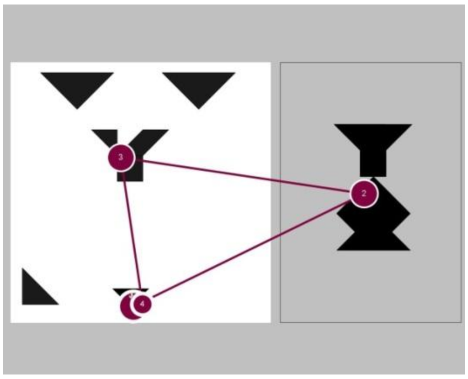
(a4)



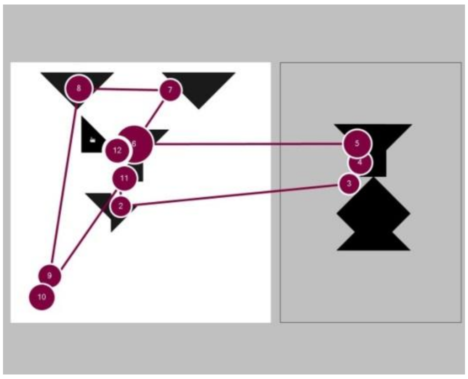
(a5)



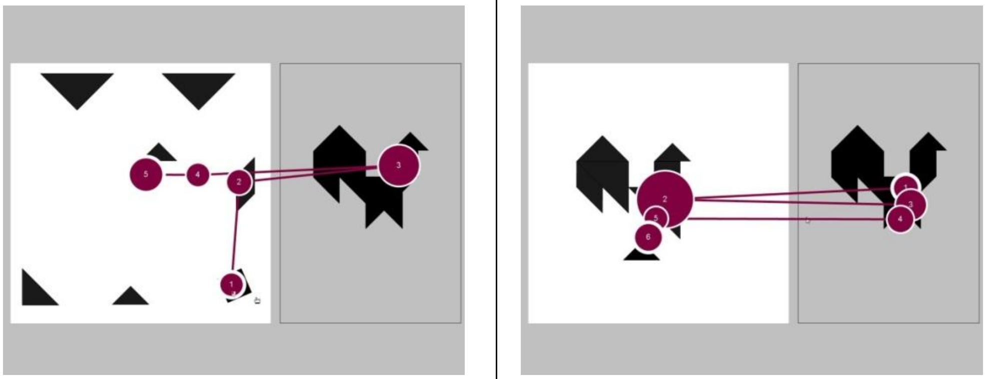
(b1)



(b2)



(b3)



(c1) (c2)

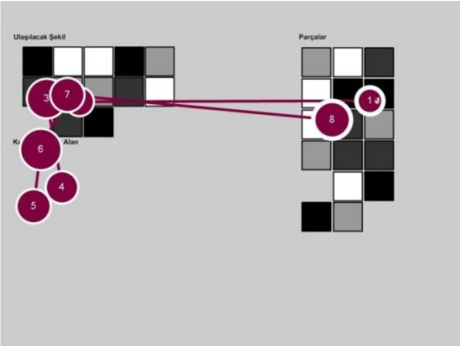
Figure 4.33 Gaze patterns of the kangaroo, rabbit and rooster tasks (No Outline)

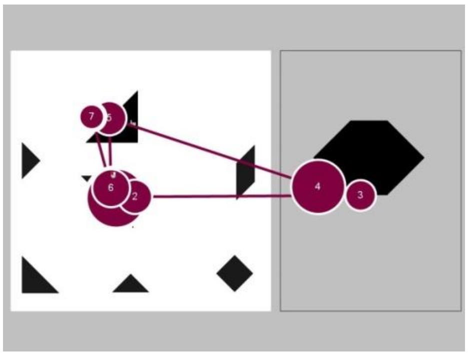
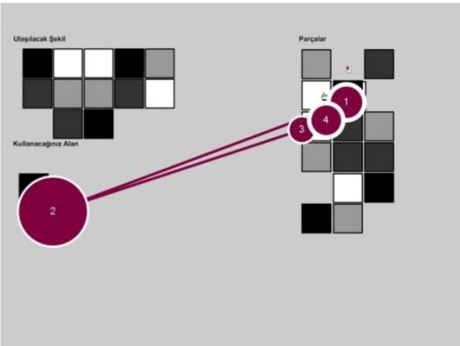
Overall Scan path Analysis

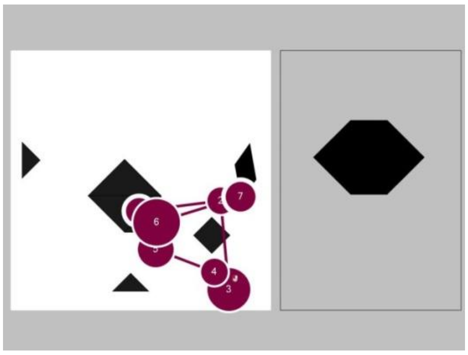
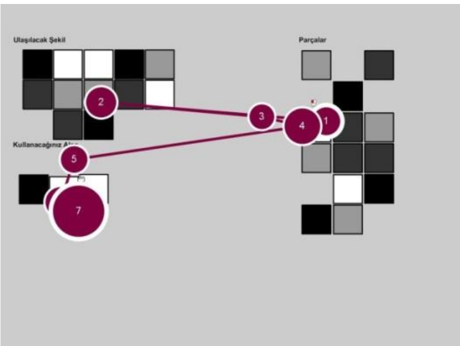
Participants demonstrated different eye movement strategies for different type of tasks and different conditions in problem space area. Comparison between block-copying tasks and tangram tasks; and comparison between geometry analogy tasks and tangram tasks will explicitly illustrate the difference in gaze patterns.

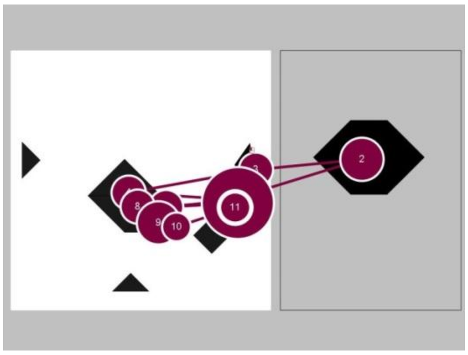
Comparison between Block-copying and Tangram Tasks

Both block-copying tasks and tangram tasks presented within a dynamic environment so that pieces can be manipulated with the mouse. Block-copying tasks and tangram tasks differ in terms of their shape characteristics. Although block-copying tasks have various colors as the complexity of the tasks increase and do not require any rotation or transformation; tangram tasks have no color and it requires rotations and transformation to construct the target model. Figure 4.34 illustrates a comparative example to gaze patterns for fourth block-copying task and hexagon task (no outline condition) of a successful player. These two tasks were selected due to the complexity of the problem structure relative to similar tasks.

<table>
<tr><th>4th Block Copying Task</th><th>Hexagon Task (NO)</th></tr>
<tr><td>

(a1)</td><td>
(a2)</td></tr>
<tr><td>25:58,270</td><td>10:28,430</td></tr>
<tr><td>

(b1)</td><td>
(b2)</td></tr>
<tr><td>26:01.483</td><td>11:11,934</td></tr>
<tr><td>

(c1)</td><td>
(c2)</td></tr>
<tr><td>26:03,873</td><td>11:13,740</td></tr>
</table>

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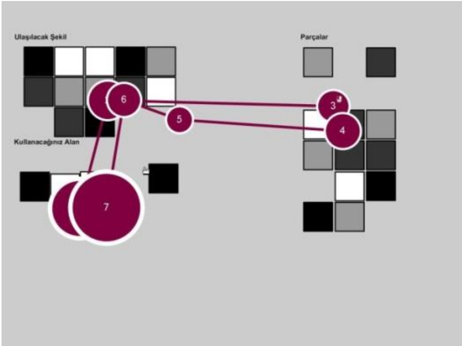
<td>

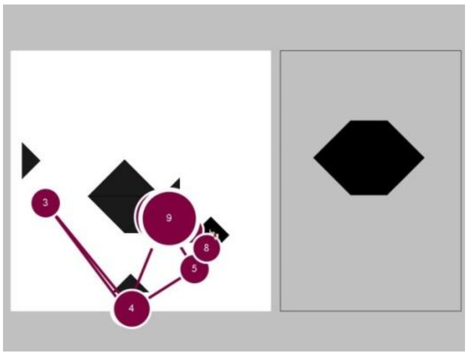
(d1)</td>
<td>
(d2)</td>
</tr>
<tr>
<td>26:06,901</td>
<td>11:28,509</td>
</tr>
</table>

Figure 4.34 Comparative gaze patterns for block-copying and tangram tasks

While solvers copy the blocks into the workspace area, they tend to follow a sequential order. Figure 4.34 (a1) shows an excerpt from the video content. After viewing the scene, participant looked at the pieces, target model and workspace areas respectively. Then, participants put the piece on workspace area, and looked at the target model again. (c1) shows that participant looked at the pieces, target model, pieces and workspace area respectively while copying the block. Next, (d1) participant looked at the target model and pieces respectively to select another block.

While solvers construct the target tangram model into the workspace, they tend to follow heuristic strategies, especially trial and error method. There is also a sequential order while selecting the appropriate piece; however, attention is allocated back and forth between the workspace and the target. Figure 4.34 (a2-b2-c2-d2) shows that at the beginning of the problem, participant selected the pieces and made excessive amount of transitions between the selected pieces located in the workspace area and the target model. (a2) shows that participant selected large triangles which are inconsistent with the actual size of the target model. (b2) shows that participant generated the sense of size after participant made comparisons between the target model and the constructed image. (c2) illustrates the selection process of the next piece. It seen from the scene that participant looked at the possible joint point of the target model by comparing with constructed image. After participant placed the parallelogram near the medium triangle, participant made visual search between remained pieces. Then, participant (d2) selected the square to place it on the parallelogram.

The snapshots sampled from a participant's video-recorded attempt to solve a block copying task and a tangram task show that block copying tasks elicit a sequential order of gaze transitions between different areas of interests. In other words, less number of gaze transitions seems to occur in general while copying a block. In contrast, tangram tasks consists of pieces in different geometrical shapes and different orientations so that participants tend to make more eye transitions between the pieces, the constructed shape and the target model while placing each single piece.

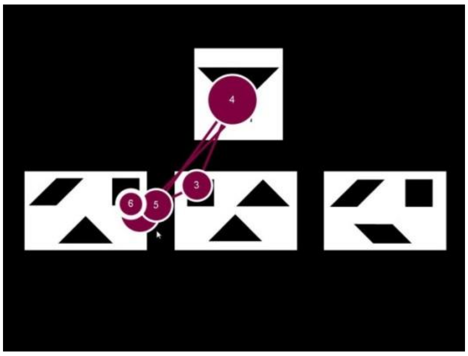
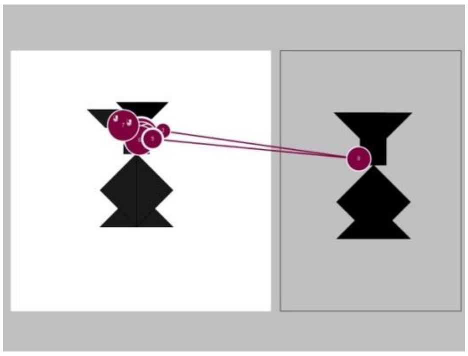
Comparison between Geometry analogy and Tangram Tasks

Geometry analogy and tangram tasks have different characteristics (see Figure 4.26). Tangram tasks are presented within a more complex environment than geometry analogy tasks. In particular, the tangram case enables sensori-motor engagement with puzzle pieces, whereas the analogy case taps in mental resources to simulate similar moves.

Figure 4.35 illustrates a comparative example to gaze patterns for funnel task and man (no outline condition) of a successful player. These two tasks were selected due to the similar patterns.

Table 4.15 Differences between geometry analogy and tangram tasks

Geometry Analogy	**Tangram**
Static environment	Dynamic environment
Participants can imagine the pieces	Participants can both imagine and manipulate the pieces
Three or four pieces	Seven pieces

Funnel Task	**Man Task (NO)**
 (a1)	 (a2)
05:45,505	18:46,593

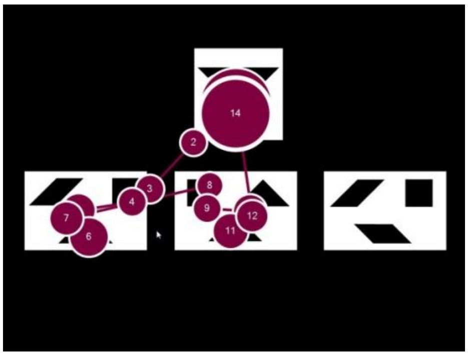
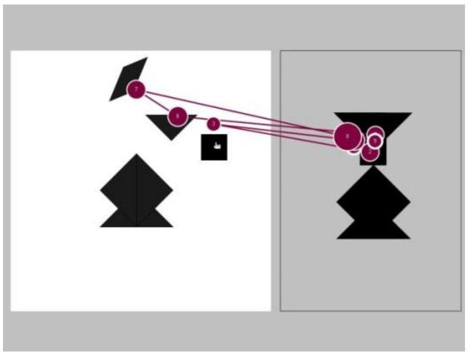
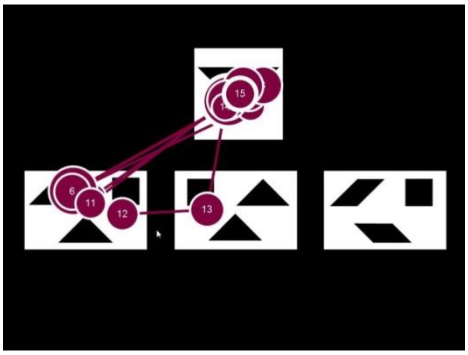
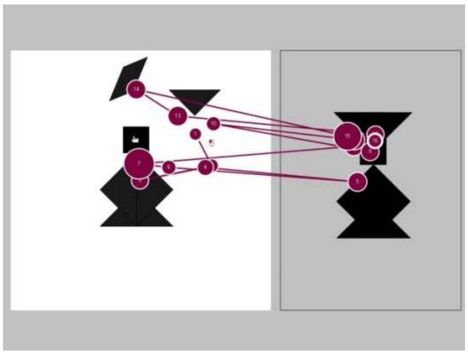
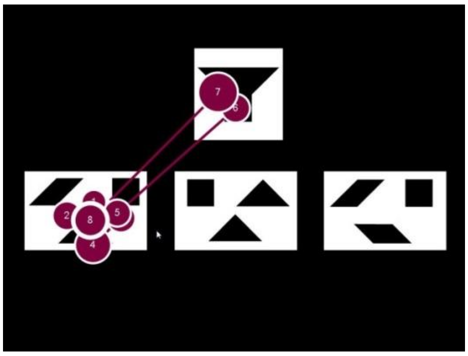
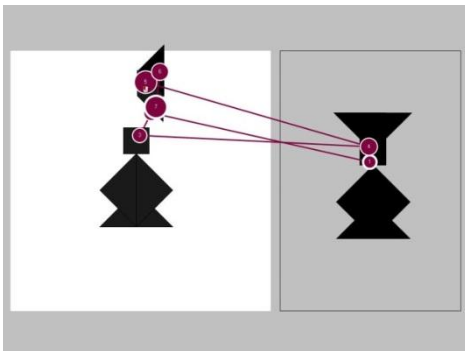
 (b1)	 (b2)
05:54,746	18:53,680
 (c1)	 (c2)
06:12,008	18:57,453
 (d1)	 (d2)
06:24,042	19:27,067

Figure 4.35 Comparative gaze patterns for geometry analogy and tangram tasks

Solvers tend to find similar features to select the appropriate pieces in geometry analogy tasks. Figure 4.35 (a1) shows that participant looked at the square and made transitions between the square and the given model. Then, participant looked at the medium triangle, square at the choices and looked back at the given model (b1). Next, participant looked at the parallelogram and square and made transitions between parallelogram and the given model and finally, participant looked at the medium triangle and the actual joint point in geometry analogy task and selected the accurate choice (d1).

Figure 4.35 (a2-b2-c2-d2) shows that an excerpt from the man tangram task which includes similar patterns with the funnel task. At the beginning of the excerpt (a2), participant looked at the constructed image and decomposed three pieces (b2). Participant looked at square area at the target model and looked at other pieces respectively. Transitions between target model and decomposed pieces occurred (c2). Then, participant placed the square and constructed the image in a separate piece (d2).

Gaze patterns of given snapshots show that participants try each piece separately to reach the target model in the geometry analogy task and transitions between pieces and the target model seem to decompose the target model into its pieces. So, back and forth saccadic eye movements occur frequently from the edges or sharp points of the pieces to the possible places at the target model. Since tangram tasks allow the manipulation of the pieces, participants can rotate and transform those pieces to construct the given shape. Since participants can manipulate pieces and observe their fit in reference to the target shape, they offload some of the work to the external world. The manipulations afford a trial and error strategy where candidate configurations of pieces can be tried and reflected upon. This is similar to Kirsh's notion of epistemic actions which augment cognitive processes such as recognition and search.

CHAPTER 5

DISCUSSION & CONCLUSION

This thesis investigated the problem solving strategies revealed by different types of visuospatial reasoning tasks, problem space organizations and model construction processes. Data were collected by the combination of the eye tracking tool which provide fixation duration, fixation count, and fixation rate; and the functional near infrared spectroscopy which provide measures of relative changes in oxygenated and deoxygenated hemoglobin concentration levels at the prefrontal cortex. Scan paths are additional features extracted from the eye tracking data, which allowed us to observe and categorize the solvers' behaviors during visuospatial problem solving process. By comparing the results obtained from the analysis of simultaneously recorded eye tracking and fNIRS data, the brain-behavior relationship was investigated in the context of visuospatial problem solving.

5.1 Block Copying Tasks

Block copying tasks results indicated that the completion time of the tasks except the first block copying task showed a rising trend as the color and the number of the blocks increase. The reason why the first block copying task resulted in higher completion time is initial recognition time which is related with understanding the task environment. Other measures were also affected with regard to the completion time of block copying tasks.

Scan paths showed that problem solvers followed a sequential order during block copying tasks. This finding is convenient with previous studies. Ballard et al. (1995) resulted that during block copying tasks, participants use "just-in-time" strategies and followed a pathway including piece, workspace and model. Although participants didn't show any difference for scan paths in reference to different block copying tasks, participants' fixation duration, fixation rate and transition rate elicited different results.

Investigation of fixation durations suggests that longer fixation duration occurred on the workspace area than model and piece areas. Although inferring specific cognitive processes from particular fixations is difficult, it is generally thought that there is a connection between where one is looking at and one's thought processes (Just & Carpenter, 1976). Fixation durations often correspond to the complexity of the task (Hegarty & Kozhevnikov, 1999) so that greater fixation durations on workspace areas may signify that greater cognitive resources were expended on workspace areas of block copying tasks than piece and model areas. Additionally, fixation rate results supported fixation duration results. Workspace area has higher fixation rate than model and piece areas. And, transition rate between areas of interests showed that transition rate between workspace and model has higher value than transition rates between model-piece and piece-workspace for block copying tasks except the first block copying tasks. The reason why the transition rate for piece-workspace is higher than workspace-model may be caused by the first recognition time of a novel environment. Also, while picking a piece for copying to workspace, subjects tend to look back model as the complexity of the target model increases. Although difference was observed between areas of interests, it appeared that differences in fixation related activities were not elicited by the types of block copying tasks. Maximum oxygenation values also support eye-tracking data, any difference with regard to types of block copying tasks was observed for maximum oxygenation change levels.

5.2 Geometry Analogy Tasks

Geometry analogy tasks require mental transformation of presented objects (pieces in our case). According to Carpenter (1992) and Kosslyn (1973), mental transformation tasks such as mental rotation and mental scanning showed that as the degree of rotation and the distance between two points increase, the time to transform tasks mentally also increase. We presented four geometry analogy tasks to participants. While funnel and arrow tasks are comprised of three pieces, hexagon and triangles tasks are comprised of four pieces. Hexagon task requires at least 315° for whole pieces to be constructed while triangles task requires 235°, funnel task requires 180° and arrow task requires 0°. The completion time of the given tasks showed differences in reference to types of tasks. Average completion times among participants showed that hexagon was the most time-consuming task among entire tasks. Average completion times from higher to lower values are hexagon, triangles, funnel and arrow task.

Additionally, fixation related measures varied between geometry analogy tasks. Arrow task has attracted lower fixation duration than other geometry analogy tasks. This finding is convenient with the completion time order and the least required degree of rotation. Aforementioned finding is also supported by the brain activation data. Maximum oxygenation levels during more complex (in reference to their completion time, degree of rotation and required number of fixation) geometry analogy tasks have greater values at the left dorsolateral prefrontal cortex (corresponds to 3rd voxel on fNIRS sensor see Figure 4.16) than for other geometry analogy tasks. As it is reported by Newman et al. (2003) in the context of an fMRI experiment using the Tower of London task, this region is known to be responsive to situations that demand increasing spatial attention among choices, especially when the individual shifts their attention among possible intermediary problem solving stages. Since participants had to imagine possible orientations of fit between multiple choices and the target image during the analogy tasks and they cannot offload some of this work to epistemic actions as in the regular tangram tasks, the difference in brain activation observed at voxel 3 can be interpreted as a sign of difference among both task types in terms of their demand for attentional and working memory resources.

5.3 Chinese Tangram Tasks

Tangram tasks require both mental transformation and manipulation of the pieces. High accuracy and low completion times were assumed to correspond to easier problems and the acquired order ranges in regard to task difficulty: kangaroo (NO), hexagon (NO), rooster (NO), swan (O), man (NO), hexagon (O), kindle (O), rabbit (O).

Numerical eye-tracking data for tangram tasks includes mean fixation duration, fixation count, fixation rate, and transition rate. Data were analyzed based on two different problem space features: symmetry vs. antisymmetry and with outline vs. without outline. Also, differences between workspace and target model areas were calculated to investigate the differences between workspace and target model areas.

First of all, mean fixation durations differentiated with regard to types of areas for tangram tasks. Overall tangram results showed that workspace area has attracted higher fixation duration than model area. Since tangram tasks had two cases such as with outline and without outline, differences in fixation durations for target model did not make sense. At the beginning of the with outline tangram tasks, video recordings showed that participants investigated and matched the features in outline and the target model. So, even few fixations dropped on target model of with outline tangram tasks, there cannot be observed and calculated any difference for fixation durations between outline and without outline. However, transition rate between target model and workspace area showed difference between outline and without outline tangram tasks. While for with outline tangram tasks transition rate between individual pieces and workspace are higher than without outline tangram task condition, for without outline tangram tasks transition rate between target model and workspace are higher than with outline tangram tasks. Although they have differences in consideration with transition rate between with outline and without outline tangram tasks for overall results, there are individual tangram tasks which have outline in their problem space but it took greater time to complete the task. So, even a problem space facilitates the construction with some cue-like features such as outline, task construction and piece-orientation affect the solution strategies of given visuospatial reasoning task.

Kindle (O), Man (NO), Hexagon (O), and Hexagon (NO) had symmetric problem features and Kangaroo (NO), Swan (O), Rabbit (O), and Rooster (NO) had antisymmetric problem features. Although observations from video recordings showed that symmetric features facilitated finding places of the online piece, no differences between symmetric and antisymmetric problem features were observed from the numerical eye-tracking data.

Additionally, brain activation data which represent maximum oxygenation values showed that there is a significant difference between antisymmetric and without outline tangram tasks and antisymmetric and with outline tangram tasks for 15th voxel. Also, 9th and 13th voxels represent differences between tangram tasks. Indeed, significant differences were found for control tangram tasks and some of experimental tangram problems which took higher mean time to complete.

5.4 Overall Results

Overall results in consideration with fixation duration on target models were compared between three different visuospatial tasks. While geometry analogy tasks has higher value on their target models, the second higher value were on the target model of tangram tasks (without outline condition) and the least fixation duration was on the target models of block copying tasks.

One possible behavioral explanation of lower mean fixation duration for block copying and tangram tasks (without outline) compared to geometry analogy tasks is that solvers were able to manipulate the pieces. This finding is consistent with previous researches that suggested epistemic activities and making arrangements of pieces can reduce the complexity of the problems (Kirsh, 1995; Kirsh & Maglio, 1994). Problem solvers often resort to he “just-in-time” strategy to solve the complex visuospatial problems (Ballard et al., 1997). As well as epistemic activities such as rotating and changings the location of the pieces enhance the understanding scene and reveal shorter fixation durations on the current object. During geometry analogy problems, solvers may fixate on the target model of the tasks and decide its relevant parts so that this increases the fixation duration. In other words, target model presented for geometry analogy tasks may serve workspace area at the same time. Conversely, during tangram problems, solvers were allowed to manipulate the pieces. In other words, being allowed to piece manipulation provides easy comparison between shapes and points out dramatic decrease on fixation durations.

Moreover, maximum oxygenation levels for tangram tasks (with and without outline) have greater values within analyzed voxels than block copying and geometry analogy tasks. Although participants were also allowed for manipulation during block copying tasks, mean fixation duration dropped on workspace area is less than tangram tasks. During block copying tasks, solvers maintained two types of information and hold a specified sequential order to reach the solution with regard to color and position. On the other hand, tangram problems have more features and have various possible combination patterns. Various combination patterns might result in greater fixation duration on workspace area of tangram tasks and working memory demand on prefrontal cortex in a parallel trend.

5.5 Scan Path Analysis

Beside the numerical data including fixation duration, fixation count, fixation rate and transition rate between areas of interest, the scan path analysis provided observing the scan patterns, gaze sequence of the participants and the interaction between various visuospatial task types.

In the experimental protocol, there were four block copying tasks. The block copying tasks were varied in reference to the number of blocks, color of blocks, and the target model construction. Block copying tasks were presented to participants with regard to difficulty level. In the first and second block copying tasks consisting of two colored eight blocks, participants followed a basic sequential order such as piece-pickup-model-workspace-drop. Aforementioned sequence includes one eye fixation point on piece, model and workspace and two hand movements for pickup and drop actions. Pickup occurred between piece and model, and drop occurred after participants looked at the workspace. Additionally, the third block copying task has three colors and ten blocks for copying. Participants followed a sequential order like previous block copying tasks but they looked back to the model after they picked up the piece. Gaze patterns followed a sequence like piece-model-workspace-model. They looked back to the model for the next piece and then selected the appropriate piece from the piece area. In fourth block copying task, the same pattern occurred. The difference between the first and the second block copying tasks and the third and the fourth block copying tasks is that participants looked back to model to encode the next location before they moved cursor to the pieces area.

In addition to block copying tasks, four geometry analogy tasks were also presented to participants. In hexagon task, participants made successive back and forth saccades and their gaze points dropped on candidate locations on target model. Eye fixations were dropped on possible join points. In funnel task, participants' eye gaze patterns also showed similar saccadic movements with hexagon tasks. Arrow task has not indicated as much look back eye movements as the previous geometry analogy tasks and participants looked at the actual joint points on target model.

Moreover, tangram tasks within different difficulty levels and different problem space and problem feature were presented to participants. Control tangram tasks were constructed with an antisymmetric shape with regard to with and without outline problem spaces. The joint points of pieces were visible and easy to distinguish. With outline and without outline control tangram tasks differentiate in reference to saccadic movements. While participants took the outline for the reference frame in outline condition, they took the target model for the reference frame in without outline condition.

Tangram tasks also have hexagons with regard to with outline and without outline conditions. The same task was presented to participant within two conditions. Eye gaze patterns of participants showed that participants did not make more saccadic movements compared to with outline condition.

Other tangram tasks were analyzed with regard to with outline and without outline conditions. Swan, Kindle and Rabbit were tasks which are constructed with an outline in their problem space. Participants looked at the pieces and the edge of the outline to place the selected piece. Gaze patterns presented various combinations while participants located the selected piece: piece-outline-rotate, outline-piece-rotate. Additionally, kangaroo, man, and rooster tasks had no outline on their problem spaces. Therefore, instead of looking at the edge of outline, participants looked at the target model while they rotate, try to find the actual location and fit the piece on the constructed image. In without outline condition, participants looked at the sharp points and distinct features before they moved and rotated the pieces. For each movement, participants showed distance related eye gaze patterns such as making saccades between the neighboring pieces and the target model.

In conclusion, while participants followed a sequential order in reference to eye and hand movements, they followed heuristic strategies to solve the tangram tasks. Excessive number of transformation required to construct the target model resulted in excessive amount of saccadic eye movements between the piece, constructed model and the target mode/outline. On the other hand, during geometry analogy tasks participants showed trial and error method, and back and forth saccadic eye movements occurred between the target model and the given pieces within choices. Participants looked at the pieces and then they looked at the candidate corresponding area on the target model and the solution was tried to be achieved by making saccades between the pieces and the target model.

5.6 Significance

The results of this study indicate that simultaneous use of eye tracking and fNIRS data can provide valuable information about cognitive processes underlying visuospatial problem solving. In this study we focused on the interrelationships between features such as fixation duration, fixation count, fixation rate and transitions; as well as changes in maximum oxygenation levels to discuss implications of problem space organization and affordances for sensorimotor engagement during visuospatial reasoning. Although fixation duration/count and gaze transition measures can be considered as important indicators of visual processing and solvers' viewing priorities, analyzing these features together with fNIRS data on brain activity at the prefrontal cortex reveal important information about neural correlates of visual working memory and attention management during visuospatial problem solving. Such multimodal analyses may inform existing theoretical frameworks in cognitive science regarding the nature of cognitive processes underlying visuospatial reasoning.

The present study demonstrates the plausibility of this multimodal analysis approach in the context of visuospatial reasoning. One significant aspect of this study is that it provides evidence that fNIRS signals are sensitive to changes in task complexity and sensori-motor access during visuospatial reasoning. This information can be used to better interpret the eye gaze patterns as captured by fixation duration/count and gaze transition features. Another significant part of this research was the method developed for investigating how solvers process visuospatial problems. The key benefit of this approach is that it provides the researcher with online information about a solver's cognitive processes, which can lead to the development of interactive systems where ocular and neural information can be monitored and acted upon in real-time. Such applications may be useful in the context of neurorehabilitation.

5.7 Limitations and Future Researches

Since few studies have investigated how combined researches of neuroimaging and eye tracking data correspond to visuospatial problem solving process, in this research it was difficult to predict gaze data characteristics and their relevance with prefrontal cortex activations. Doing a combined research limited the number of participants so that the lack number of participants also limited the statistical tests and results in nonnormal distribution of the data. Since sample size of the thesis study included university students, it is difficult to generalize results to a more diverse population. Moreover, experimental protocol did not support task order randomization. All participants engaged with tasks in consideration with the same order.

For future researches, video recorded eye tracking data can be analyzed for tangram tasks with regard to transitions between individual geometric features such as square, triangle, and parallelogram. Transition between individual geometric features may provide finding the average sequence including geometrical pieces for a tangram task.

Also, given tasks have different model construction for block copying tasks and use of just-in-time strategy during block copying tasks decreases working memory demand beside the limited number of pieces and encoded information during block copying tasks. To test this in a control environment, an experiment showing target for a while then allowing subjects to reach the solution can be designed as a future work.

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APPENDICES

Appendix A

Gönüllü Katılım Formu

Bu çalışma, Orta Doğu Teknik Üniversitesi Enformatik Enstitüsü Bilişsel Bilimler Bölümü'nde, Bilişsel Bilimler Anabilim Dalı öğretim üyesi Yrd. Doç. Dr. Murat Perit Çakır danışmanlığında yüksek lisans öğrencisi Gamze Türkmen tarafından yüksek lisans tezi kapsamında tangram problemleri çözümünde görsel-mekânsal nedenlemeye bağlı olan stratejilerin incelenmesi amacıyla yürütülmektedir.

Çalışmacının amacı, iki-boyutlu farklı zorluktaki tangram problemlerinin çözülmesi aşamasında kullanılan farklı stratejileri mekânsal nedenleme başlığı altında incelemektir. Bu çalışma süresince kullanıcıların problem çözme esnasında göz hareketleri ve alın bölgesindeki oksijenleşme oranları ölçülecektir. Uygulama öncesi kullanıcıların yaş/cinsiyet/bölüm/sınıf bilgileri ve problem çözme oyunlarıyla ilgili geçmiş bilgilerini edinmemizi sağlayacak bir anket verilmektedir. Yapılacak çalışma 20 genç yetişkine uygulanacak ve bütün çalışmalar Bilgi İşlem Daire Başkanlığı İnsan Bilgisayar Etkileşim Araştırma ve Uygulama Laboratuvarı'nda gerçekleştirilecektir. Bilgileriniz tamamıyla gizli tutulacak ve sadece araştırmacılar tarafından değerlendirilecektir. Elde edilen bilgiler yüksek lisans tezi kapsamında ve bilimsel yayımlarda kullanılacaktır. Uygulama sürecinde herhangi bir nedenle kendinizi rahatsız hissettiğiniz takdirde uygulamayı bırakarak çıkmakta serbestsiniz. Buna benzer bir durumda uygulama yürütücüsüne, uygulamayı tamamladığınızı söylemek yeterli olacaktır. Uygulama sonunda, bu çalışmayla ilgili sorularınız cevaplanacaktır. Bu çalışmaya katıldığınız için şimdiden teşekkür ederiz.

Çalışma hakkında daha fazla bilgi almak için Gamze Türkmen ile (e-posta: gamze.turkmen@metu.edu.tr) iletişim kurabilirsiniz.

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

Appendix B

Katılımcı Verileri

Katılımcı No: _______

1. Yaş: ______
2. Cinsiyetiniz

Erkek ☐

Kadın ☐

3. Mesleğiniz: _______________

4. Mezun olduğunuz veya şuan devam etmekte olduğunuz okul türü.

Lise ☐

Lisans ☐

Yüksek Lisans - Doktora ☐

5. Daha önce görsel yetenek testlerine katıldınız mı? Evet ☐ Hayır ☐

6. Yukarıdaki soruya cevabınız "Evet" ise hangi yaş aralığında? ________________

Bu bölüm "Tangram problemleri hakkında temel bilgi", "Geometrik şekiller hakkında temel bilgi" ve "Birleştirme oyunları hakkında temel bilgi" başlıkları altında 1 ile 14 arasında hazırlanmış maddeler içermektedir. Lütfen bu maddeleri okuduktan sonra; 1.Kesinlikle Katılmıyorum 2.Katılmıyorum 3.Kararsızım 4.Katılıyorum 5.Kesinlikle Katılıyorum seçeneklerinden size en uygun olan bir tanesini seçerek X ile işaretleyiniz.

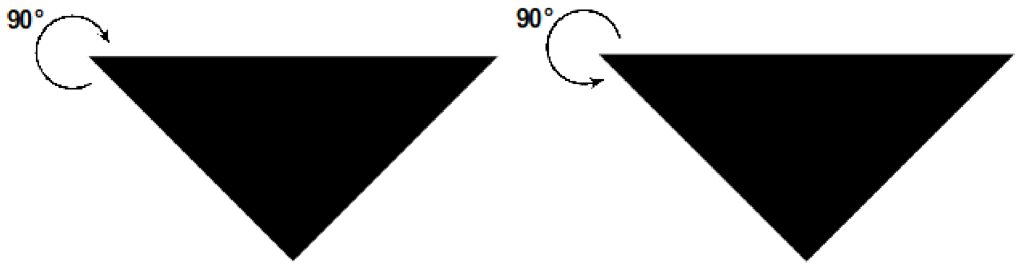
Tangram problemleri hakkında temel bilgi						
1	"Tangram" kelimesini daha önce duydum.	1	2	3	4	5
2	"Tangram"ın ne demek olduğunu biliyorum.	1	2	3	4	5
3	Bir tangram şeklinin kaç parçadan oluştuğunu biliyorum.	1	2	3	4	5
4	Bir tangram şeklini oluşturan parçaların şekillerini biliyorum.	1	2	3	4	5
5	Daha önce tangram problem(ler)i çözdüm.	1	2	3	4	5
6	Daha önce tangram problem(ler)ini gerçek ortam(lar)da çözdüm.	1	2	3	4	5
7	Daha önce tangram problem(ler)ini sanal ortam(lar)da çözdüm.	1	2	3	4	5
Geometrik şekiller hakkında temel bilgi						
8	Temel geometrik şekilleri biliyorum.	1	2	3	4	5
9	Geometrik şekillerin adını duyduğumda zihnimde canlandırabilirim.	1	2	3	4	5
10	Geometrik şekillerle yeni bir şekil oluşturabilirim.	1	2	3	4	5
Birleştirme oyunları hakkında temel bilgi						
11	Yap-bozun ne demek olduğunu biliyorum.	1	2	3	4	5
12	Tetrisin ne demek olduğunu biliyorum.	1	2	3	4	5
13	Daha önce yap-boz parçalarıyla resim oluşturdum.	1	2	3	4	5
14	Daha önce tetris oynadım.	1	2	3	4	5

Appendix C

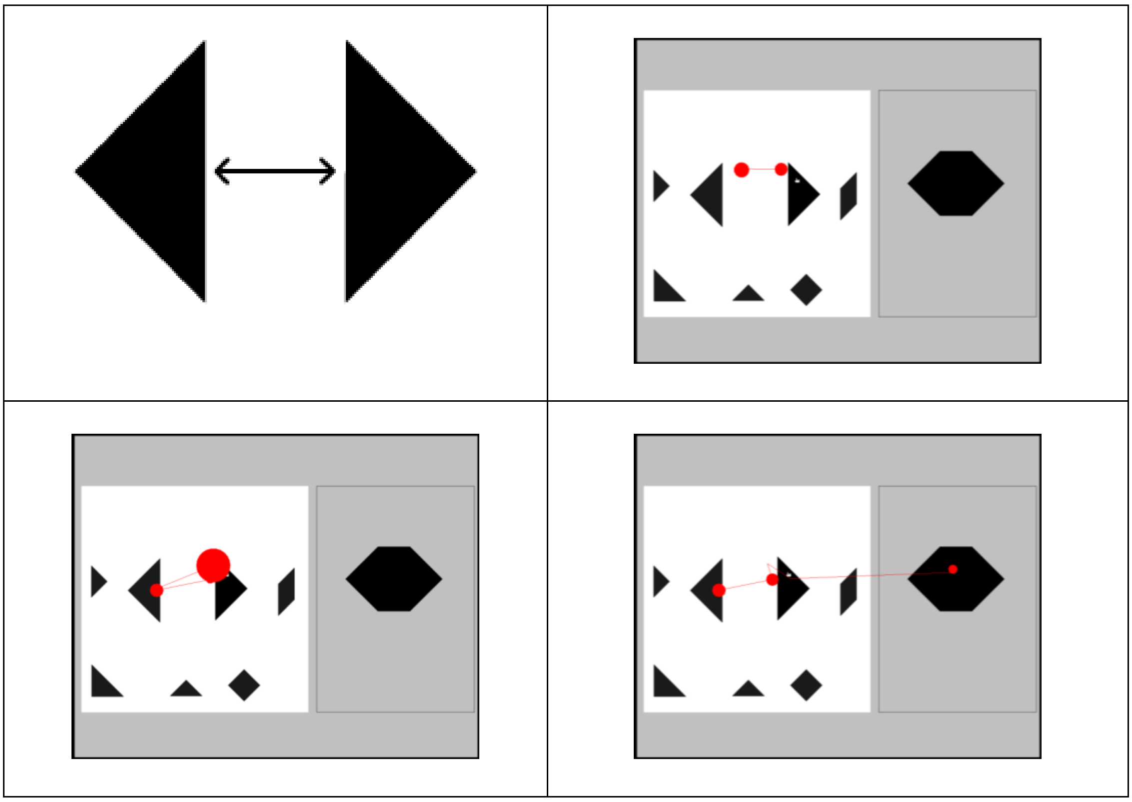
Analyzed excerpts from the Participants Data

Hexagon: A symmetrical geometric shape without outline (Unsuccessful Solver)

After the participant looks at the pieces, he takes one of the large triangles and rotates it to provide sharp points for the model. So, outer frame can match with the target model.

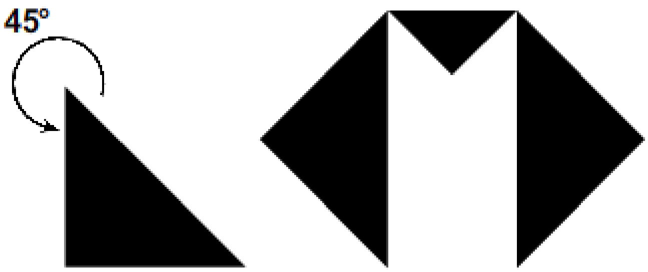


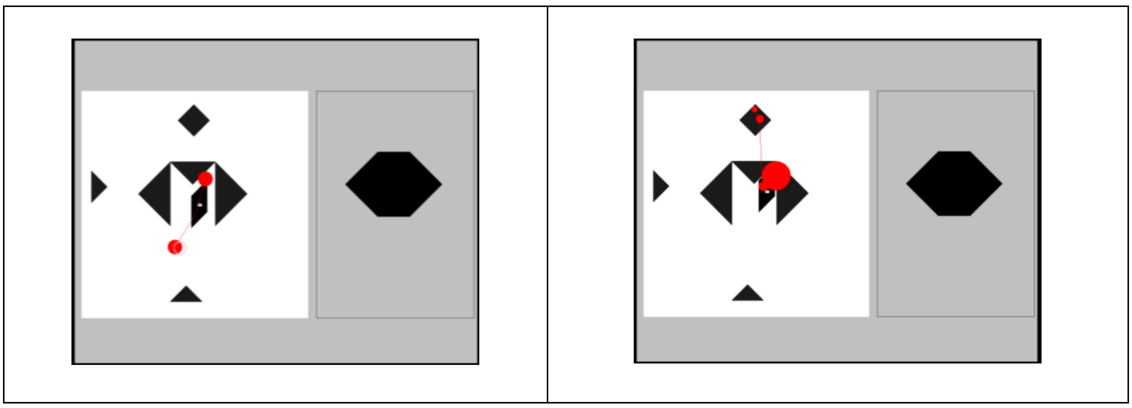
After he matches the large triangles with the target model, he looks at the target model to determine the distance between two large triangles.

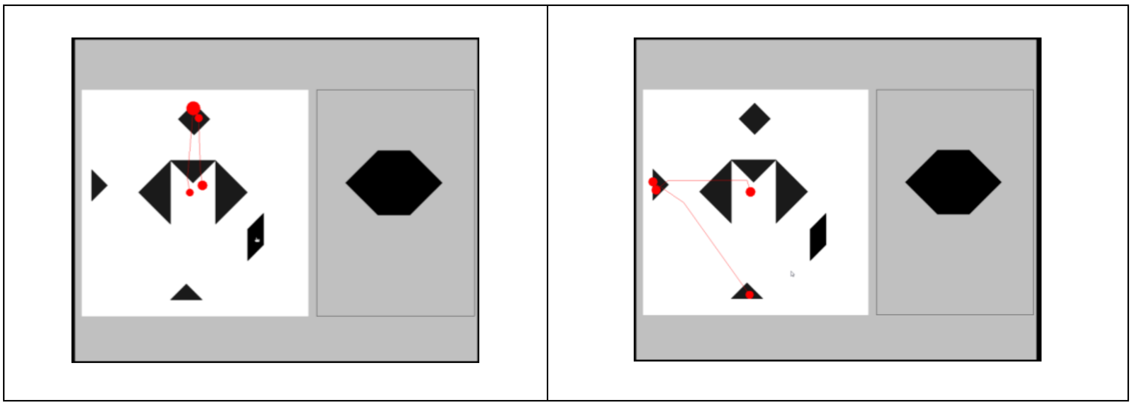


After determining the distance between two large triangles, he begins to try different pieces to fill the rectangular gap. Although he takes the parallelogram and square, without any manipulation he puts off them and takes the medium triangle. After rotating, he puts the medium triangle between the two large triangles.

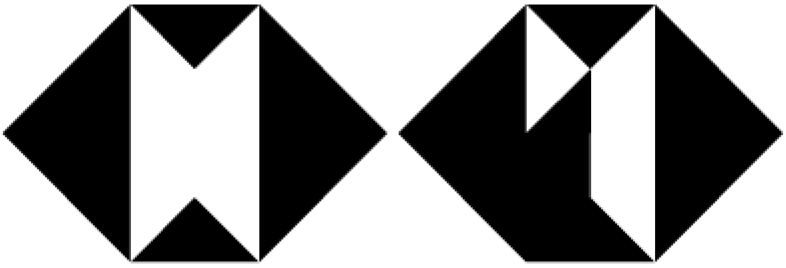
After he puts the medium triangle between two large triangles, he puts the parallelogram between the medium and the large triangles. He searches for the objects around the workspace area and by looking at the target model he extracts the parallelogram and the medium triangle. After he looks at the large and small triangles, his movement sequence is as the following order: (1) looks at the target model, (2) takes the little triangle, (3) looks at the target model, (4) rotates the small triangle, (5) puts the little triangle between the two large triangles.

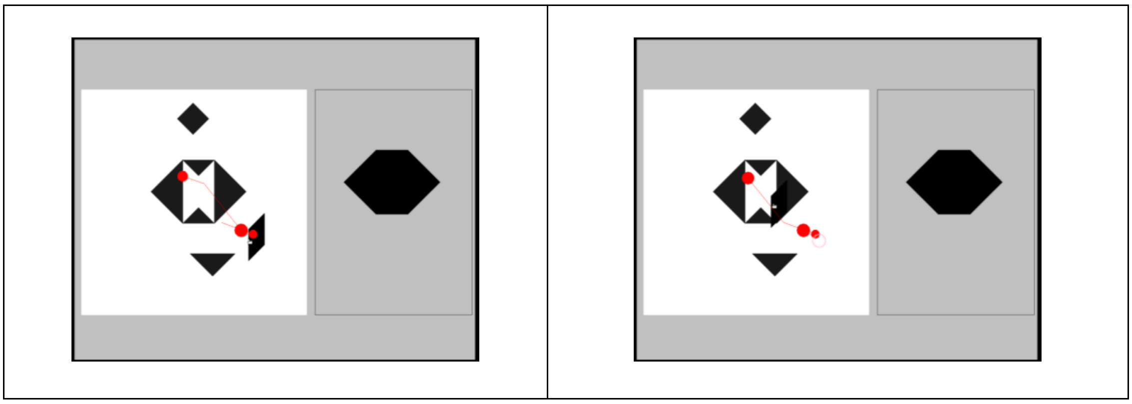




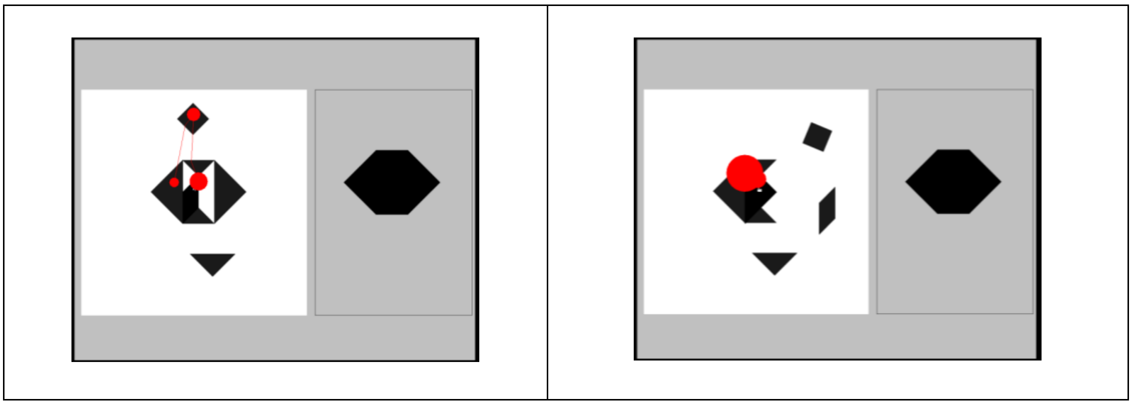


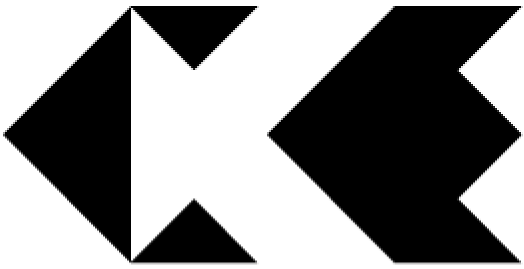
He looks at the target model during the second small triangle selection. Taken small triangle is put on the base of the constructed model located in workspace area. After he puts the small triangle, he takes the parallelogram and puts it in an appropriate gap without looking at the target model.



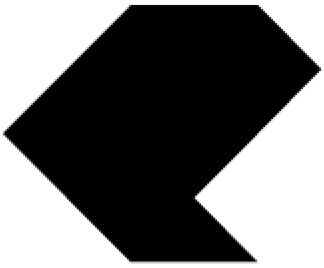


After he puts the parallelogram, he cannot see an appropriate gap for the square and he looks at the target model one more time. He extracts the parallelogram and searches for appropriate arrangement of pieces. Finally, he puts the second large triangle near the first one.

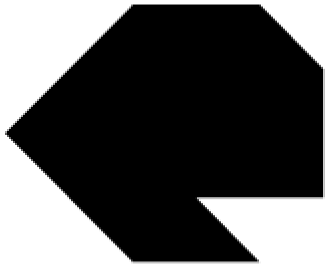




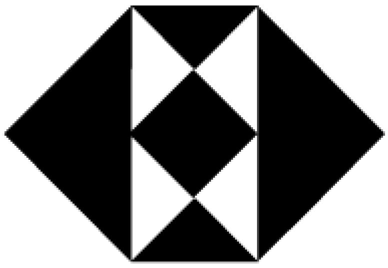
After this movement, square is put in an appropriate gap.



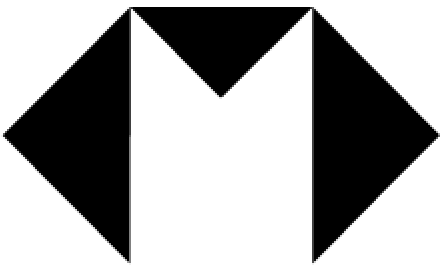
The rest of the pieces (medium triangle, parallelogram) are tried to be put in the gap. During the medium triangle selection, he looks at the sharp point of the target model and tries to arrange the medium triangle as it. However, he rotates the triangle and puts it. After this movement, since parallelogram doesn’t fit the remained gap, he extracts the medium triangle and tries to put parallelogram by making rotations.



Since he cannot place the parallelogram, he begins to decompose the parts of the constructed model and begins with the same variations considering two large triangles. He puts small triangles and the square between the two large triangles.

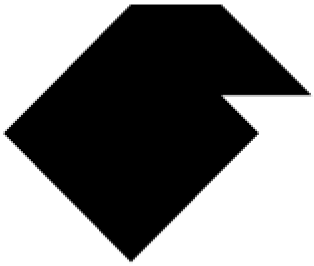


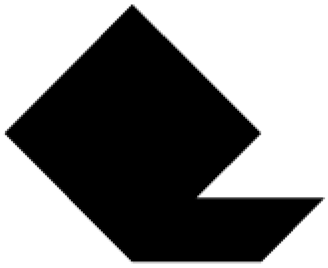
He searches for the other pieces that can be put in the gaps. He looks at the pieces located between two large triangles and the target model. He begins to extracts the pieces located between two large triangles. He puts the medium triangle and while he takes the parallelogram, the time is up.



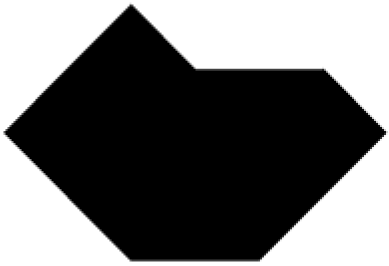
Hexagon: A symmetrical geometric shape without outline (Successful Solver)

She begins the task as selecting one of the large triangles. She puts the large triangles to an appropriate position referencing the target model. She continues by selecting the second large triangle. She looks at the target model and she puts the second large triangle near the first one. Her third piece is parallelogram. After parallelogram is selected, she looks at the target model and puts it near the constructed model located in the workspace area. Then, she rotates the parallelogram and puts it on the base of the model.

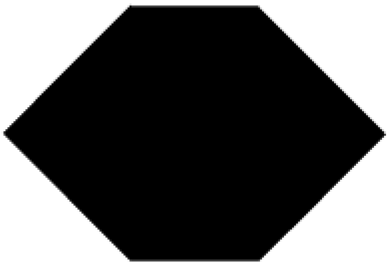




Little triangle is selected to fill the gap. By small and the medium triangles, sharp points are satisfied.



Since there is no gap for square, she extracts the last two pieces (medium and small triangles). She puts the square considering the sharp point and completes the shape with the small triangle.



TEZ FOTOKOPİSİ İZİN FORMU

ENSTİTÜ

Fen Bilimleri Enstitüsü ☐

Sosyal Bilimler Enstitüsü ☐

Uygulamalı Matematik Enstitüsü ☐

Enformatik Enstitüsü ☐

Deniz Bilimleri Enstitüsü ☐

YAZARIN

Soyadı : ……………………………………………………………………………………………

Adı : ……………………………………………………………………………………………….

Bölümü : ………………………………………………………………………………………….

TEZİN ADI (İngilizce) : ………………………………………………………………………

…….

…….

…….

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 : ……………………