VILNIUS UNIVERSITY

LIFE SCIENCES CENTER

Marta Purvinytė

Visual Strategies Across Mind and Art: Eye Movements in Reasoning Tasks and Aesthetic Viewing

Master's thesis

Neurobiology study program

Thesis supervisor

Dr. Alvydas Šoliūnas

Thesis completed at

Departament of Neurobiology and Biophysics of the LSC

Contents

Abbreviations

AOI – Area-of-interest

RPM – Raven's Progressive Matrices

ICAR – International Cognitive Ability Resource

CSI – Cognitive Style Index

MR – matrix reasoning

R3D – Three-Dimensional Rotation Task

g – general intelligence factor

G*f* – fluid intelligence

Introduction

Humans have visual exploration differences that also heavily depend on the context at hand, and this can be noticed through the performance of different tasks. Reasoning tasks and aesthetic viewing both rely on visual exploration, though the demands differ: reasoning requires analytical problem-solving, while aesthetic viewing is more interpretative. Yet both are similar in that they require attention allocation and information sampling.

Eye tracking is a method that allows seeing the external manifestations of internal cognitive processes. Previous studies have shown that gaze reflects different problem-solving strategies and aesthetic processing and can even reveal different internal states. There have been studies on matrix reasoning, mental rotation, and aesthetic appreciation, but these domains were always studied separately, leaving the possibility of an unexplored connection in between.

The current research is highly limited in its comparison of intra- and interpersonal stability in this domain. It remains unclear whether individuals do show stable exploration patterns in their ways of attending to different task demands. It is also unknown if these features persist as traits reflected in broader individual cognitive tendencies beyond a single task.

Aim

To assess how visual strategies, inferred from eye movement patterns, relate to cognitive abilities, individual cognitive styles, and aesthetic exploration across task-based reasoning and free viewing of paintings.

Objectives

1. To characterize visual strategies during cognitive task performance using eye movement measures.
2. To determine how different visual strategies relate to performance on cognitive tasks measuring reasoning and visuospatial ability.
3. To compare visual strategies and eye movement patterns between participants with different cognitive styles
4. To assess whether identified visual strategies during cognitive tasks generalize to eye movement patterns during free viewing of paintings.
5. To examine the relationship between cognitive abilities and eye movement patterns during aesthetic viewing.

1. Literature review

1.1. Intelligence, fluid reasoning, and visuospatial cognition

1.1.1. The concept of intelligence

As a curious species, humans have always wanted to put a mathematical or spectral spin to understanding of concepts. One of the most notable aspects of our mind – the intelligence – is not an exception. To begin the discussion, it is important to define what intelligence is, although it is a much more difficult task than it would look like at a first glance. Robert J. Sternberg opened his book called "The Handbook of Intelligence" (2000) with this thought "looked at in one way, everyone knows what intelligence is; looked at in another way, no one does. Put another way, people all have conceptions – which also are called folk theories or implicit theories – of intelligence, but no one knows for certain what it actually is". Though not an easy task, many have tried: Legg & Hutter (2007) collected 71 definitions suggested by groups, organizations, psychologists, and AI researchers. Together, observing the common features, they found that intelligence:

- Is a property that an individual agent has as it interacts with its environments.
- Is related to the agent's ability to succeed or profit with respect to some goal or objective.
- Depends on how able the agent is to adapt to different objectives and environments.

Although the final definition by Legg & Hutter (2007) is quite obscure "intelligence measures an agent's ability to achieve goals in a wide range of environments". Some decades after intelligence was first started to be studied, a more in-depth definition was proposed by American pioneer in psychometrics L. L. Thurstone, who in his 1921 article stated that intelligence is "the capacity to inhibit an instinctive adjustment, the capacity to redefine the inhibited instinctive adjustment in the light of imaginally experienced trial and error, and the capacity to realize the modified instinctive adjustment in overt behavior to the advantage of the individual as a social animal". Even though it's old, it has stood the test of time and captures the essence of the concept to the point, not breaking the important features distilled by Legg & Hutter. Nonetheless, one might not be able to define intelligence, yet it most definitely can be observed and measured, which provides more merit than any words ever could.

1.1.2. General intelligence and fluid reasoning

A so-called general intelligence (or *g* factor) was discovered by Charles Edwards Spearman in 1904: by using factor analysis he found that the results of different cognitive tests tend to positively correlate with each other, suggesting that people who perform well in one mental task would usually perform well in others too. He argued that all cognitive tests measure two things, firstly the general factor (*g*) and secondly, the task-specific factor (*s*). Spearman believed that g is the factor underlying the involvement in reasoning and solving novel problems rather than recalling learned knowledge. He likened *g* metaphorically as "mental energy" and *s* to "specialized engines" for performance of certain types of tasks, claiming that individual differences in task performance results from differences in the amount of mental "energy" that is able to be delivered to the specific "engine" that would mediate performance of the task, as well as differences in the efficiency of energy utilization by the "engine", adding that the efficiency of these different kinds of "engines" differ within the same person independently (Jensen, 1998; p. 18). Working on this idea, Raymond Cattell (1963) developed the revolutionary theory of fluid intelligence (G*f*) and crystallized intelligence (G*c*), which function as second-order factors in tests, with Gf primarily acting in tests that are highly culturally reduced and G*c* being highly culture-specific problem-solving. This idea is based on Spearman's *g* not being a unitary factor but rather a composite of these two quite different general factors, with one of them dominating depending on the nature of the task (Jensen, 1998: p. 123). Fluid reasoning (G*f*) is the capacity to figure out novel problems in which specific prior knowledge, skills, and conscious strategies are of relatively little use. Carroll (1983) examined various researchers' frameworks and concluded that fluid intelligence abilities include induction, logical reasoning, general reasoning, integrative processing, judgment, and planning. The most relevant to the topic at hand are induction, or the ability to find rules and patterns from the information, and logical reasoning, or ability to use relationships systematically.

1.1.3. Matrix reasoning and fluid intelligence

While there are multiple ways to estimate fluid, or analytical, reasoning, Raven's Progressive Matrices Test (RPMT) (Raven, 1938) has stood the test of time with minimal updates and many others adapting the same principal construct to measure non-verbal reasoning. The series of problems consist of a 3 × 3 matrices of which one entry is missing and must be selected from a number of response alternatives arranged below. Each entry typically consists of figural elements, such as geometric shapes. The participant must figure out the underlying logic in the matrix sequences to correctly choose the answer – this elicits the participant to generate rules by which the matrix was constructed, while some of the incorrect answer options are designed to satisfy an incomplete set of rules (Carpenter et al. 1990). Trials usually consist of varying difficulty items, with the more difficult problems entailing more difficult rules and a greater number of them, as well as more figural elements per entry. An example of such trial is presented in Figure 1.1. There are five different types of rules that could arise from solving Raven's Progressive Matrices or an analogical version of it, with many of the problems requiring the participant to involve multiple different rule types or several instances of the same type of rule (Carpenter et al., 1990). Taxonomy of rules in the Raven test can be seen in Table 1.1. It is proposed that fluid intelligence is strongly linked to the ability to manage multiple goals and relations simultaneously and that good performance in Raven's task depends mostly on abstract rule induction and working memory (Carpenter et al. 1990; Duncan et al., 2000; Jung & Haier, 2007).

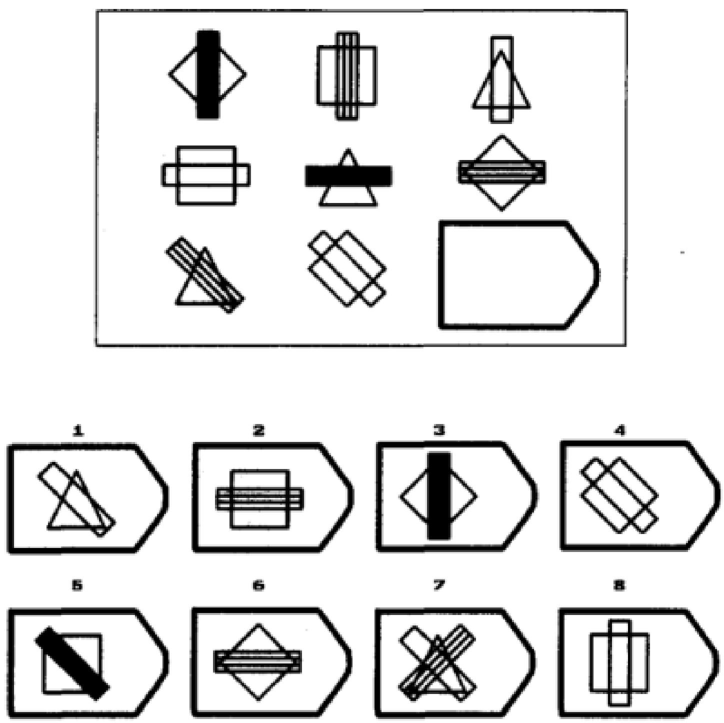


Figure 1.1. A problem illustrating the format of Raven's Progressive Matrix Test trial (Carpenter et al., 1990).

Table 1.1. A taxonomy of rules in Raven's Progressive Matrix Test (adapted from Carpenter et al., 1990)

Rule	Taxonomy
Constant in a row	The same value occurs throughout a row, but changes down a column.
Quantitative pairwise progression	A quantitative increment is decrement occurs between adjacent entries in an attribute such as size, position, or number.
Figure addition or subtraction	A figure from one column is added to (juxtaposed or superimposed) or subtracted from another figure to produce the thirds
Distribution of three values	Three values from a categorical attribute (such as figure type) are distributed throughout a row.
Distribution of two values	Two values from a categorical attribute are distributed through a row; the third value is null

1.1.4. Mental rotation and visuospatial reasoning

Another factor associated with fluid intelligence and general cognitive ability is visuospatial reasoning that can be examined through mental rotation tasks. The foundational study in this topic is Shepard & Metzler's "Mental Rotation of Three-Dimensional Objects" (1971): they presented participants with pairs of drawing of three-dimensional assemblages of cubes that were identical yet differed in a certain amount of rotation that could be make them a mirror image of the other. The task was to identify if the assemblages were identical with a different rotation or a mirror image, as soon as possible. It was found that the decision-making time increased with angular rotation difference between them. This raised the idea that participants formed a mental image of the structure and then transformed it to assess whether it could be aligned with the corresponding assemblage. This theory was later confirmed by follow-up studies varying critical features of the original experiment, concluding that mental rotation takes place in real time and the time course of such internal mental transformation can be mapped out (Shepard & Cooper, 1982).

Initially, mental rotation was conceptualized as relatively uniform process between different individuals, although later research suggested that participant differ in their ways of mental transformation. Just and Carpenter (1985) claim that strategic differences in these types of tasks can be explained through different cognitive coordinate systems that subjects adopt. The idea is that people differ in their internal representation of spatial objects as they organize them using different principles, influencing recognition, spatial transformations, memory retrieval, and mental manipulations. They propose that human coordinate systems differ from mathematical ones by an addition of a viewing point, or a location from which the 'mind's eye' would be viewing the object, meaning it is not perfectly precise, objective, or geometrical rather they are shaped by perspective, attention, visibility, and internal organization. So, it is evident that spatial reasoning depends not only on the object itself but also on how the object is manually represented and this is the space where individual differences may arise. Several strategies of mental representation creation emerge, mainly the *piecemeal* and *holistic* transformations. *Piecemeal* theory suggests that transformations exist as an analytical process that transforms the object piece-by-piece or one feature at a time (Pylyshyn, 1973), whereas *holistic* theory proposed a dynamic imagery process that resembles physical rotation only done in mind (Cooper & Shepard, 1973; Metzler & Shepard, 1974). While the debate between which theory of transformation underlies mental rotation processing has been long-standing, Zhao & Della Sala (2017) argue that both of these co-exist, and different people may use different strategies depending on task demands and individual abilities. They claim that flexibility between these strategies is what makes on a "good imager", as everyone process simple integrated objects similarly, meaning holistic rotation may be more universal, but with increased fragmentation of the objects, better problem-solvers are able to switch to more piecemeal processing. So, the implication here is that efficient visual-cognitive processing depends on selective attentional organization and task demands. Altogether, these findings suggest that visuospatial reasoning is not necessarily a single uniform cognitive operation as it depends not only on spatial ability itself, but also on efficient organization of internal representational formats, attentional organization and ability to adapt to task demands. Therefore, individual differences in visuospatial reasoning may emerge from broader differences of adaptive processing rather than more superficial differences in processing speed of intelligence level.

1.2. Neural correlates of fluid reasoning and visuospatial cognition

1.2.1. Neural correlates of reasoning and intelligence

To understand how the *g* factor or, in particular, fluid intelligence is represented in the brain several theories have been proposed. Namely, frontal parts have been speculated to be implicated for a long time as connection between lower part of *g* distribution and frontal lobe lesions has been noticed (Duncan, 1990; Duncan et al., 1995; Engle et al., 1999). To test this, Duncan et al. (2000) investigated the neural basis of intelligence by opposing two competing theories: Spearman's theory that says that intelligence reflects common central cognitive mechanism (*g* factor) (Spearman, 1904) versus Thomson's theory saying that intelligence reflects the combined efficiency of many distributed systems working together efficiently (Thomson, 1916). They utilized positron emission tomography during spatial and verbal reasoning tasks as well as perceptual tasks, hypothesizing that if intelligence reflects broad sampling of many abilities, then high-*g* tasks (highly correlated with *g* factor) should activate many regions diffusely, whereas if it reflects a specific control system, then the tasks should only activate a selective neural network. They found out that high-*g* tasks did not produce broad diffuse activation, conversely, they consistently recruited lateral frontal cortex even though the tasks varied a lot, thus concluding that general intelligence heavily depends on specific frontal control system, particularly, lateral prefrontal cortex, sometimes anterior cingulate and frontoparietal systems. The findings fit with Jung & Haier's (2007) Parieto-Frontal Integration Theory (P-FIT) of intelligence. In another study, Duncan (2010) proposed that intelligent behavior depends on Multiple-Demand (MD) system – a system that becomes active across many kinds of cognitively demanding tasks and this network involves frontal and parietal cortices, especially inferior frontal and intraparietal sulci, as well as anterior insula and anterior cingulate cortex. He also found that fluid intelligence recruits the MD system especially strongly, suggesting that different cognitive tasks should be sharing a common underlying control mechanism. A concept of mental programs also is raised in this article, meaning that to achieve complex goals one should be able to divide behavior into separate sub-tasks, organize these sequentially, keep focus on the current step, and have capability to switch flexibly between operations. These kinds of operational sequences for successful complex goal completion have been described for both matrix reasoning tasks (Just et al., 1990; Bethell-Fox et al. 1984, Vigneau et al., 2006) as well as mental rotation tasks (Shepard & Metzler, 1971; Pylyshyn, 1973; Sternberg, 1977). Specifically for reasoning tasks, an fMRI study was done with participants taking the Raven's Progressive Matrices Test distinguishing it into figural and analytical reasoning. Figural reasoning in this study's RPMT relies on visuospatial analysis, namely perceptual transformations and pattern continuation, while analytical reasoning requires executive control and strong abstract rule induction. They found that different reasoning types recruit different neural systems: figural reasoning mainly activated right frontal cortex, bilateral parietal regions, occipital areas, and visuospatial working memory systems, indicating more mental imagery and visual transformations, while analytic reasoning activated bilateral frontal cortex, especially left regions, left parietal cortex, temporal regions, and executive working memory systems. The latter areas are associated with verbal working memory, relational integration, strategic flexibility, and executive control (Prabhakaran et al., 1997). They also attest to the fact that fluid reasoning is mediated by a network of working memory systems. As for mental rotation, superior parietal lobes, motor and premotor cortices, lateral occipital cortex (LOC), and dorsolateral prefrontal cortex were classified as visuospatial network regions, with importance of LOC being emphasized, as it is associated with mental object representation, encoding parts of the objects and understanding spatial relationship between them (Moen et al. 2020). All in all, it is apparent that fluid intelligence is a kind of network, that is uniform yet manifests differently in different individuals, and to successfully solve the high-*g* problems a certain adaptability is necessary especially with raising task demands.

1.3.Eye-tracking and cognitive processing

1.3.1. Beginnings of eye-tracking in cognitive research

Cognitive ability and reasoning are closely tied to attention allocation and problem-solving processes, therefore eye-tracking has become an increasingly valuable method for examining cognitive functioning. Just & Carpenter (1980) studied the allocation of eye fixations of college students reading scientific papers as a reading comprehension task. The idea was that the reader makes longer pauses at points where processing efforts are greater. The authors then concluded that greater loads of processing occur when readers are observing infrequent words, integrating information from important clauses, and making inferences at the end of the sentence. The study makes a great connection between gaze duration and the involvement of various levels of processing. Another research implementing eye-tracking in studying problem-solving and decision-making behavior was Glöckner & Herbold (2011) analyzing decision making in risky, fast, gambling situations, showcasing another process in the brain by observing the reduce in long fixations over time, suggesting individuals investigate information more thoroughly in the beginning. The study also greatly describes the thought process of the subjects through measures obtained from eye-tracking analysis, demonstrating how they can reflect changes in attention allocation and information processing strategies throughout the task.

Visual attention can be described through the interaction of bottom-up and top-down processing mechanisms: Bottom-up approach in visual attention is defined as operating on raw sensory input, rapidly and involuntarily shifting attention to salient visual features of potential importance, such as contrast, brightness, motion, novelty, and top-down mechanisms as implementations our longer-term cognitive strategies, as it is goal-oriented and voluntarily guided by observer's task, expectations, prior knowledge, and intentions (Corbetta & Shulman, 2002; Connor et al., 2004). In complex cognitive tasks these two forms of attentional control interact dynamically: salient visual features attract attention while higher-order cognitive goals guide interpretation of the task relevant information (Corbetta & Shulman, 2002; Tatler at al., 2011).

1.3.2. Eye movements in matric reasoning tasks

Eye-tracking has also been used to observe inner mental workings while completing reasoning tasks. Vigneau et al., (2006) took interest in this topic and observed ocular movements of university students while taking Raven's Advanced Progressive Matrices (RAPM) test. They measured the gaze time distribution across matrix cells (Fig. 1.2). The authors considered aggregate data and individual difference data, with individual-difference data revealing significant strategic correlates. They described what makes the item difficult to solve – it is related to the solution latency, matrix inspection, response-choice inspection, the number of alternations between interest areas, and latency to first alternation, suggesting that all these variables relate to intelligence (higher performing participants generally demonstrated more efficient inspection patterns in these domains). Also, the number of rules and rule instances correlates to item difficulty, suggesting involvement of working memory capacity. Besides that, the article further supports a multifaceted model of intelligence, incorporating both processing speed and strategic behavior. Eye-movement metrics like Proportional Time-on-Matrix, Matrix-Time Distribution, and Latency-to-First-Toggle predicted performance on the test and revealed qualitative differences in problem-solving strategies. An article by Heyes et al., (2011) described a method that "captures statistical regularities in temporally extended eye movement sequences" and demonstrated its effectiveness in analyzing the gathered RAPM test data. The analysis revealed interpretable individual differences in scanning patterns (Fig. 8) providing new insights into the role of strategic thinking on the test.

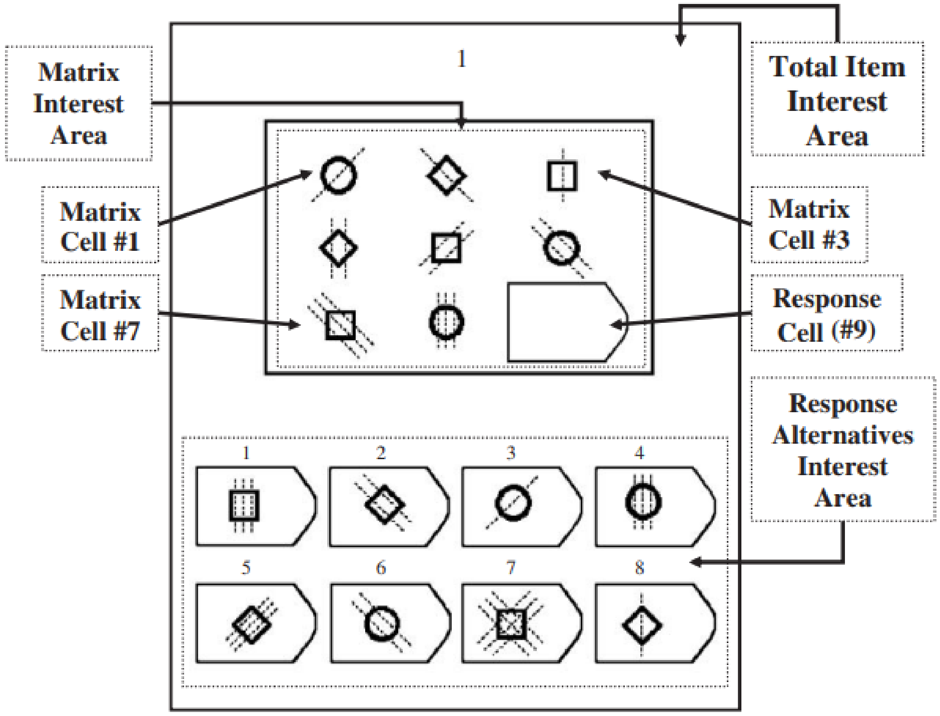


Figure. 1.2. Matrix cells and interest areas on a short form of the *Raven's Advanced Progressive Matrices test (SAPM)* item *(*Vigneau et al., 2006*)*.

1.3.3. Strategy differences and gaze behavior in reasoning tasks

Building on this perspective, Laurence et al. (2018), explored whether eye movements can predict the outcome of an intelligence test and found that The Toggling Rate (the number of toggles on each test item equalized by the item latency) explained 45 % of the test score variance. Furthermore, regression analyses indicated toggling rate as the best measure for score prediction. One particularly relevant study by Thompson (2021) addressed the relationship between strategy use (gathered from eye-gaze patterns), cognitive ability (CA), and reasoning performance on a ratio-bias task (selecting which of the two ratios was bigger). The test was repeated under a deadline (Time1) as well as in free time (Time2). CA was positively associated with correct solution at Time2 and increased performance from Time1 to Time2. Although, strategy predicted the test outcome at Time2 independently of CA and accounted for the relationship between CA and improvement from Time1 to Time2. The author concludes that some may rely on immediate intuitive responses, while others distinguish in analytical processing, nevertheless, this has an effect on efficiency of their reasoning strategies. Finally, Thompson establishes the relationship between CA and good strategy use, meaning it could be used as a predictor for performance. An important finding to mention is that gaze patterns can explain a substantial portion of intelligence testing variance and this was analyzed independently from personality traits (Bardach et al., 2024). This is crucial in supporting the theory that visual exploration behavior reflects cognitive rather than just dispositional characteristics. Collectively these findings suggest that eye movements reflect broader strategic and cognitive organization during reasoning tasks as well. Patterns of individual visual exploration may therefore provide insight into problem-solving approaches beyond what traditional psychometrics measure.

1.3.4. Sequential organization of mental rotation processes

Mental rotation performance examined though eye movement patterns also reveal important insight into the internal organization of visuospatial reasoning. In the typical mental rotation task, a person is supposed to determine if the two stimuli are rotated versions of the same object. This process requires at least two components: 1. Encoding a representation of the fixated object, and 2. Rotation of said representation to determine if it matches the second object (Moen et al., 2020). Efficiency and accuracy of this task improve when a more complete version of representation is encoded (Heil & Jansen-Osmann, 2008), and this is especially important when the object has more complex spatial configuration (Erdogan et al., 2016). To measure encoding – saccade amplitudes can be analyzed as larger distance between sequential fixations is interpreted as more complete mental representation of an object (Larsen, 2014; Davitt, 2014; Moen et al., 2020). True rotation aspect of the mental transformation can be interpreted from response time which increases as a function of angle of disparity (Shepard & Metzler, 1971) and greater activation of motor areas and visuospatial network if the brain is monitored (Carpenter et al., 1999; Logie et al., 2011). Other studies have proposed more in-depth models based on sequential stages revealed by eye movements. Mental rotation tasks are assumed to follow a five-step sequence of cognitive processing: (1) perceptual encoding of the stimulus, (2) identification of the stimulus and orientation, (3) mental rotation of the stimulus, (4) judgement of parity, and (5) response and execution (Corballis, 1988). A simplified version of the stages was suggested by Just & Carpenter (1976) after observing how fixation paths of the subjects change with angular disparity: (1) search, (2) transformation and comparison, and (3) confirmation of a match or mismatch between stimuli. Both stage summaries directly connect gaze behavior to cognitive processing. Xue et al. (2017) continues with the sentiment that visual exploration directly reflects cognitive organization, emphasizing that fixations are not random occurrences, as gaze follows what the task demands, and concludes that eye movements actively represent reasoning processes.

1.3.5. Strategic flexibility in mental rotation

Although earlier theories often describe mental rotation as a rather uniform process between individuals, later research suggests that participants differ in ways they internally organize and solve these tasks. Stieff (2007) argues that mental rotation tasks are not solved only through spatial visualization, but that people can flexibly switch between visuospatial and analytic strategies, meaning that good performance in spatial tasks may not directly represent superior mental rotation ability. In the authors' work on organic chemistry stereochemistry mental rotation tasks, they found that analytical shortcuts could be used instead of mentally rotating the molecules: they can inspect symmetry, apply previously learned rules, or use feature-based heuristics. The students did spontaneously use mental rotation especially with increasing angular disparity, but they could also switch to analytical strategies like checking symmetry, applying rules, inspecting features, pattern matching, meaning they wouldn't be using pure mental rotation anymore. The paper argues that visuospatial strategies may dominate novices, while analytical heuristics are more prominent in experts, meaning mental rotation may act as a default strategy until a better one is found. Similarly, Just & Carpenter (1985) argued that people differ not only in spatial abilities themselves, but also how the objects are mentally represented internally and what coordinate system they would be using during transformations. Such differences of internal processing of the representations and strategies may become externally observable though eye-movement specificity, influencing fixation sequences, comparison patterns, and visual exploration during the task. Therefore, it is evident that eye-movement could provide insight into transformation processes, and also broader differences in how individuals use cognitive strategies during visuospatial reasoning.

1.4.Neuroaesthetic perspectives on visual experience

1.4.1. Neural and cognitive mechanisms of aesthetic experience

While cognitive science traditionally focuses on problem-solving and logical reasoning, there are new waves of scientists exploring the perceptual and emotional processes involved in aesthetic experience. Neuroaesthetics is an emerging discipline investigating the biology of aesthetic experiences. According to Chatterjee & Vartanian (2014), aesthetic experiences include "emotions, valuation, and actions engendered by these objects, as well as processes that underlie their interpretation and production". Scientists in this field typically investigate the brain mechanisms of aesthetic experiences that are initiated and how they inform our understanding of these experiences, merging empirical aesthetics with cognitive and affective neuroscience. A sub-field called descriptive neuroaesthetics focuses on qualitative measurements, while experimental neuroaesthetics produce quantitative and statistically vetted data. Experiments in these fields usually focus on the properties between this triad of neural systems being sensory-motor, emotion-valuation, and meaning-knowledge circuity. The brain's visual intake is segregated into simple input like luminance, color, and motion, but also into higher-order objects like faces, bodies and landscapes, making this field perfect for eye-tracking analysis. Aesthetic experience has been associated with reward, emotional, and semantic neural systems, suggesting that aesthetic perception goes beyond simple visual analysis and involves broad cognitive and affective processing (Chatterjee & Vartanian, 2014). But the aesthetic experience is not purely visual, it depends on intellectual perception of the piece: it was found that people are often more responsive to the 'art status' than to the actual content of visual image (Lacey et al., 2011). Furthermore, people have different neural responses when told that they are looking at an authentic or a copied piece of art (Huang et al., 2011), further proving that aesthetic pleasure is tightly related to thinking processes. Default mode network (DMN) has also been implicated in some special aesthetic states. It is engaged when subjects focus on their emotions and internal thoughts. Deactivation of principal brain regions constituting the DMN was suppressed when viewing paintings rated as 'most moving' (Vessel et al., 2012). Mental signature of deeply aesthetic moments is an internal orientation evoked by external stimuli (Vessel et al., 2013). Ramachandran & Hirstein (1999) argue that abstract art acts as sort of a supernormal stimulus to excite areas of the brain more strongly than the normal stimulus. They also add that art is most appealing if "it produces heightened activity in a single dimension rather than redundant activation of multiple modules".

1.4.2. Aesthetic appreciation and intelligence

Several brain regions in aesthetic appraisal and cognitive ability overlap: Brown et al., (2011) suggested the core aesthetic network of the human brain (Fig. 1.3) and several of the brain areas mentioned overlap with structural correlates of intelligence (Fig. 1.4) found by Jung & Haier (2007). The overlaps suggest that both intelligence and aesthetic evaluation may partially rely on shared networks, so research in this topic could bring new insights into the understanding of the relationship between the two. Expanding on the previous findings, Myszkowski & Zenasni (2016) proposed a concept of Aesthetic Quotient (AQ) and Taste (T), suggesting that stable individual differences may also exist within aesthetic abilities in a similar way to broader cognitive abilities. They claim that "T" is to aesthetic ability what g (general factor of intelligence) is to mental ability, further relating similarities between the two domains.

These findings suggest the possibility of certain cognitive and attentional tendencies extending across both reasoning and aesthetic processing domains.

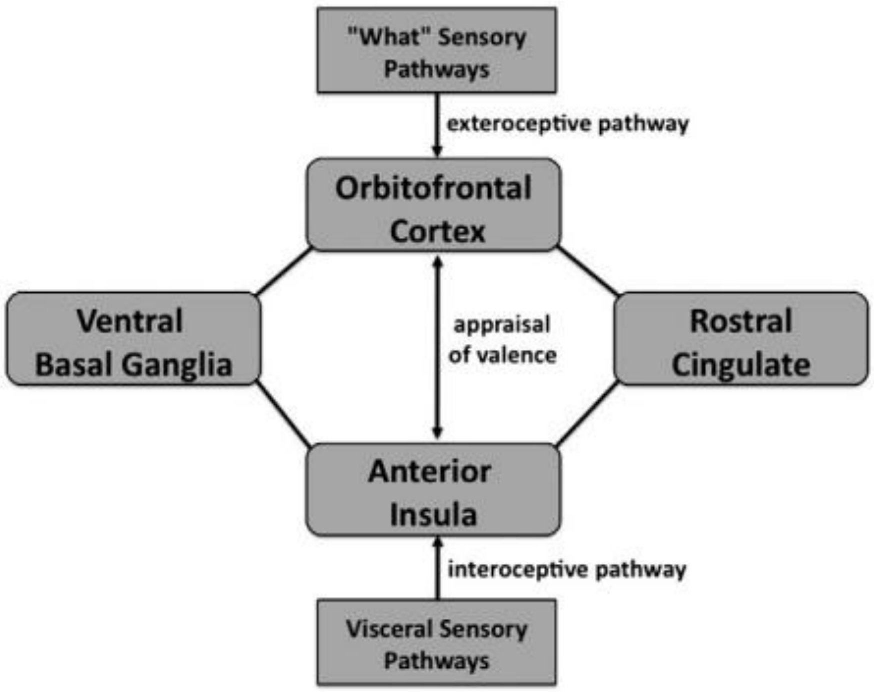


Fig. 1.3. The core aesthetic network of the human brain (Brown et al., 2011)

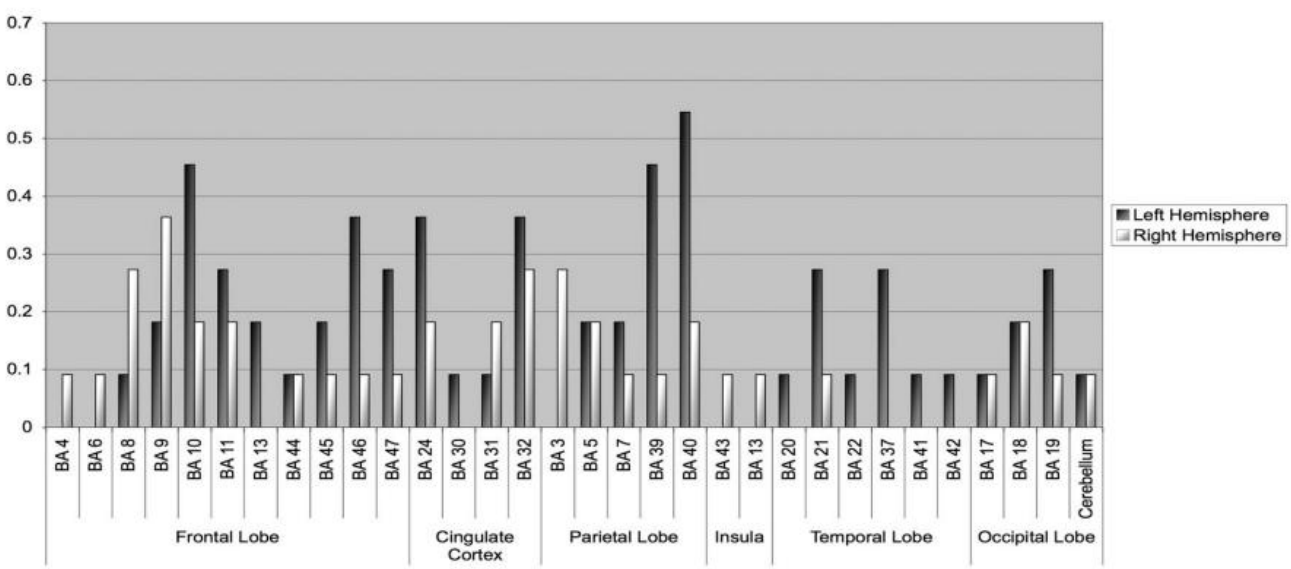


Fig. 1.4: Graphical representation of the proportion (Y-axis) of structural neuroimaging studies describing relationships between intelligence and/or reasoning and discrete Brodmann areas by lobe (X-axis) (Jung & Haier, 2007)

1.5. Eye movements during aesthetic viewing

Aesthetic viewing differs from reasoning tasks by lacking a goal orientation or a direct solution to a problem, or even a problem itself. Nevertheless, both domains still rely on selective attentional allocation and visual exploration organization, making aesthetic viewing particularly relevant for comparison with reasoning tasks. While the majority of eye-tracking studies exploring aesthetics have been done in marketing scenarios, there have been a few looking into visual aesthetic experiences. One such example is the work by Nayak and Karmakar (2019a), where they explored the bottom-up approach from different eye-tracking variables. Bottom-up approach in visual aesthetics deals with features of visual stimuli like color, novelty, form, texture, contrast, composition, order, and complexity, revealing subjects' perception during aesthetic experience. It was observed that the level of complexity and quality of composition of the visuals could be considered as well-accepted measures to judge the aesthetic experience and gives insight by affecting the viewing patterns (fig. 1.5). Building on this perspective, another review by the same authors later in the year (Nayak & Karmakar, 2019b) examined aesthetic experience from the visual scanning behavior of the human eye. Authors further argued that eye-tracking can be used to quantify the amount and variance of information present in visual stimuli, making gaze behavior closely related to perceptual complexity measures. Moreover, Mühlenbeck and colleagues (2016) compared two distinct human cultures with Orangutans in their viewing behaviour regarding symmetric and asymmetric patterns in two levels of complexity, and found that humans from both cultural groups fixated on symmetric patterns for longer periods of time regardless of stimuli complexity, while Orangutans did not clearly differentiate between the symmetricity of the pattern, but were much faster in processing the given image (both human groups rested on the symmetric pattern after short scanning time, unlike Orangutans who scanned the complete screen). The authors concluded that humans prefer well-ordered structures in visual processing tasks, with positive bias for symmetry.

Continuing on the topic, humans appear to favor organized distribution of informative elements within aesthetic stimuli, while fixation data plays an important role in identifying compositional structure (Nayak & Karmakar, 2019b). Locher (2006) found that center compositions of paintings were fixed more compared to the outer grid locations, and that aesthetic experience is generally a top-down process, where fixations increase with increased time in free viewing, signifying complex internal processes. Kapoula et al. (2009) explains this phenomenon that initial fixation on compositional axis of the painting helps focus gaze for exploration of the visual stimuli. To conclude, the findings from aesthetic eye-tracking research suggest that visual exploration during free-viewing is not random, but shaped by perceptual saliency, semantic interpretation, compositional organization and attentional guidance. central idea of the aesthetic experience is that the brain tries to reduce cognitive load by searching for meaningful patterns, which can be used to quantify aesthetic perception with the help of eye-tracking, as it provides insight into semantic understanding and visual attention patterns (Nayak & Karmakar, 2019b).

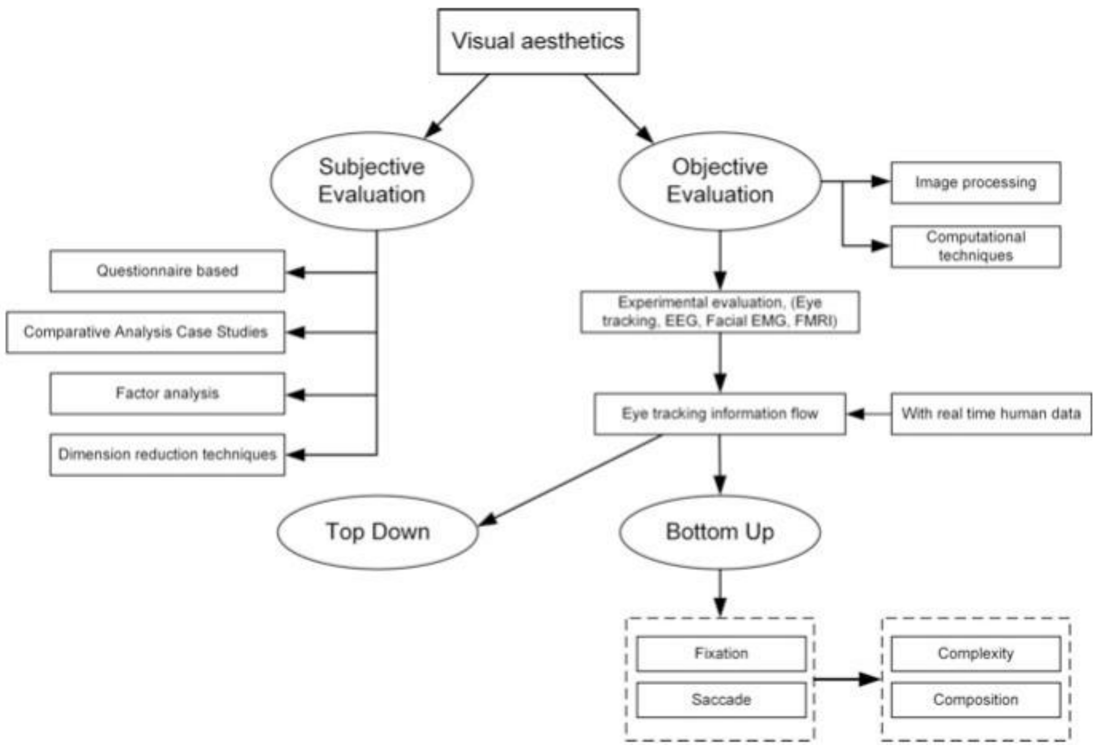


Fig. 1.5: Schematic diagram from review findings, showing the relationship between eye tracking variable and aesthetic variable during bottom-up information flow (Nayak & Karmakar, 2019a).

1.6.Stable exploration patterns across domains

Reasoning tasks differ from aesthetic viewing in substantial ways, although both appear to have specific ways that exploration, information sampling, and attention allocation are organized, also at an individual level (Just & Carpenter, 1980; Locher, 2006; Xue et al., 2017). Previous research suggest eye movement are able to reflect broader cognitive strategies in both task domains. Therefore, there is a real possibility that individuals would exhibit relatively stable tendencies in how they explore visually and how they organize information for different types of tasks. The gap in research lies precisely here as these domains are usually studied separately. Existing studies mainly focus on task-specific performance predictions or isolated aspects of visual cognition, while much less attention has been given to the crosstalk between visual exploration tendencies in fundamentally different task domains. In particular, there is very little known about how these manifestations of the processes crosstalk through the domains. Therefore, examining the patterns shown across these domains as well as inter- and intrapersonal stability of these features could provide interesting insight into the broader cognitive tendencies.

2. Methods

2.1. Participants

The participants were recruited utilizing an online questionnaire. All of them have signed and agreed to the informed consent form warning about possible mild eyestrain or mental fatigue due to screen-based tasks. All were volunteers and did not receive any monetary compensation, although they were offered to receive a summary of their personal experimental results. Demographic data was collected including participant age, sex, highest education level, study field (if one received higher education), occupational status and field (if the person is working). Additionally, subjects were asked to self-assess their engagement in logical and visual art activities, each on a scale*: 0 – Never; 1 – Rarely; 2 – Sometimes; 3 – Often; 4 – Very Often*. Exclusionary factors included visual impairments that cannot be corrected to normal by wearing glasses or contact lenses, and use of medication that would significantly impair attention, decision-making abilities, or eye movements. In addition – all participants had to complete a Cognitive Style Index questionnaire (CSI; Allinson & Heyes, 1996) to assess and group people based on their preferred way of gathering, processing, and evaluating data. CSI is comprised of 38 items, each of them having 'true', 'uncertain', and 'false' response options that correspond to a score of 0, 1 or 2, depending on polarity of the item. The interpretation of the scores exists on a spectrum with proximity to the maximum score of 76 indicating stronger 'analytical' tendencies, while scores closer to zero representing the more 'intuitive' respondent (Allinson & Heyes, 2012). To include a wider local population, the participants had an option to complete the questionnaire either in English or Lithuanian languages. The Lithuanian version was carefully translated from the original by the thesis author to not lose or change any context or meanings.

Twenty-five respondents were deemed suitable to continue with the further steps of the analysis. The largest proportion of the subjects (44 %) were in age group of 26 – 35 years old. The second largest group was 18 – 25-year-olds at 35 %, the remaining 21 % contained groups of 36 – 45 and 56 + year-olds. Age was not a primary variable in this research as the tested cognitive abilities show substantial individual difference stability across adult population (Breit et al. 2024). 68 % of participants were female, with the rest being male. Most respondents had reached higher education with 60 % having bachelor's, 28 % - master's degrees. There was also one person with a PhD and one with vocational education. 40 % had a degree in life sciences fields, another 40 % - in arts or humanitarian fields, and the rest either had miscellaneous field degrees or they did not note it at all. Due to incomplete eye-tracking recording, one participant was excluded from further analyses, resulting in final sample size of n = 24.

2.2.Hardware and software

The experiment was built relaying on SR Research software, utilizing ExperimentBuilder to prepare the procedure, EyeLink1000 to record eye-movements, and DataViewer to access and process the recorded data. EyeLink1000 camera recorded monocular eye-movements at a sample rate of 1000Hz. DataViewer was used in post-processing, creating areas-of-interest (AOIs) and creating reports of the recorded data.

2.3.Experimental environment

The experiment took place in a separate room where one participant at the time rested their head on a chinrest while sitting on a height-controlled chair. The monitor displaying the experiment was set up at 50 cm distance from the participant. The resolution of the display monitor was 1920 × 1080 pixels. To make sure the person could clearly see the display, a sample slide with the same font size and a similar painting was shown, and the participant had to confirm that they were seeing clearly and identify details in the image to continue with the experiment. In addition, monitor brightness settings were set according to the participant's preference to reduce squinting, eyestrain, and eye watering. The experimentation room had dim warm light, and the door was kept slightly ajar to observe and communicate with the subject if needed. The experimental procedure consisted of three blocks corresponding to the three tasks. Before each of them, the instructions were shown, and participants were asked to press any button on the keyboard to signify that they understood and wished to continue. If the participant had trouble understanding the task or had any questions, they could ask the attending experimenter in the adjacent room to clarify. A standard keyboard was set between the chinrest and monitor to select the answers. The participants were allowed to gesture or verbalize freely but were instructed not to obstruct the camera or the infrared light box. There were no time limits on the cognitive tasks, so they could take as long as needed.

2.4.Calibration and drift correction

Before the beginning of the experimental procedure, a calibration process took place. Automatic drift-correction was integrated into each trial recording. The camera was manually set up to obtain the optimal tracking of one eye, then calibration and validation procedures were repeated until acceptable eye tracking accuracy was achieved. Validation accuracy below 1° was considered acceptable, while higher error values required additional recalibration.

2.5. Experimental tasks and stimuli

2.5.1. Cognitive ability tasks

Two different tasks were used to assess non-verbal reasoning and record eye movements during the solving of the problems. Both tasks were obtained from the International Cognitive Ability Resource (ICAR), an open-source item bank offering well-validated cognitive assessment battery for researchers. It has been used in over 200 studies (Dworak et al. 2021) and the measures have been reviewed by external researchers, supporting their validity, especially for non-verbal ability measures (Young et al. 2025). The eye movements recorded during these tasks were later used to analyze visual exploration patterns and strategy-related problem-solving differences between participants.

2.5.2. Three-dimensional rotation task

The three-dimensional rotation task (R3D task) was used to assess visuospatial reasoning in participants. 30 items were presented to each of the subjects asking them to identify which of the presented cube renderings represented a possible rotation of the target stimulus, knowing that all six faces of the cube are presumed to be different. Example of the task is shown in Figure 2.5.1. The chosen items varied in difficulty based on ICAR normative statistics (M = 0.21, SD = 0.09, range = 0.09 – 0.39). The participants had to choose the most suitable answer by pressing a corresponding letter key on the keyboard. Choices A, B, C, E, F, G had different renderings of possible cube rotation choices with different faces on each side, while choice D signified that none of them could be a rotation of the target cube X, and choice H was "I do not know the solution". The task was self-paced, although reaction time from stimulus onset to response was recorded to calculate efficiency.

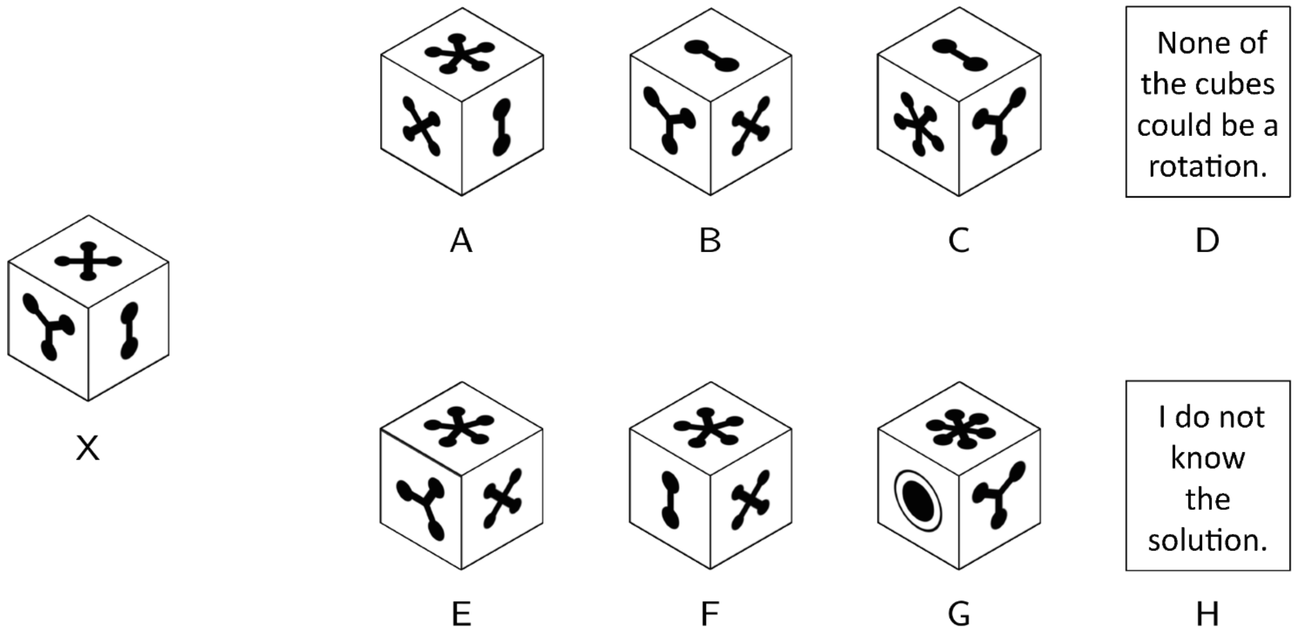


Figure 2.5.1. An example of three-dimensional mental rotation task trial used in the experiment.

2.5.3. Matrix reasoning task

Matrix reasoning (MR) was used to assess fluid and non-verbal abstract reasoning abilities. The participants were given 11 items, each consisting of 3 × 3 matrices with an array of geometric shapes, with one of the 9 being missing. They were asked which of the six response choices would best complete the stimulus. Example of the task is shown in Figure 2.5.2. The MR items varied in difficulty based on ICAR normative statistics (M = 0.46, SD = 0.16, range = 0.23 – 0.74). The task was self-paced, and timing was not limited.

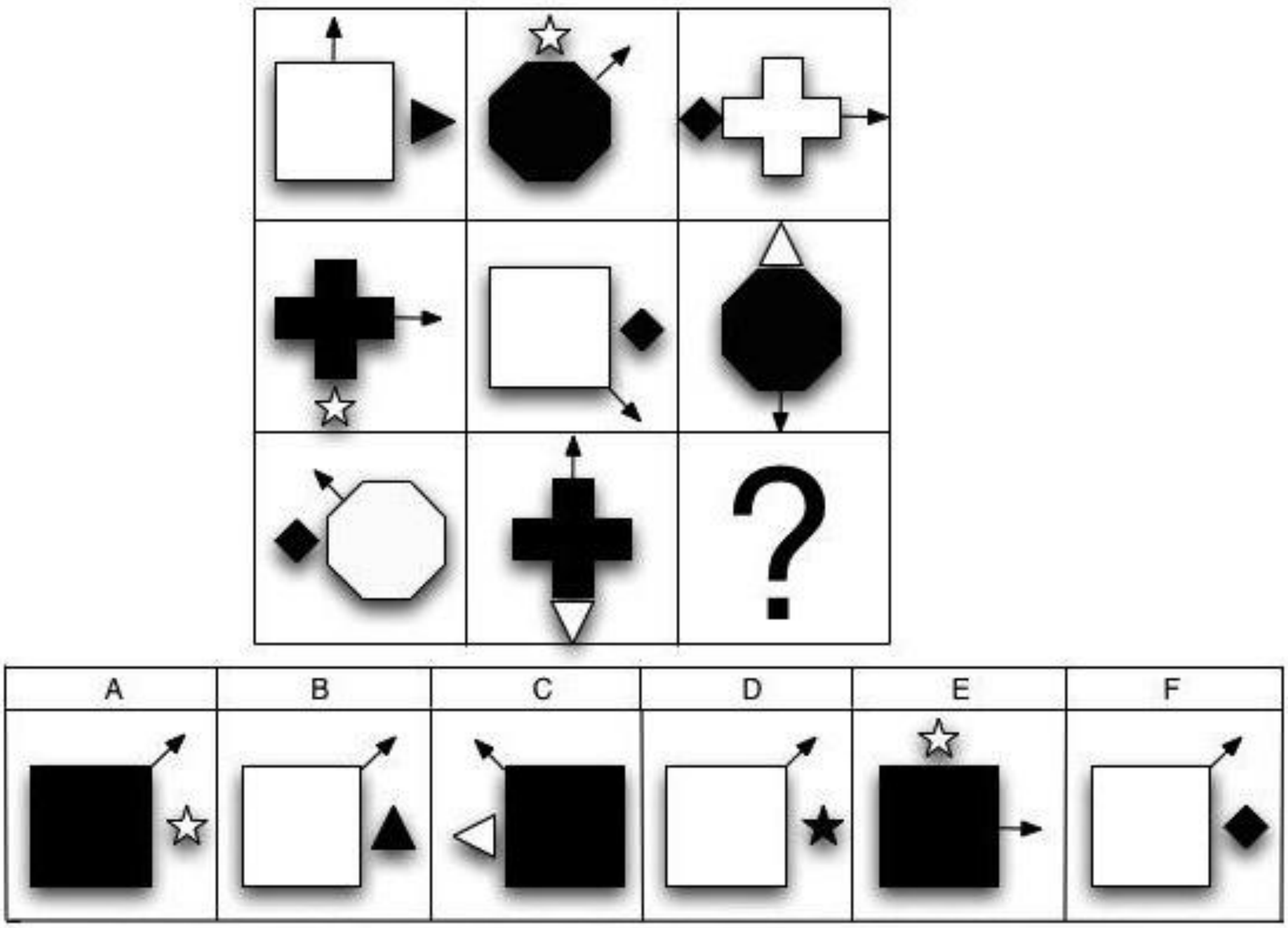


Figure 2.5.2. An example of the matrix reasoning task trial used in the experiment.

2.5.4. Aesthetic task

An aesthetic exploration task was conducted to analyze visual exploration. Unlike cognitive tasks, this one did not have objective rules or specific answers. The participants were instructed to look at a series of paintings as if they were in a gallery – freely and naturally, with no objective in mind. After these instructions ten paintings were shown in succession, each lasting 30 seconds. The stimuli were digital versions of paintings all downloaded from The Metropolitan Museum of Art, New York City collection web site (http://www.metmuseum.org/ accessed January 2026) listed in order of appearance in Table 2.1. and can be seen in Appendix A. The painting selection was primarily based on a study done by Lecher et al. 2007 where they also used "*Young Woman with a Water Pitcher*", "*The Harvesters*", "*Adoration of the Magi*", "*Olive Trees at Collioure*", and "*Under the Wave off Kanagawa*". Due to inaccessibility to high resolution images Leger's "*Woman with a Cat*" was changed to "*The Woman with a Child*" by the same artist, Klee's "*Temple Gardens*" was changed to "*Ad Parnassum*", and Marin's "*Brooklyn Bridge*" was changed to "*the Blind Girl*" to introduce higher variation in artistic styles. Two additional paintings were selected to broaden aesthetic variation from Wallraven et al. (2009) study, where "*The Angelus*" was rated as most aesthetically pleasing, and "*The Dinner at the Ball*", where it was rated as the most complex artwork by participants among 275 paintings. The aesthetic task was deliberately placed as last to reduce the task-oriented problem-solving behavior and encourage more natural visual exploration.

Table 2.1. A list of paintings shown for the aesthetic viewing task, listen in order of appearance.

No.	**Painting title**	**Artist**	**Year**	**Artistic style**
1	*The Angelus*	Jean-François Millet	1857	Realism
2	*The Dinner at the Ball*	Adolph von Menzel	1878	Realism
3	*The Blind Girl*	John Everett Millais	1856	Pre-Raphaelite
4	*The Woman and the Child*	Fernand Léger	1922	Cubism
5	*Ad Parnassum*	Paul Klee	1932	Modernism
6	*Young Woman with a Water Pitcher*	Johannes Vermeer	1660-1662	Dutch Golden Age
7	*The Harvesters*	Pieter Bruegel the Elder	1565	Northern Renaissance
8	*The Adoration of the Magi*	Giotto di Bondone	1320	Proto-Renaissance
9	*Olive Trees at Collioure*	Henri Matisse	1906	Fauvism
10	*Under the Wave off Kanagawa*	Katsushika Hokusai	1830-1832	Ukiyo-e

2.6.Areas of Interest

Areas of interest (AOIs) are the most focal point in this research as it defines the areas of the images the gaze is allocated to. Further analysis of strategies is mainly focused on manually predefined AOIs.

2.6.1. Mental rotation task AOIs

The structure of all 30 three-dimensional mental rotation task trials remains fairly stable, therefore, areas of interest are also stable, consisting only of two levels: primary and secondary. The first level incases the whole area of the cube in the shape of a square, occupying as much area to the sides as possible without intruding on other cube's areas. The second layer AOIs encompass the three different faces of the cubes visualized, going past the outlines of the cubes to account for possible minor errors of exact gaze fixation location. These were then indexed into functional AOIs of target cube (X) and answer options (A-H). The functional areas were then used to track comparison behavior, identify solving strategies, and observe how participants transition between target and response choices. An example of mental rotation task's AOIs can be seen in Figure 2.6.1.

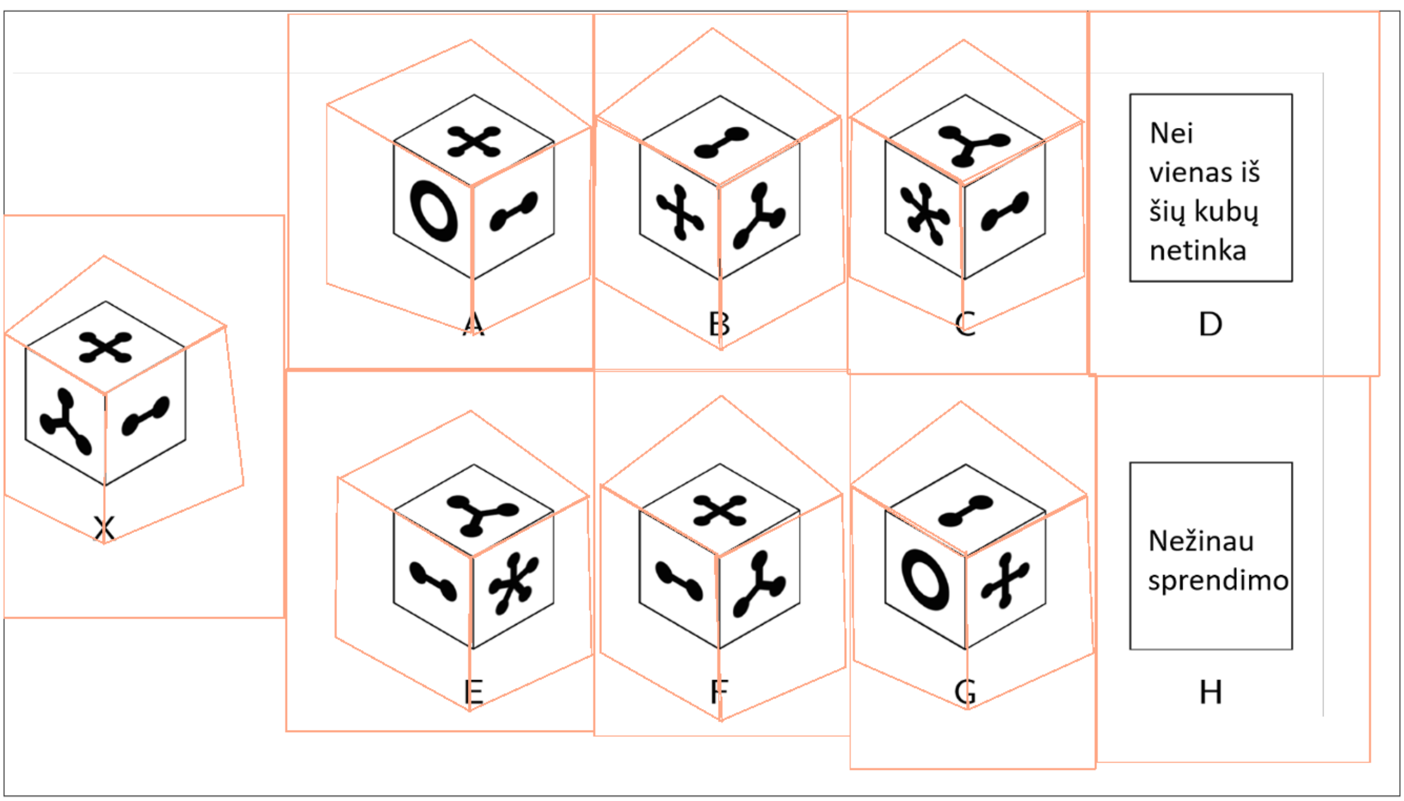


Figure. 2.6.1. Example of mental rotation task trial's AOIs: The orange square surrounding the whole cube area signifies primary AOI level, while smaller rectangles extending through the sides of the cube faces note the secondary level AOIs.

2.6.2. Matrix reasoning task AOIs

Although all matrix reasoning task trials hold stable basic structure, the geometrical shapes inside the matrices are completely different in most of the trials, therefore three layered AOI structure was created. The first functional layer consists of the whole area of the matrix or the area of the choices sheet, later used to separate reasoning and response-selection behaviors. The second layer encompassed the separate compartments of the matrix and of the choices sheet, with the purpose of analyzing scanning orders, systematic explorations, revisits, and comparison patterns. The third and most detailed AOI layer defines areas of the separate parts of the geometric shapes inside the matrix and choice boxes, this was done to investigate fine grade visual strategies. Again, the AOIs were made to go beyond the actual geometrical area to cover all possible fixation errors while keeping them from overlapping. The example of matrix reasoning AOIs used can be seen in Figure 2.6.2.

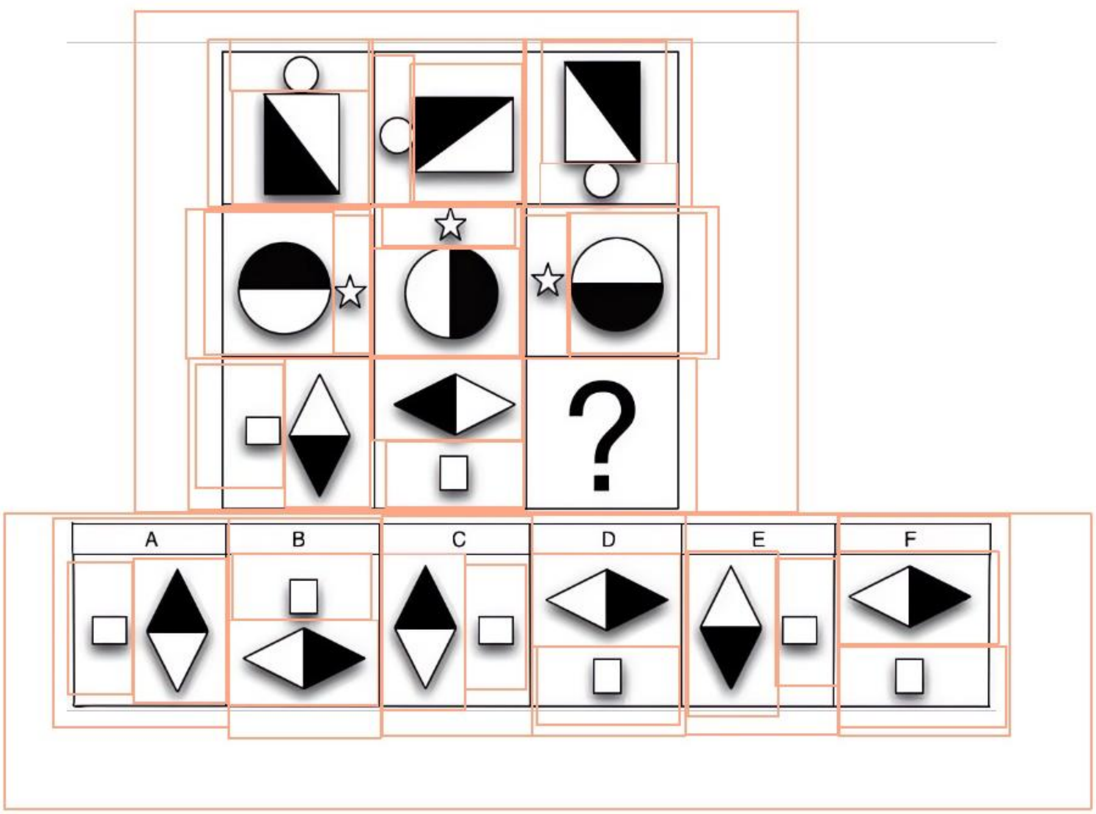


Figure 2.6.2. An example of matrix reasoning task AOIs.

2.6.3. Painting AOIs

Aesthetic task requires the most complex AOIs as all the 10 paintings used are vastly different in composition. Custom AOIs for every painting were drawn manually to encompass and name all the important details in the paintings. The first layer on every artwork was a 3 × 3 grid with a size corresponding to individual paintings dimensions. The further layers were semantic and vastly different, naming all areas that set out from others. These were then categorized into broader types based on semantic content and dominant visual meaning of said painting element, e.g.: level 2 AOIs with words like '*people*', '*man*', '*face*' fit in a semantic category of '***human***'; '*tree*', '*grass*', '*bush*' fit in a category of '***nature***'; '*building*', '*church*', '*wall*' fit in '***structure***'; '*tool*', '*cup'* or other non-living focal elements would fit in category '***object***'. These were used to categorize people based on which semantic categories they tend to shift their gaze to. An example of AOIs used for the aesthetic task in the experiment can be seen in Figure 2.6.3.

Figure. 2.6.3. Example of Painting viewing task AOIs. On the left: AOIs for Jean-François Millet's "*The Angelus*". On the right: AOIs for John Everett Millais' "*The Blind Girl*". A grid dividing the painting into nine parts can be seen, as well as semantic AOIs noted in color

2.7. Data analysis

2.7.1. Data preprocessing

Data reports from DataViewer were generated separately for fixation, saccade and AOI data. The raw data preprocessing was performed both in MS Excel (version 2508) and R/RStudio software (version 2025.05.0). The data was standardized, major inconsistencies were fixed, and trials were grouped in order into R3D (trials 1 – 30), MR (trials 31 – 41), and paintings (trials 42 – 51). Incomplete recordings were removed (n = 1), as well as fixations shorter than 80 ms, as such short fixations are generally considered to be insufficient for meaningful information processing. All variables were aggregated at participant level. Demographic information, CSI, spatial, fixation, saccade, and AOI metrics were computed for further analysis. In addition, manual data review was done to determine and fix noticeable inconsistencies.

2.7.2. Performance and efficiency measures

To evaluate the success of cognitive reasoning task performances among individual participants, measures including accuracy, response times, and combined efficiency were calculated. Accuracy scores were extracted as proportions of correct responses within each task. To allow better comparison between measures, normalized accuracy scores were computed using z-score standardization separately for each task. Additionally, item difficulty was considered: correctly solved items contributed proportionally according to their normative difficulty weights that were based on ICAR difficulty coefficients reported in their psychometric data. Response times (RT) were standardized for each participant using z-score transformations and in order to ensure faster response times contributing positively to performance efficiency, RT z-scores were inverted prior to further calculations. Efficiency scores were calculated as such:

$$Efficiency \ = z(Accuracy) - z(RT)$$

Higher efficiency scores reflect on more accurate task performance achieved within shorter time, while taking difficulty of the item into account. These measures were then used to evaluate trade-off tendencies between speed and accuracy across the different visual exploration strategy profiles.

2.7.3. Eye-tracking metrics

After initial preprocessing and excluding fixations shorter than 80 ms long, useful eye-tracking measures were calculated for each participant across tasks. Mean fixation duration along with its standard deviation were used to assess fixation behavior variabilities. In order to calculate gaze movement distances between fixations, mean saccade amplitudes (°) were calculated. To define spatial exploration, metrics like horizontal and vertical fixation spread, or dispersion of all fixation locations, were calculated as standard deviations of coordinates of fixations along vertical and horizontal axes (expressed as pixels), where higher spread values indicate broader visual exploration and vice versa. Additionally, AOI viewing time proportions were calculated based on dwell time within semantic and functional AOIs. These spatial exploration measures were calculated excluding saccadic movement periods, only utilizing fixation event metrics.

2.7.4. Strategy clustering

Participants were assigned strategic profiles based on their gaze behavior in different eye-tracking variables. Clustering was performed for all the tasks separately using k-means clustering. The different variables of which the grouping was performed on were fixation, saccade, spatial exploration, jump metrics and AOI proportions depending on the task. The resulting groups were interpreted behaviorally, and descriptive names were assigned.

2.7.5. Statistical analysis

All statistical analyses were performed in RStudio, firstly calculating descriptive statistics for behavioral and eye tracking variables. Prior to parametric analyses, variable distributions were inspected and assessed for normality using Shapiro-Wilk tests: here major participant-level variables did not significantly deviate from normality ($p > .05$), therefore parametric statistical analysis methods were considered appropriate. Pearson correlations were then used to analyze relationships between exploration metrics across all tasks. Groups differences were assessed utilizing independent samples t-tests and one-way ANOVA tests, confirming results with Tukey HSD post-hoc comparisons if applicable. To compare categorical variables chi-square tests were used. Furthermore, linear regression analyses were used to evaluate predictive relationships where fit. Cohen’s d effect sizes were calculated for selected group comparisons. K-means clustering was used to identify visual strategy groups across different tasks.

3. Results

3.1. Descriptive statistics and task differences

3.1.1. Participant level descriptive statistics

Descriptive statistics for participant-level behavioral and eye movement variables are presented in Table 3.1 Participants demonstrated higher average accuracy in the matrix reasoning task compared to the mental rotation task. Painting viewing behavior showed substantial inter-individual variability in spatial exploration measures, particularly in horizontal and vertical gaze jumps.

Table 3.1. Descriptive statistical measures for experimental tasks completed at participant level

Variable	Mean	SD	Min	Max
CSI	45.24	10.31	24	61
R3D accuracy	0.47	0.27	0.00	0.87
MR accuracy	0.75	0.19	0.27	1.00
R3D RT (ms)	50959.79	21101.99	14218.90	95235.60
MR RT (ms)	62899.47	28229.16	23445.64	137248.18
Painting vertical fixation spread	246.8	20.4	207.00	311.8
Painting horizontal fixation spread	319.50	23.30	272.60	369.60

3.2.4. Fixation behavior differences across task types

To examine visual fixation behavior differences across tasks, a one-way analysis of variance (ANOVA) was performed, where mean fixation duration was used as the dependent variable and task type (R3D, MR, and painting viewing) was considered as an independent variable. The analysis revealed that task type had a significant effect on average fixation duration ($F(2,71) = 62.02$, $p < .001$). Post hoc Tukey HSD comparison revealed that fixation durations during the aesthetic task were significantly longer than both reasoning tasks – mental rotation task (mean difference = 77.13 ms, $p <.001$) and matrix reasoning task (mean difference = 83.39 ms, $p < .001$). The same difference was not found in between the two cognitive tasks (mean difference = 6.26, $p = .737$). Overall, participants had reliably longer fixations while participating in the aesthetic viewing task, which generally lasted shorter in time, than solving the reasoning tasks. This suggests that aesthetic viewing elicits more sustained visual engagement, compared to the two reasoning tasks, which demonstrate relatively similar fixation duration patterns. Differences in fixation duration across tasks can be seen in Figure 3.1.

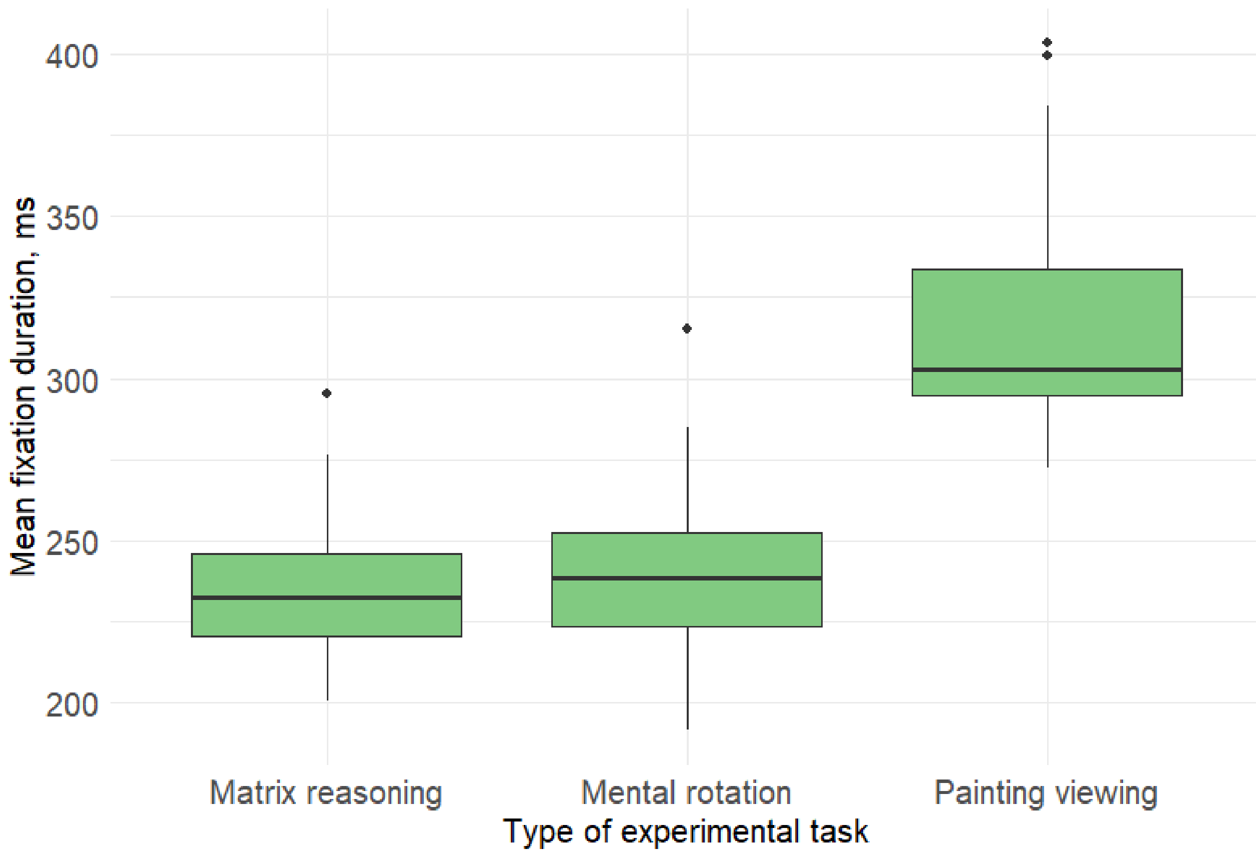


Figure 3.1. Distribution of fixation durations across experimental tasks. The boxes here represent interquartile ranges, the central horizontal lines represent median values, whiskers show distribution ranges (excluding outliers), dots highlight extreme values.

3.2.1. Task differences in saccadic behavior

Mean saccade amplitude was used as a dependent variable and task type as independent variable in ANOVA analysis to determine if saccadic eye movement behavior differed across task types.

Significant effect of task type on saccade amplitude was revealed ($F(2, 71) = 135.40$, $p < .001$). Post hoc Tukey HSD analysis showed that mental rotation task produced significantly larger saccade amplitudes than both matrix reasoning (mean difference = 2.11, $p < .001$) and painting viewing (mean difference = 2.24, $p < .001$) conditions. No significant differences were observed between saccade amplitudes on both latter tasks (mean difference = -0.12, $p = .706$). To conclude – the mental rotation task elicited significantly broader gaze shifts through the whole visual display compared to the other task types, suggesting an increase of visual scanning behavior between spatially separated elements in the task design. Differences of mean saccade amplitude across experimental tasks can be seen in Figure 3.2.

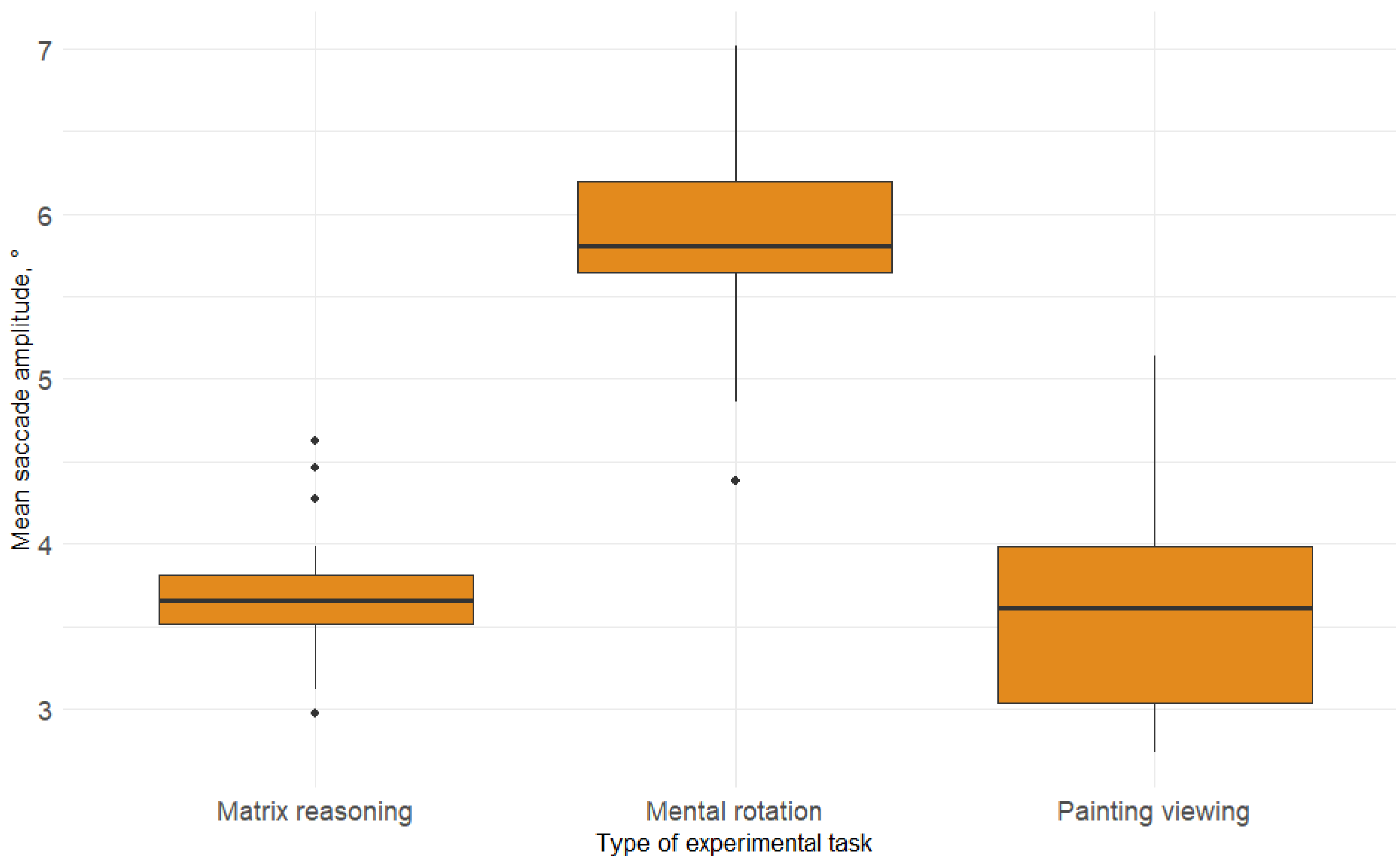


Figure 3.2. Distribution of mean saccade amplitudes across experimental tasks.

3.3. Strategy clustering across tasks

The goal of the thesis requires identifying, naming, and characterizing visual exploration patterns across tasks and individuals. To reach this goal, k-means clustering analyses were conducted separately for all three tasks. The clustering was based on eye-movement and exploration-related variables from fixation, saccade, and AOI measures. Distinct strategic profiles were identified within each task, although the distribution of these profiles was not equally spread among participants, creating more dominant and more rear mental strategic profiles. Taking the small sample size into account, the definitive generalization of the smaller group's characteristics should be done with caution.

3.3.1. Strategies for solving mental rotation tasks

Three visual exploration strategies were classified for mental rotation tasks and were given names: *Chaotic explorer* (n = 2), *Focused heuristic* (n = 5) and *Systematic verifier* (n = 17). The most abundant strategic profile, the *Systematic verifier*, was set apart by comparatively structured and highly repetitive visual comparison behavior between the reference and response stimuli. The second largest group, the *Focused heuristic* profile, was characterized by more selective inspection strategies, likely rapidly evaluating prominent response options. The rarest of the profiles, the *Chaotic explorer*, was defined by more broad and less structured visual exploration patterns of the stimulus. All the metrics have been standardized for the sample and can the differences between groups can be seen in Figure 3.3, and transition networks further illustrate distinct problem-solving gaze patterns (Figure 3.3). Systematic verifier profile demonstrated most frequent transitions between reference cube and multiple response options, signifying verifying behavior with systematic option comparison, whereas Focused heuristic group showed more selective transitions between fewer options. Chaotic explorer, on the other hand, showed overall lack of structure in exploration behavior.

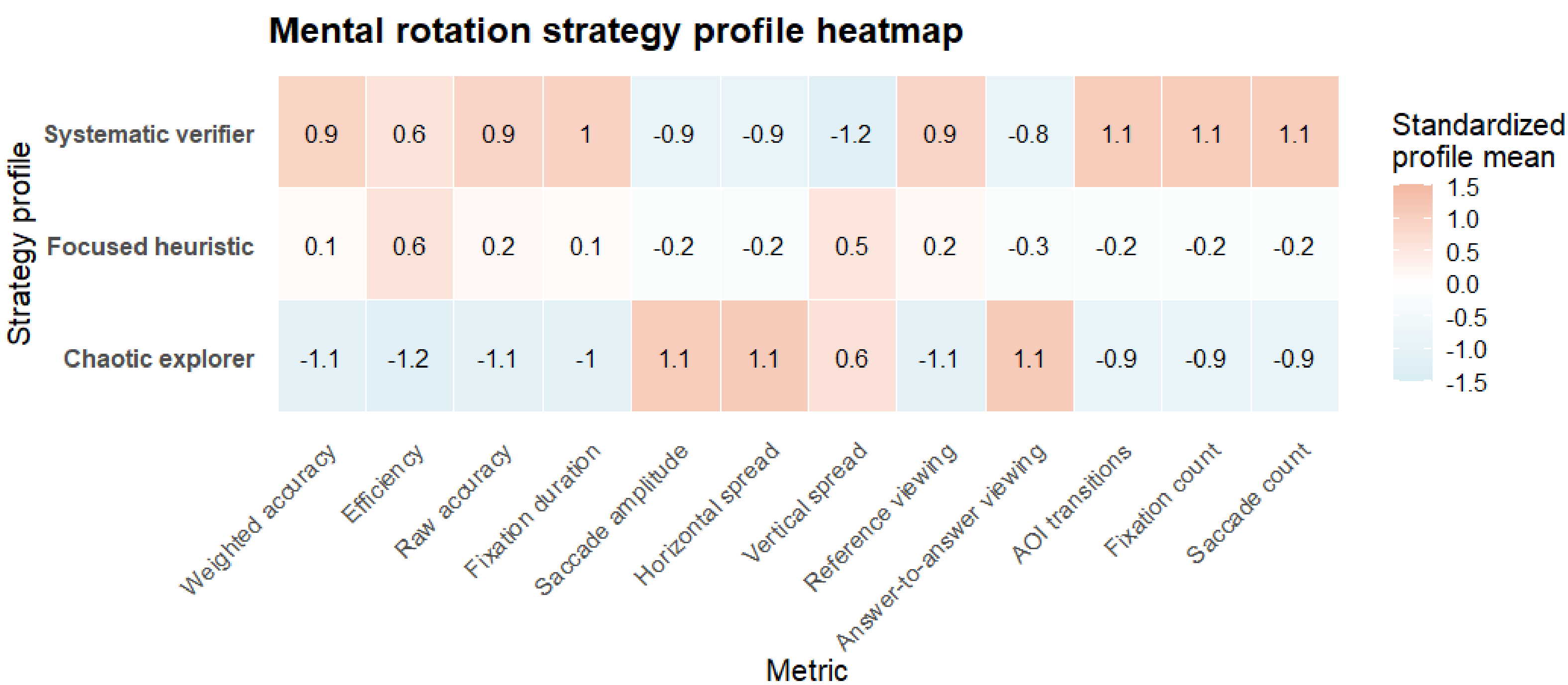


Figure 3.3. Heatmap of standardized eye-movement and performance measures across mental rotation strategy profiles. Warmer colors indicate above-average values within a profile, whereas cooler colors indicate below-average values. The Systematic verifier profile demonstrated higher accuracy, efficiency, fixation duration, AOI transitions, and reference viewing proportions, while the Chaotic explorer profile showed broader exploration and larger saccade amplitudes. The Focused heuristic profile displayed narrower and more selective exploration patterns with reduced verification behavior.

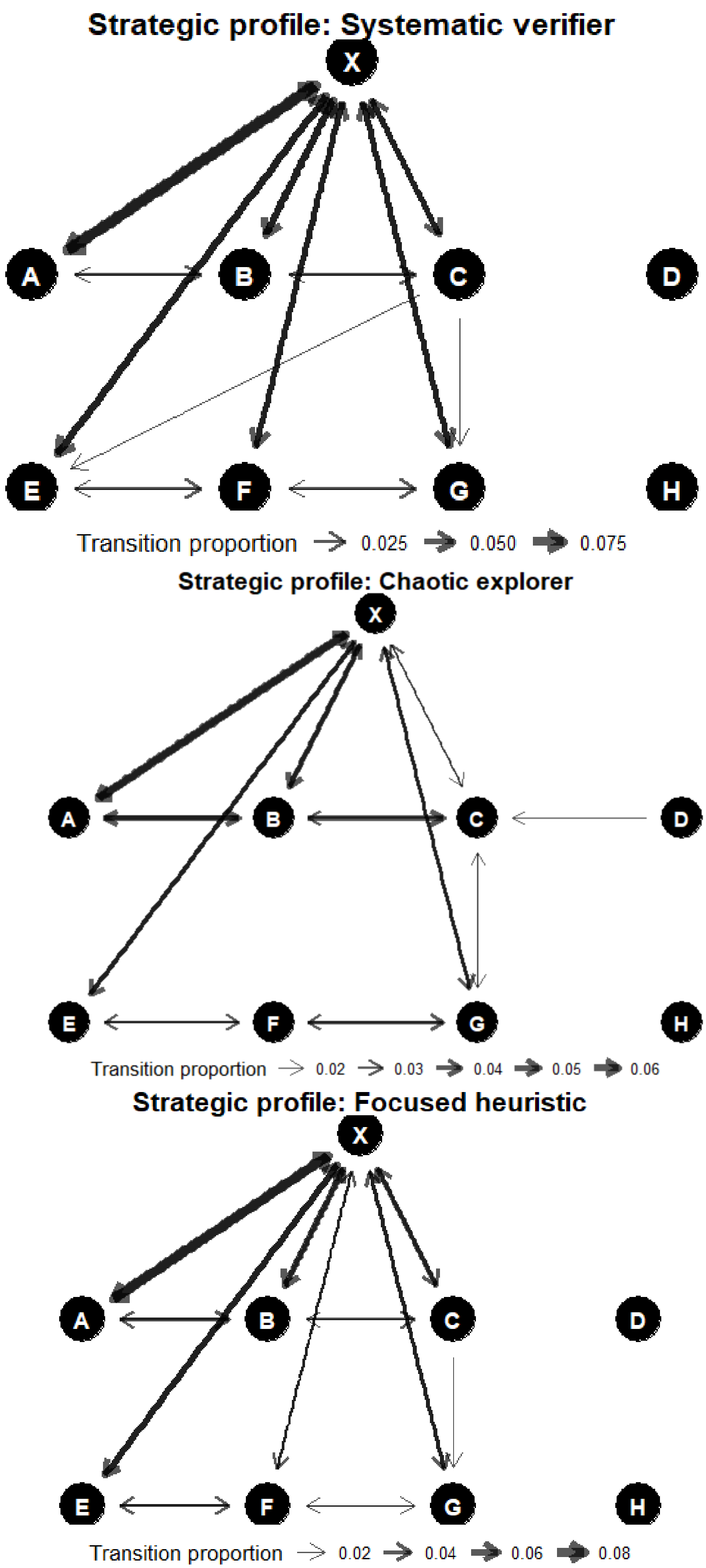


Figure 3.4. Transition networks representing mean gaze shifts between mental rotation AOIs across mental rotation strategic groups. Nodes show the reference stimulus (X) and response alternatives (A-H). Arrow thickness show the relative proportion of gaze transitions between AOIs.

3.3.2. Strategies for solving matrix reasoning tasks

Three distinct exploration profiles were also identified in ways of solving the matrix reasoning tasks: *Exhaustive eliminator* (n = 10), *Analytical verifier* (n = 9), and *Focused heuristic* (n = 5). The *Exhaustive eliminator* strategy profile was characterized by broad and extensive exploration patterns, which suggest sequential elimination of incorrect alternatives, whereas those fitting in the *Analytical verifier* strategic profile demonstrated systematic inspection of the items and repeated verification of both the matrix elements and the response options. The smallest profile group, the *Focused heuristic*, had behavior that was characterized by more selective visual processing and little overall exploration. To illustrate the broader tendencies associated with the MR profiles, both standardized heatmaps (Figure 3.5) and network diagrams (Figure 3.6) were examined to allow broader interpretation of the overall patterns on visual exploration.

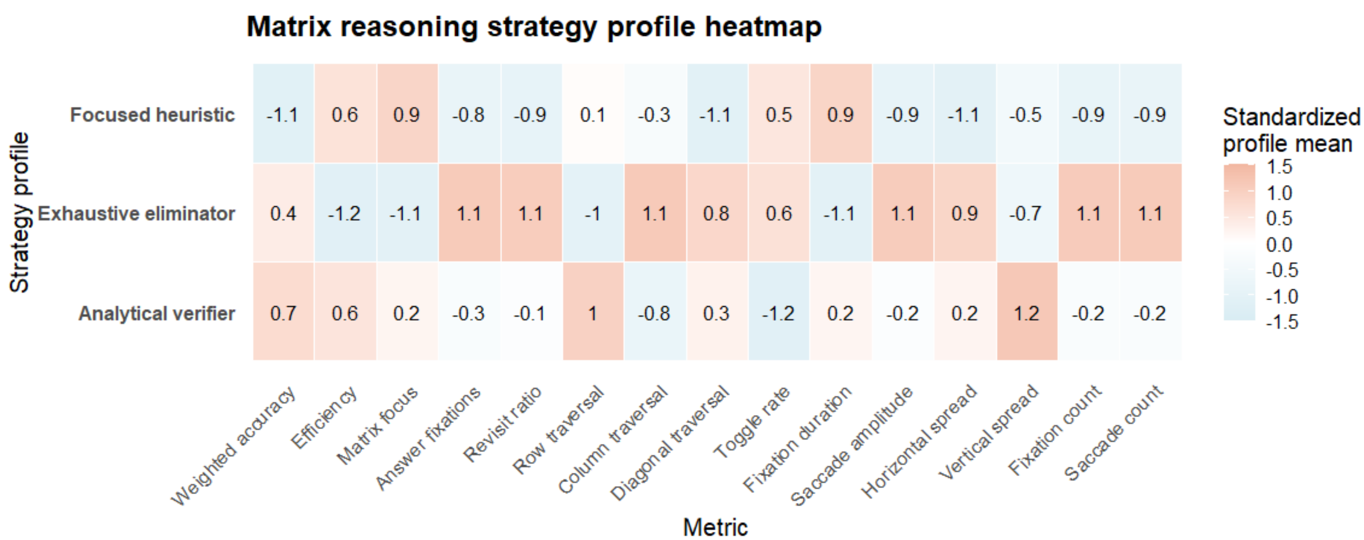


Figure 3.5. Heatmap of standardized eye-movement and performance measures across matrix reasoning strategy profiles. Warmer colors indicate above-average values within a profile, whereas cooler colors indicate below-average values. The Analytical verifier profile demonstrated higher accuracy and efficiency with more systematic verification behavior, while the Exhaustive eliminator profile showed broader and more repetitive exploration patterns. The Focused heuristic profile displayed narrower and faster information sampling with reduced exploration and lower overall accuracy.

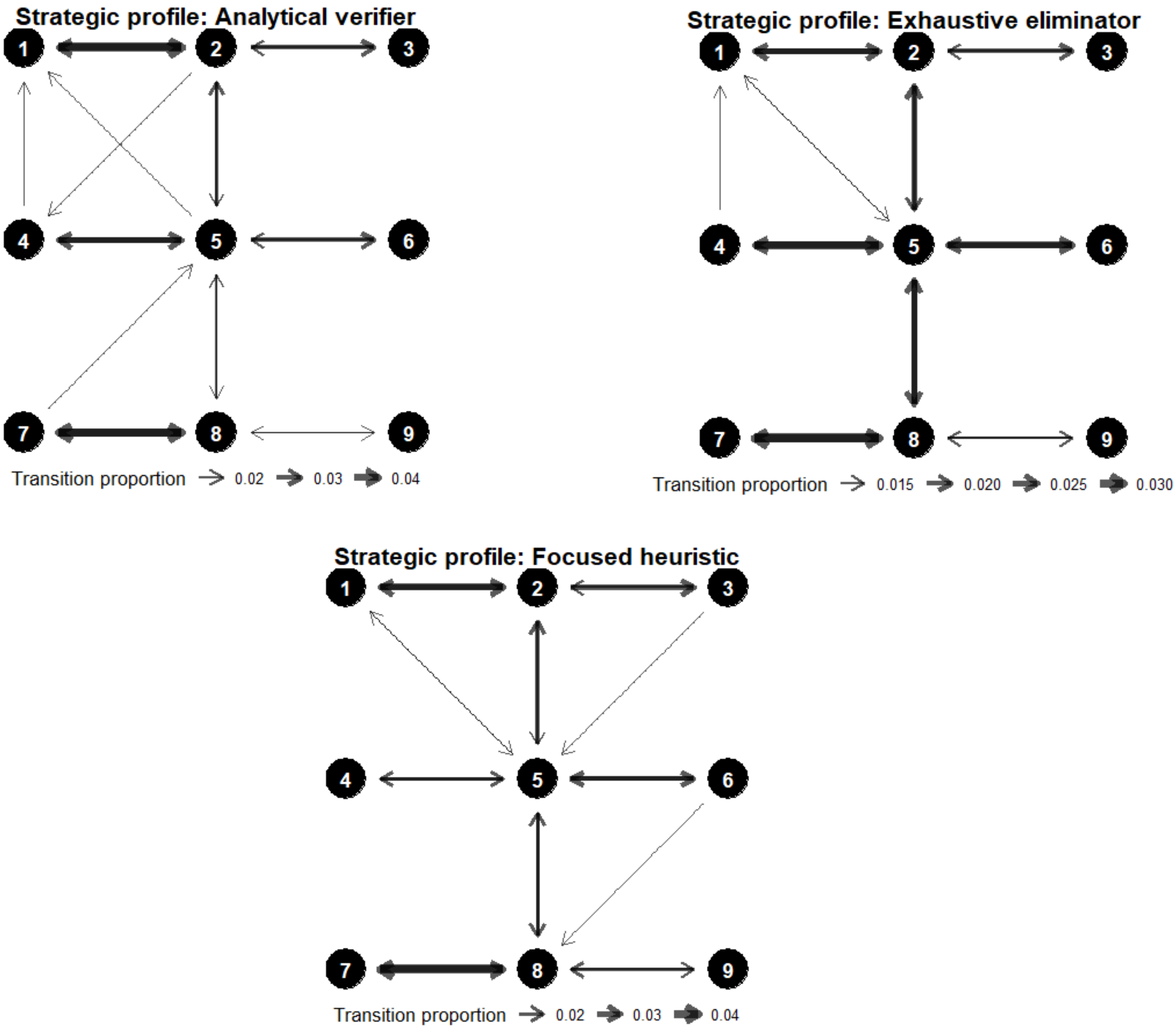


Figure 3.6. Transition diagrams of matrix reasoning strategy profiles based on AOI transition proportions between matrix regions. Thicker arrows represent more frequent gaze transitions. The Analytical verifier profile demonstrated structured comparison behavior, the Exhaustive eliminator profile showed broader repetitive scanning, while the Focused heuristic profile displayed narrower and more selective exploration patterns.

3.3.3. Painting viewing strategies

The participants differed in their way of exploring art, thus creating two dominant strategies – *Central integrative viewer* (n = 12) and *Exploratory contextual scanner* (n = 10), with one smaller group of *Global compositional explorer* (n = 2) emerging as well. The *Central integrative viewer* profile was set apart by relatively concentrated visual attention towards central and the most prominent regions of the paintings, while participants classified as *Exploratory contextual scanners* showed broader exploration behavior and frequently transitioning across multiple regions of the paintings. The least abundant profile – the *Global compositional explorers* – exhibited the broadest exploration behavior with extensive scanning across large areas of the visual composition. A heat-map of standardized painting viewing- strategy metrics can be seen in Figure 3.7. Transition network images could not be made as the amount of AOIs make it uninformative, although the sequencing data was still analyzed mathematically

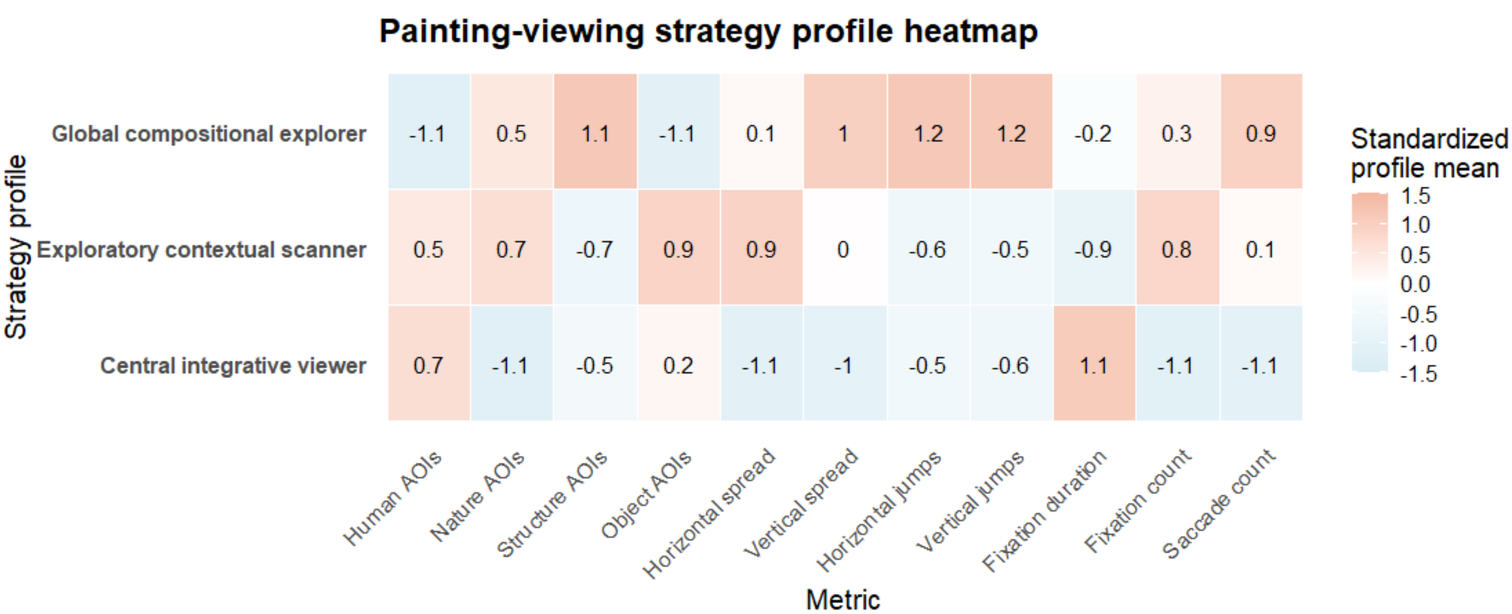


Figure 3.7. Heatmap of standardized eye-movement and AOI viewing measures across painting-viewing strategy profiles. Warmer colors indicate above-average values within a profile, whereas cooler colors indicate below-average values. The Global compositional explorer profile demonstrated broader exploration and increased viewing of structural AOIs, while the Central integrative viewer profile showed stronger fixation on human AOIs and narrower exploration patterns. The Exploratory contextual scanner profile displayed broader object-focused contextual exploration behavior.

3.4.Profile summaries

Strategic profiles were defined and main characteristics with possible behavioral interpretations are summarized in Table X. Profiles with very small participant numbers should be interpreted cautiously.

Table 3.2. A summary of all defined strategic profiles and their features across the different tasks

Task	Strategy profile	n	Characteristic eye-movement patterns	AOI attention tendencies	Performance characteristics	Behavioral interpretation
R3D	Systematic verifier	17	Highly structured, systematic scanning; repetitive reference-response comparison	Longer proportional viewing time directed to reference stimulus and response options	Highest accuracy with high efficiency	Careful, methodical reasoning strategy based on verification of all options
	Focused heuristic	5	Inspection of most visually prominent and relevant areas; reduced scanning	Attention concentrated on limited number of responses	Moderate accuracy, high efficiency	Fast, heuristic-based evaluations. Speed prioritization. High confidence.
	Chaotic explorer	2	Less structured, highly variable exploration across the whole stimulus	Unstable viewing allocation to response regions	Lowest accuracy and efficiency	Disorganized, highly exploratory strategy with ineffective problem solving

Table 3.2 (Continued). A summary of all defined strategic profiles and their features across the different tasks

Task	Strategy profile	n	Characteristic eye-movement patterns	AOI attention tendencies	Performance characteristics	Behavioral interpretation
MR	Analytic verifier	9	Repeated inspection of both matrix and answer alternatives; highly structured verification behavior	Balanced attention allocation to both matrix regions and answer options	Highest accuracy with high efficiency	Careful and analytical reasoning with repeated verification
	Exhaustive eliminator	10	Extensive inspection of matrix regions followed by eliminatory scanning of response alternatives	Distributed viewing allocation across multiple matrix and answer regions	Relatively accurate, yet less efficient	Thorough and elimination-based strategy
	Focused heuristic	5	Highly selective inspection of limited matrix and answer regions	Reduced attention to matrix components	Less accurate yet faster performance	Heuristic strategy with an emphasis on rapid elimination over exhaustive analysis

Table 3.2 (Continued). A summary of all defined strategic profiles and their features across the different tasks

Task	Strategy profile	n	Characteristic eye-movement patterns	AOI attention tendencies	Performance characteristics	Behavioral interpretation
Painting viewing	Central integrative viewer	12	Concentrated viewing focusing on central and semantically prominent regions	Highest attention towards human AOIs	Most focused and stable exploration behavior	Stable viewing of center and most prominent elements
	Exploratory contextual scanner	10	Frequent transitions distributed across multiple compositional areas	More evenly distributed semantic AOI viewing behavior	Intermediate exploration width across paintings	Context-oriented, flexible exploratory viewing
	Global compositional explorer	2	Extensive scanning across large compositional regions and the whole painting surface	Lowest proportional time directed towards human AOIs	Broadest overall spatial exploration	Exploration of the whole global composition prioritizing overall visual structure rather than isolated semantic details

3.5.Strategic differences in visual exploration

3.5.1. Horizontal exploration differences across aesthetic viewing

To examine whether painting viewing strategies differed in horizontal visual exploration behavior, a one-way analysis of variance (ANOVA) was done by using horizontal gaze jump distance measurements as the dependent variable and painting viewing strategy as an independent variable, revealing a significant effect on horizontal gaze jumps ($F(2,21) = 14.51$, $p < .001$). Horizontal gaze jump distance, or in other words horizontal fixation transition distance, represents an average horizontal distance between two consecutive fixations. Differences between painting viewing strategy profiles in this measure can be seen in Figure 3.7. The larger values represent broader horizontal exploration of recorded visual fields. Post hoc Tukey HSD comparison showed that the *Global compositional explorer* strategy exhibited significantly larger horizontal jumps, compared to both the *Central integrative viewer* ($p < .001$) and *Exploratory conceptual scanners* ($p < .001$). These findings indicate that the *Global compositional explorers* scan significantly more across the horizontal axis across all paintings. No significant differences were found between the Central integrative viewers and Exploratory contextual scanners ($p = .898$). Overall, the differences in the width of horizontal viewing of paintings support the validity of such profiling, although the small sample size calls for additional caution in interpreting the given results.

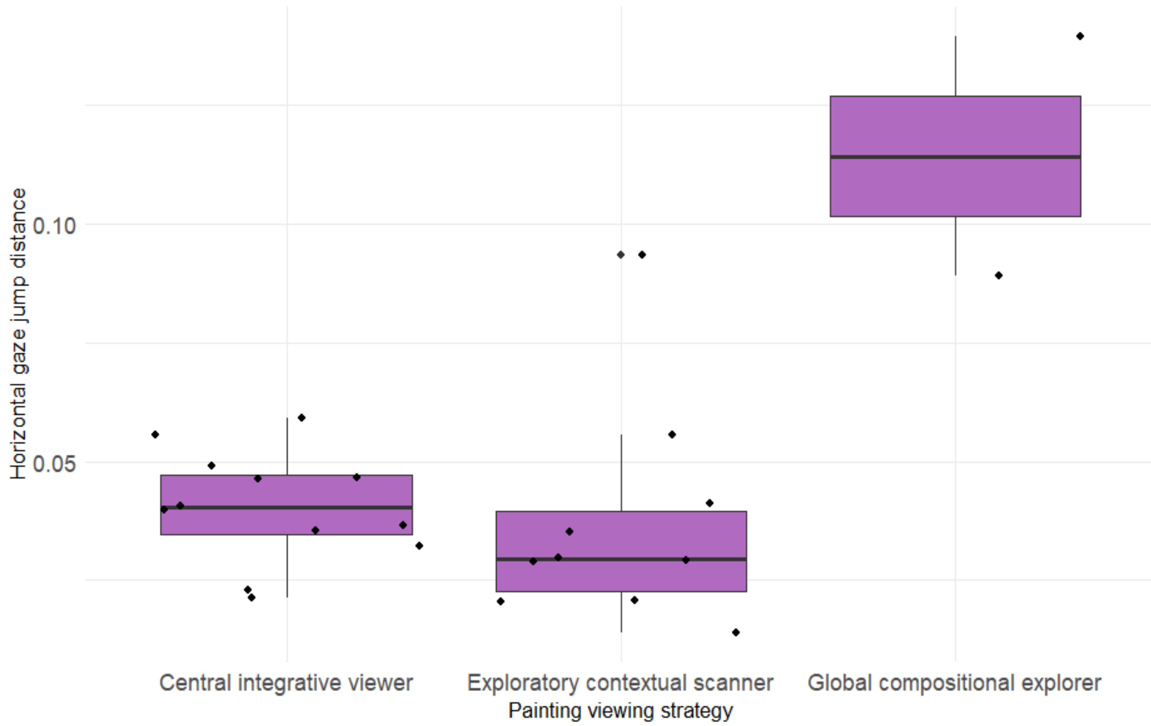


Figure 3.7. Differences in horizontal gaze jump distances (relative coordinate distance between consecutive coordinates) across the distinctive painting viewing strategic profiles.

4.3.2. Vertical exploration differences across painting strategies

The profiles of viewing the paintings also significantly differed in vertical axis exploration, measured by vertical fixation spread ($F(2,21) = 5.34$, $p = .013$). Participants classified as *Global compositional* explorers demonstrated broader vertical exploration patterns compared to the other aesthetic viewing strategy groups, revealing more extensive scanning across vertically distributed compositional regions of the artworks. These findings further support the presence of distinct stable visual exploration patterns during aesthetic viewing. Differences in vertical gaze jump distances between the groups can be seen in Figure 3.8.

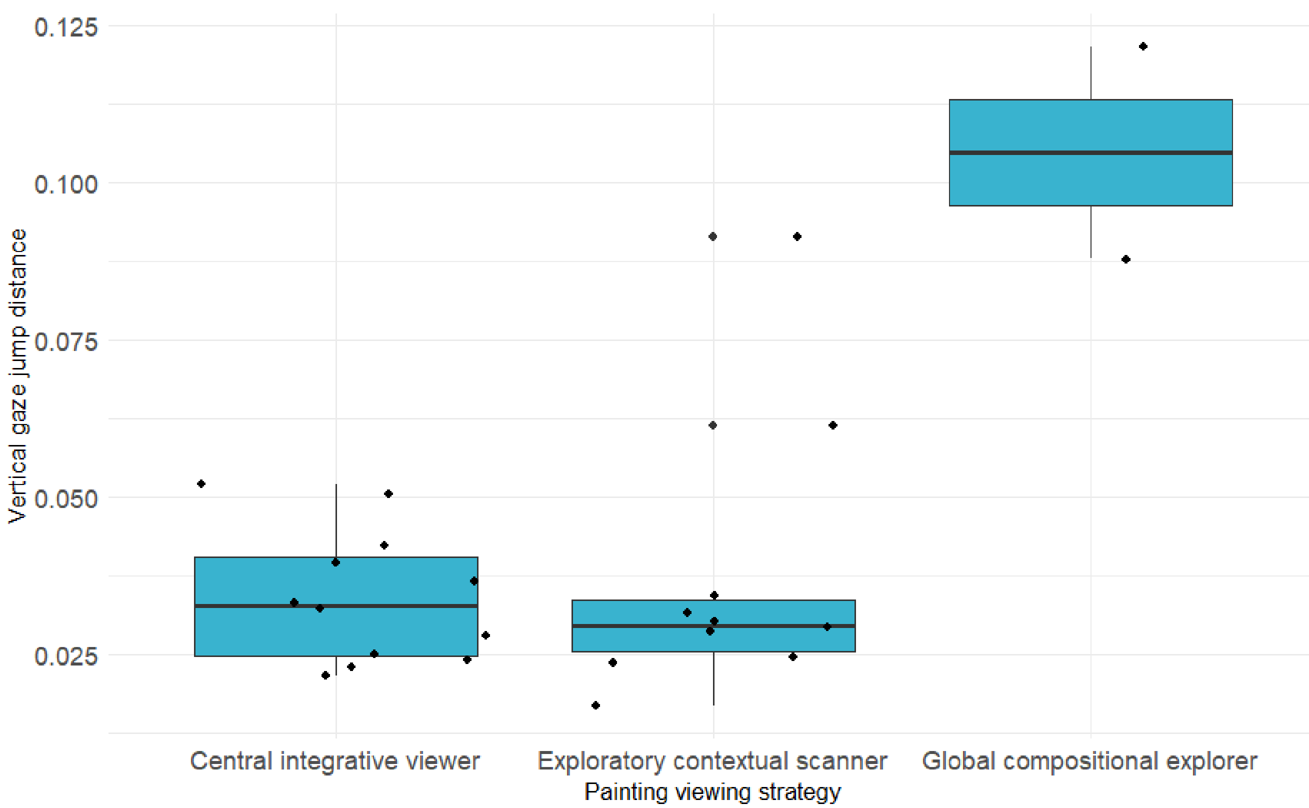


Figure 3.8. Differences in vertical gaze jump distances (relative coordinate distance between consecutive coordinates) across the distinctive painting viewing strategic profiles.

3.5.2. Painting AOI preferences across viewing profiles

To further characterize the identified painting-viewing strategies, the proportional viewing time directed towards the previously defined semantic AOI categories was examined. Prior to statistical analysis AOI viewing proportions and exploration measures were averaged across all paintings. Significant differences were found between the painting viewing behavior strategies and human-focused viewing behavior ($F(2,21) = 11.30$, $p < .001$). Post hoc Tukey HSD comparisons revealed a tendency of those participants fitting the *Global compositional explorer* profile to spend significantly less viewing time directed towards human AOIs compared to both the *Central integrative viewer* ($p < .001$) and *Exploratory conceptual scanner* ($p = .001$) profiles. All in all, *Global compositional explorers* exhibited the lowest proportional viewing time towards human elements within the paintings, which set them apart from the other strategic groups, however it is important to mention that the profile included only two participants during this study, therefore this part of the results should be interpreted cautiously. It was found that across all participants, greater proportion of viewing time directed towards human AOIs was associated with lower horizontal ($r = .61$, $p = .002$) and lower vertical ($r= .59$, $p = .002$) exploration spread, indicating that participants who tended to focus more on human elements exhibited less broad visual exploration across the paintings. Meanwhile, other semantic painting AOI categories, like nature, structural, or object-related areas, were not shown to exhibit significant relationship to the painting viewing strategic profiles. However, proportional viewing time directed towards structural elements had a positive association with fixation duration ($r = .49$, $p = .016$). This suggests that architectural or compositional features in paintings do elicit a stand-out prolonged inspection of said elements. Together, these findings mark that the created aesthetic viewing strategic profiles have not only the eye-movement measurement differences but also the distinctions in semantic attention allocation during aesthetic viewing. The differences between attention directed towards different semantic AOI categories across the mentioned profiles can be seen in Figure 3.9.

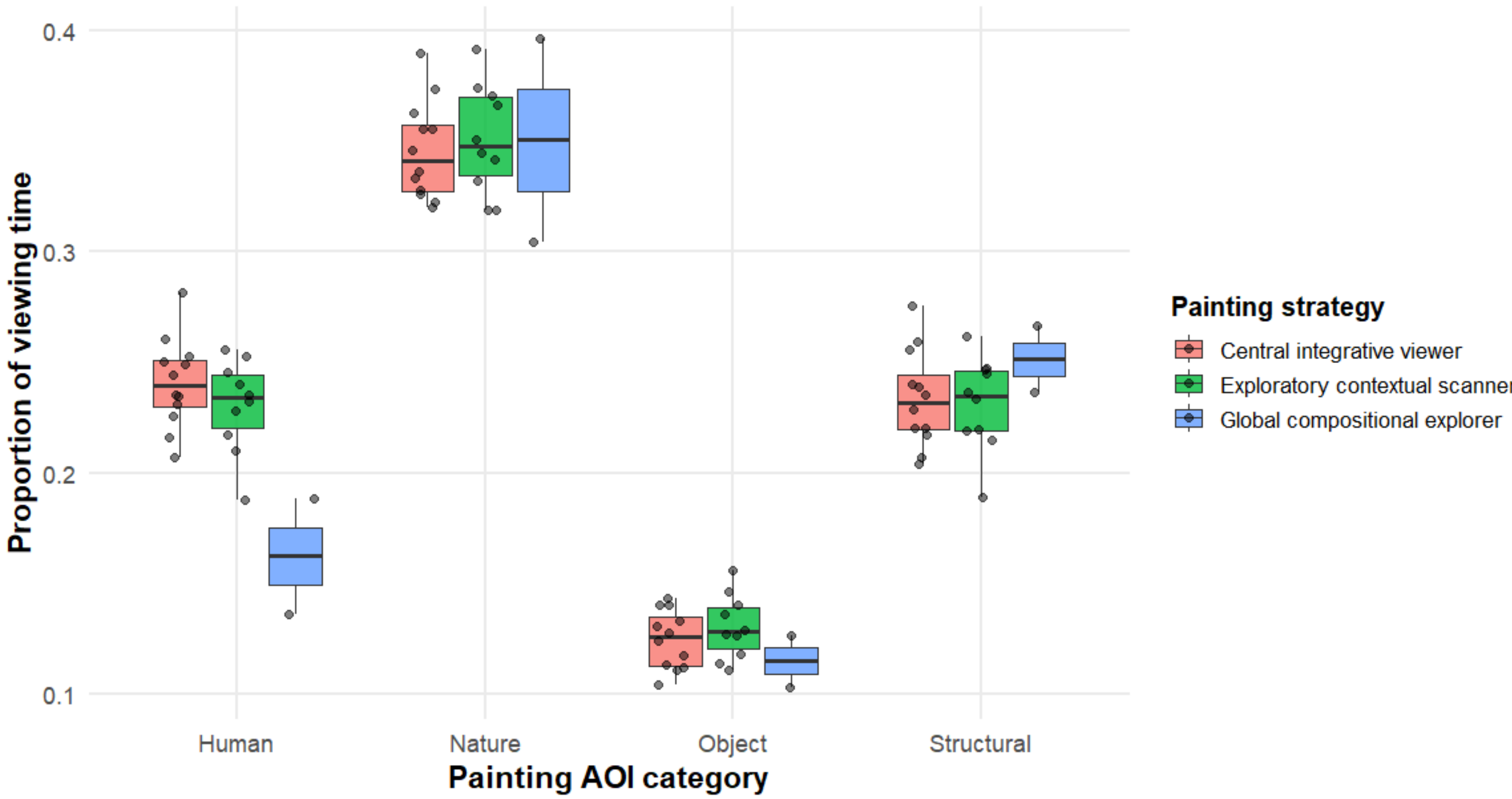


Figure 3.9. Differences in time allocated to viewing different AOIs between the different painting viewing strategies.

3.5.3. Strategic profiles and task performance

Task performance measures were compared across strategy groups within reasoning tasks in order to evaluate the cognitive relevance of the identified visual exploration profiles. Significant differences were observed in the mental rotation task within the normalized accuracy measures and visual exploration strategic profiles ($F(2.21) = 6.69$, $p = 0.006$). The participants fitting the *Systematic verifier* profile were the highest scoring ones, while the *Focused heuristic* approach, and particularly the *Chaotic explorer* groups exhibited substantially lower accuracy rates, suggesting that repetitive and structured approaches with repetitive comparisons support successful mental rotation performance. The efficiency of solving R3D task did not differ significantly, although a trend was observed with quite high effect ($F(2.21) = 2.71$, $p = .09$). That said, the *Focused heuristic* and *Systematic verifier* groups were observed to have comparable efficiency values despite differences in accuracy levels, potentially reflecting differences in a tradeoff between speed and accuracy in these strategies. Differences in the accuracy of solving mental rotation problems can be seen in Figure 3.10.

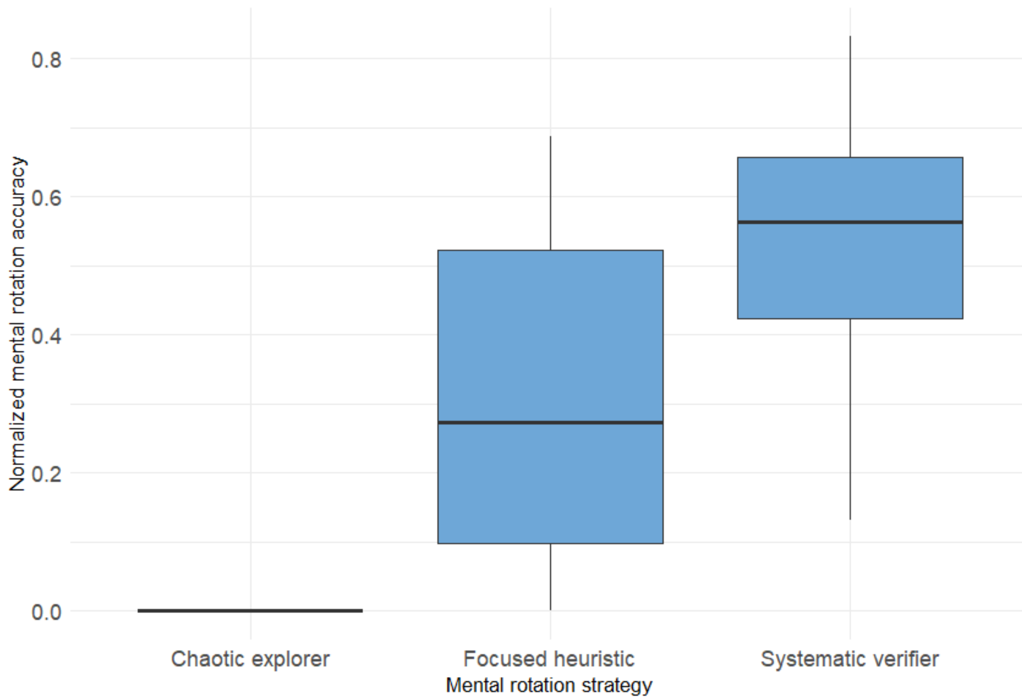


Figure 3.10. Differences in normalized accuracy of mental rotation task across the mental rotation strategic profiles. Note: all participants classified as Chaotic explorers failed to successfully solve any trial in the task

The results of matrix task normalized accuracy scores comparison within observed strategic groups yielded no significant differences ($F(2.21) = 2.11$, $p = .146$), however the differences in this task lay in efficiency across different visual exploration profiles ($F(2.21) = 5.90$, $p = .009$). Tukey HSD comparisons revealed that those in the Exhaustive eliminator group demonstrated significantly lower efficiency compared to both Analytical verifiers ($p = .015$) and also - Focused heuristic ($p = .040$) groups. There were no significant differences in efficiency measures between the latter two profiles ($p = .999$). In solving this task, the *Analytical verifier* profile demonstrated the highest accuracy and high efficiency levels, whereas the *Exhaustive eliminators* showed relatively strong accuracy, yet lower efficiency levels, suggesting the latter elimination-based solving strategy to be more time-consuming. In contrast, the *Focused heuristic* strategic profile demonstrated lower accuracy despite relatively high efficiency values. The differences in efficiency of solving the matrix reasoning task across the different strategic profiles can be seen in Figure 3.11.

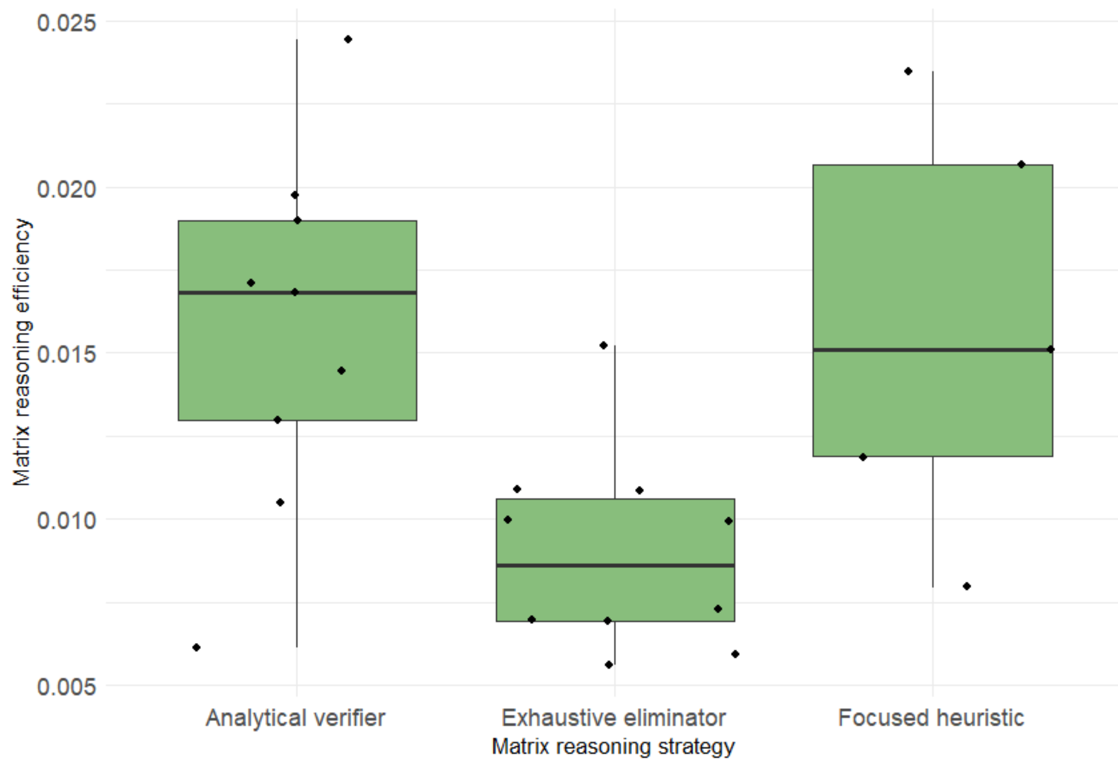


Figure 3.11. Efficiency of solving matrix reasoning task differences across the distinct matrix reasoning strategic profiles.

Together, these findings indicate that more systematically organized visual exploration strategies in solving logical problems were associated with more successful reasoning-task performance, while more heuristic based strategies appear to favor efficiency over accuracy.

In addition, to examine whether the identified cognitive strategic profiles differed in lower-level oculomotor characteristics like fixation durations or saccade amplitudes, an ANOVA test was conducted, although it yielded no significant results. Significant differences in matrix rotation task were not found neither in mean fixation duration ($F(2,21) = 0.11$, $p = .901$) nor mean saccade amplitude ($F(2,21) = 0.04$, $p = .958$). Likewise, mental rotation task strategy groups did not significantly differ in mean fixation duration ($F(2,21) = 2.27$, $p = .128$) nor measuring mean saccade amplitudes ($F(2,21) = 0.73$, $p = .492$). These findings hint that strategic profiles identified were characterized more strongly by broader exploration organization and task-solving approaches rather than isolated low-level oculomotor properties alone.

3.6. Cross-task consistency of visual exploration tendencies.

To examine the stability of the visual exploration tendencies across cognitive and aesthetic task domains, relationships between spatial exploration measures obtained during the different tasks were analyzed.

3.6.1. Correlations between reasoning and painting exploration measures.

To see if the visual exploration tendencies are stable across all performed task domains, correlations were calculated between spatial exploration measures obtained during both cognitive tasks and painting viewing. Here, significant positive associations arose between vertical exploration spread during the mental rotation task and painting viewing ($r = .63$, $p = .001$), as well as between matrix reasoning and painting viewing ($r = .55$, $p = .005$). Other measures, including horizontal exploration spread, fixation durations, and saccade related variables did not yield statistically significant cross-domain associations, although a weak positive trend was observed between horizontal exploration in matrix reasoning and painting viewing ($r = .35$, $p = .094$), yet this relationship failed to reach significance. These findings suggest that participants who explored the visual field more broadly in the vertical axis during reasoning tasks also tended to explore paintings in the same manner. This observed crosstalk association supports the presence of stable individual differences in visual exploration behavior across both cognitive and aesthetic contexts.

3.6.2. Regression model predicting painting exploration

To further examine if the exploration tendencies during reasoning tasks predicted aesthetic viewing behavior, a multiple linear regression analysis was conducted using painting vertical exploration spread as the dependent variable and reasoning-task measures as predictors. The overall regression model was statistically significant ($p = .003$) explaining approximately 44 % of the variance in painting exploration behavior ($R^2 = .44$). Vertical exploration spread during mental rotation task was shown to be a significant independent predictor of painting exploration width. These findings suggest that individual differences in visual exploration behavior extend across distinctive cognitive domains and substantially contribute to aesthetic viewing patterns. Linnear relationships between the cognitive and aesthetic domains can be seen in Figure 3.12.

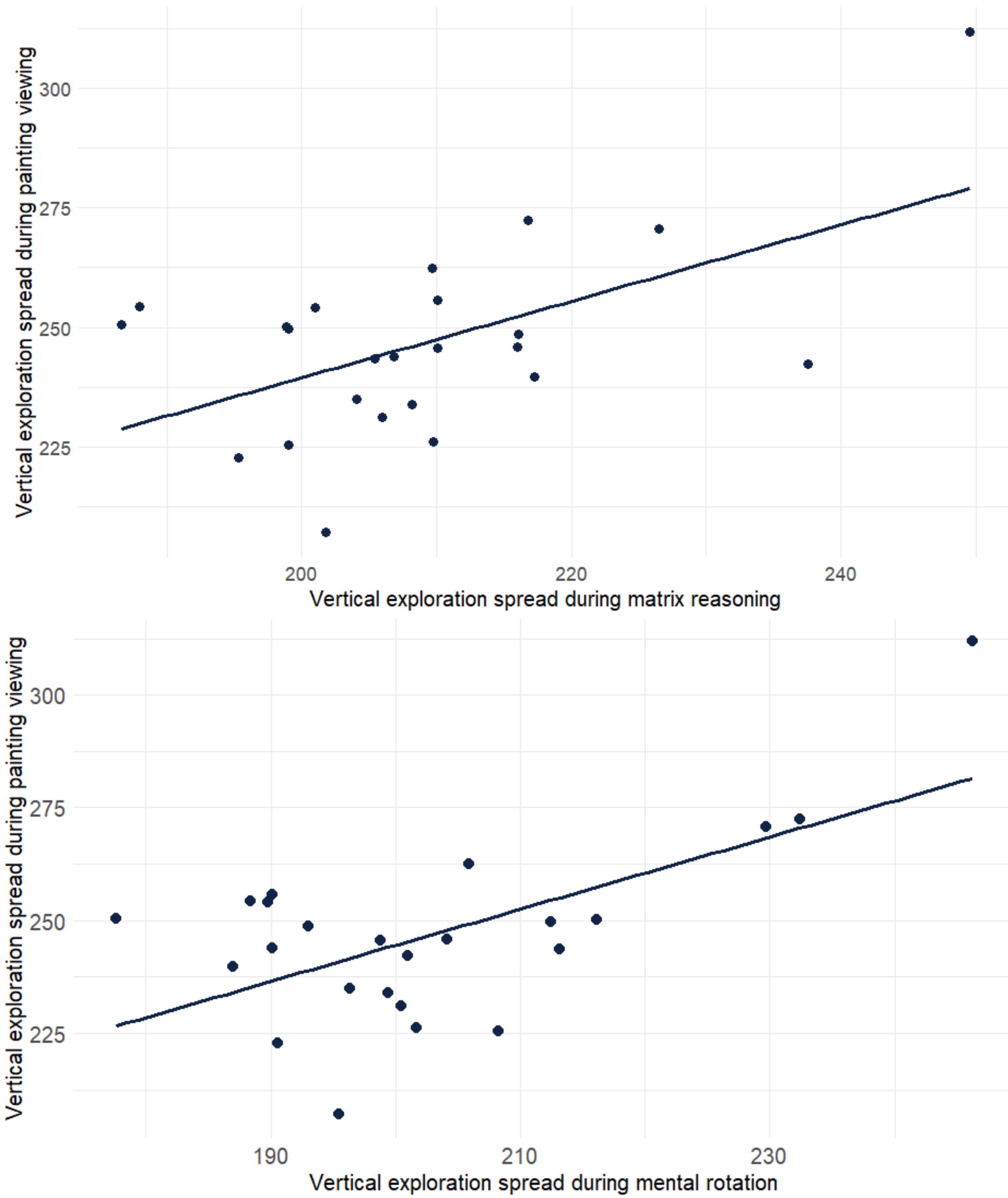


Figure 3.12. Linear association between vertical exploration spread during reasoning tasks and painting viewing. The upper panel shows the relationship between matrix reasoning and painting exploration spread, whereas the lower panel represents the relationship between the mental rotation task and painting exploration.

3.6.3. Overlap of strategic profiles across tasks

To further examine the stability of participant's personal visual exploration patterns across the three tasks, overlap of strategic profiles was examined. Strategic profile overlap analysis showed partial consistency in strategies between the reasoning tasks. Participants fitting the *Analytical verifier* profile during mental rotation task trials most frequently demonstrated either *Exhaustive eliminator* or *Systematic verifier* profiles in matrix reasoning. This might suggest preservation of the characteristic structure and systematic exploration patterns across cognitive domains. Similarly, those assigned the *Focused heuristic* profile during mental rotation task frequently demonstrated either *Focused heuristic* or *Analytical verifier* profiles in matrix reasoning.

Overlap between strategies of cognitive tasks and painting viewing appeared much weaker, although some tendencies could be seen (Fig.3.12). Participants who exhibit broader exploration strategies in reasoning tasks tend to be classified as *Exploratory contextual scanners* or *Global compositional explorers*, whereas those who show more structured cognitive strategies were more often associated with *Central integrative viewer profiles*.

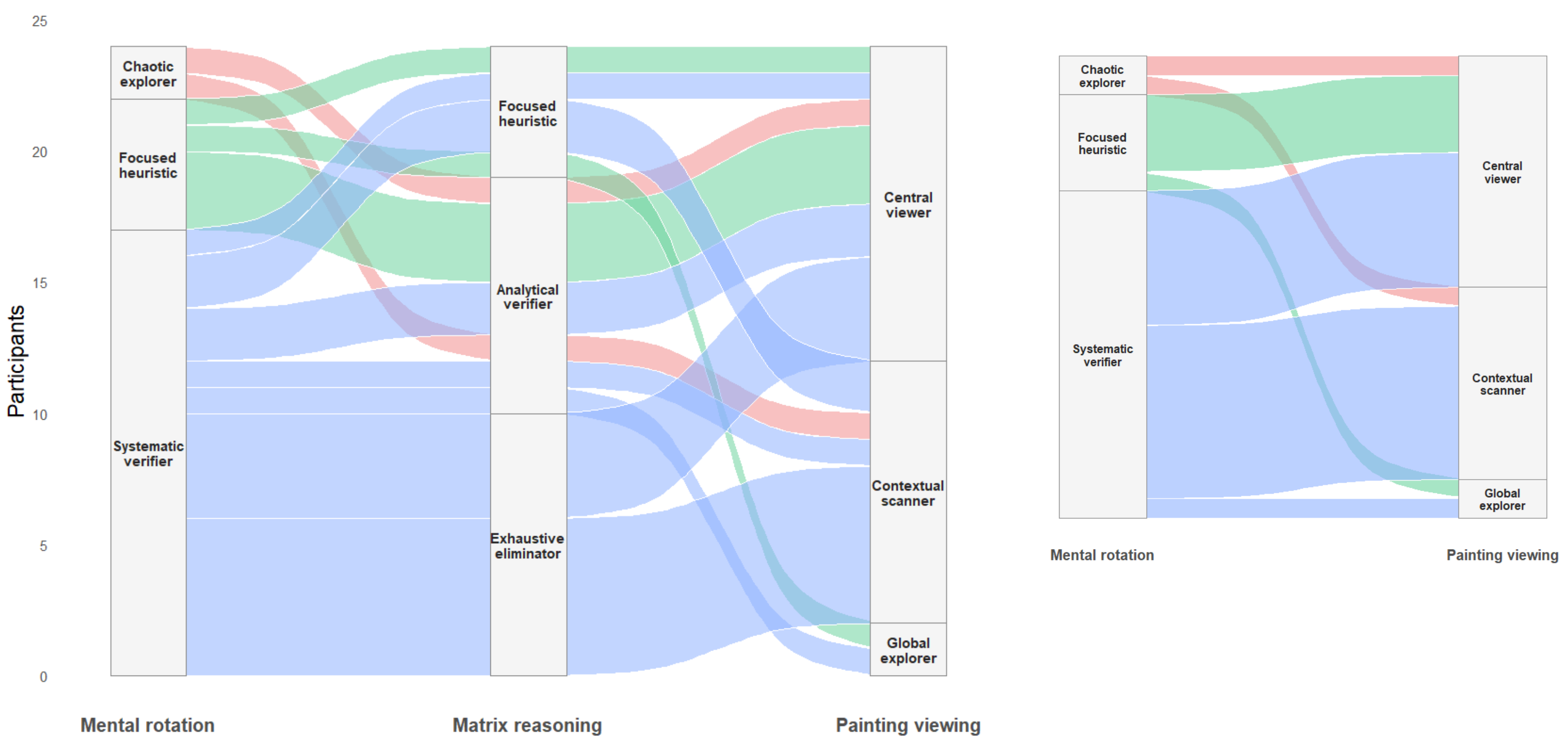


Figure 3.12. Sankey diagrams representing overlap between visual exploration strategy profiles across mental rotation, matrix reasoning, and painting-viewing tasks. Flow widths indicate the number of participants sharing corresponding profiles across domains. Stronger overlap was observed between cognitive reasoning tasks, whereas overlap between reasoning and aesthetic viewing profiles appeared weaker and more distributed.

A chi-square test was conducted to examine the overlap between mental rotation and matrix reasoning tasks, and it nearly reached significance ($\chi 2(4) = 9.14$, $p = .058$), although this should be interpreted with caution due to small subgroup sizes.

3.7.Cognitive Style Index associations

3.7.1. CSI and task performance

Cognitive Style Index (CSI) scores were compared with behavioral performance measures across reasoning tasks to examine a potential link between cognitive styles and task performance. Although, overall CSI scores demonstrated relatively weak associations with task performance variables, participants classified as within the more analytical side of cognitive style spectrum exhibited moderately higher mental rotation efficiency scores compared to participants with more intuitive profiles. Although the significance of this effect was not reached, the observed effect size could be classed as moderate to large (Cohen's $d \approx .98$), suggesting that there might still be a potential relationship between analytical cognitive tendencies and reasoning task efficiency to be explored further. Overall, CSI measures demonstrated substantially weaker associations with task performance than the visual exploration measures from previous analyses.

3.7.2. CSI and eye movement measures

The correlational relationship between CSI scores and eye movements was extensively explored, although it provided generally weak and inconsistent associations across tasks. Most fixation, saccade and spatial exploration measures did not reach significance in correlation with cognitive style scores. Some moderate tendencies were observed for selected spatial exploration variables, however, these effects were smaller and less consistent than the cross-task exploration associations reported previously. To conclude, the findings suggest that stable visual exploration tendencies were more strongly associated with task -independent exploration behavior rather than the self-reported cognitive style measures.

3.8. Additional AOI and accuracy findings

3.8.1. Difficulty and "I do not know" viewing behavior

Additional interesting analyses were done to explore how participants visually interacted with response alternatives during mental rotation tasks. One expected result came from investigating item difficulty. It was found that increased task difficulty was associated with longer response times ($r = .16$, $p < .001$), logically indicating greater processing demands for more difficult items. Another finding was that task difficulty was also positively associated with the proportion of viewing time directed towards the “I don’t know” response option ($r = .11$, $p = .002$). Furthermore, increased visual attention towards the “I don’t know" option was associated with lower task accuracy, suggesting that this response area represents inner uncertainty or unsuccessful problem-solving attempts. To further examine this relationship between uncertainty-related viewing behavior and task performance, a logistic regression analysis was done using task accuracy as the dependent variable and proportional viewing time directed towards the “I don’t know” answer box AOI as the predictor. It was found that increased visual attention towards the “I don’t know’ answer option significantly predicted lower probability of correct task performance ($\beta = -39.03$, $z = -4.67$, $p < .001$). These findings suggest that increased allocation of visual attention towards options related to uncertainty was associated with unsuccessful problem-solving outcome during mental rotation task and may reflect uncertainty related processing or reduced confidence during solving of the task.

3.8.2. AOI exploration and task accuracy

Visual exploration behavior within the mental rotation was also closely associated with task performance: greater proportional viewing time directed towards the reference stimulus was positively associated with task accuracy ($r = .10$, $p = .008$). Also, increased detailed AOI-level exploration was positively associated with successful task performance, suggesting that more systematic inspection of stimulus features contributed to improved reasoning accuracy. The findings, together with the “I don’t know” answer visual allocation suggest that systematic exploration and reference-based comparison behavior supported successful problem solving, whereas uncertainty-related viewing behavior was associated with unsuccessful performance.

4. Discussion

The defined cognitive task strategic profiles do follow the general notion of previous data on problem-solving strategies, but they also introduce new questions of how the data is processed in the mind and how people transition between similar yet different task domains.

4.1. Matrix reasoning strategic profiles

The foundational research on matrix reasoning strategies (Snow, 1978, 1980; Bethell-Fox et al., 1984) have proposed a systematic and efficient strategy of Constructive matching – in essence – understanding the matrix first and then checking the answers. Vigneau et al. (2006) have also conducted an eye-movement experiment with a matrix reasoning task and found a negative relationship between the accuracy score and the time domain, especially time spent looking at the answer sheet and matrix-answer transitions, developing this strategy into a predictor of good performance. Laurence et al. (2018) also found that those finely analyzing the matrix first and then systematically matching the answers performed the best. An analogous strategy in this thesis would be the *Analytic verifier*, which was associated with the highest accuracy and efficiency, with behavior that could be interpreted as figuring out the logic of the matrix and then verifying the results. The Exhaustive eliminator profile here also resembles the response-elimination strategies in the previously mentioned literature and is characterized by repeated transitions between matrix and answer regions.

Although in this thesis result section, a third strategy arose, which would not be usual in preexisting literature – here the characteristics of the *Focused heuristic* profile did not seem to fit in the previous groups. This latter profile has a recognizable pattern of reduced exploration, faster processing, yet lower accuracy with more selective information sampling, and does not exhibit exhaustive verification. Here, it seems that people are more willing to accept the earliest satisfactory option as the right one. Looking closer into the participants in this strategic category – they do not have much in common – this group has a good spread on CSI scores ($M = 49$, $SD = 11.94$, range: 32 – 61), different educational fields (arts and sciences), all of them report spending varying amounts of time between logical and art activities in their free time, and all have focused the longest at different painting AOIs, frankly, all of them individually have more in common with people in the other profiles than each other, yet in this matrix reasoning task they innately choose the same eye-movement strategy of rapid eliminations and only inspecting limited display regions. The classic Tversky and Kahneman (1974) article could explain psychologically what this thesis explains mechanistically: they argue that most people use mental shortcuts (heuristics) instead of logical/statistical calculations in their lives because they are fast, useful, and efficient, but the stronger they use them, the more systematic biases and errors are produced. Here, the most relevant of the proposed heuristics in the article would be anchoring and adjustment: they propose that people usually start from an initial reference point (anchor) and then adjust from that, only that adjustments are usually insufficient and the final judgment stays biased towards the anchor. It seems that the Focused heuristic groups have a strong mental anchor towards the "right" answer and have a strong bias against others. Tversky and Kahmen (1974) also postulate about confidence interval anchoring, meaning people give confidence ranges that are too narrow because they innately anchor on "their best guess" initially and fail to adjust enough outwards. But the *Focused heuristic* strategy is mechanistic and not "predetermined" to fail, contrary – some of the participants employing this strategy actually has comparable and even strong accuracy scores but were also the fastest to solve these problems, it is that overall, the mean accuracy of the group was the lowest but highly variable (M = 0.56, SD = 0.25). In the early experiment on chess perception, de Groot (1965) found that masters and weaker players do have a lot in common in their thought processes but was unable to find the qualitative differences that do underlie those chess skills. Chase and Simon (1973) expand on this research noticing that master's invariably explore the strong moves, while weaker players spend a long time analyzing the consequences of bad moves. Also, that the best move or at least a good move, just "seems to come to the top of the Master's list of plausible moves for analysis". To explain this, they utilize a concept of the "Mind's eye" – "a system that stores perceptual structures and permits them to be subjected to certain mental operations", which does have a property of spatial relations to be derived readily from the image. To bring it all together, it seems that the masters in chess use a mental anchor, that Tversky and Kahmen mention, to their advantage, although it can be also a detriment in solving cognitive tasks as a big mental limitation, fixing a person to one answer. The same may be happening the Focused heuristics group here in this thesis experiments, not that they explicitly choose an answer, but they experience a stronger anchor to it than those using verification of elimination strategies, meaning that they couldn't and shouldn't be put in those groups as the underlying mental processes seem to be vastly different, not depending on the final accuracy results. In other words, two strategic categories, that are usually mentioned in the literature, could be too one-dimensional, therefore three described profiles may be and improvement: based on anchoring strength the strategies could be divided into heuristic (strong anchor) and analytic (more adaptable) groups, where the analytic group would be separated into the more well-researched strategies of eliminators (Exhaustive eliminator) and verifiers (Analytic verifier). This type of grouping would also be justified by modern research, especially in Type 1 (fast, automatic, intuitive) and Type 2 (slow, effortful, reflective)(Fredrick, 2005; Teovanović, 2019): it was found that cognitive capabilities do not protect against biases and it has more to do with the willingness to engage in reflective thinking and that more impulsive or intuitive people may rely mostly on the automatic anchor-consistent intuition, and reflective people actually attempt to reevaluate and adjust their notions. However, it is not yet surely known what exactly makes one anchor to the "right" answer and another to the "wrong" answer, although it is thought to have something to do with prior experience and stored patterns, even in the tasks, that usually prevent the such bias (Raab et al., 2026). So, the existing literature does justify the deeper profiling of the strategies beyond only verifiers and eliminators in matrix reasoning, and also raises new questions and research ideas of combining mechanistic problem solving strategies, heuristics, anchor strengths, and the "Mind's eye", as all of these together may be what determines the strategy innately chosen, and eye-metrics could be used to measure it.

4.2.Mental rotation strategic profiles

Talking about three-dimensional mental rotation task – three distinct strategic profiles also arose: *Systematic verifier, Focused heuristic,* and *Chaotic explorer*. While there doesn't seem to be articles that would definitively describe the strategies used in mental rotation tasks as there are in matrix reasoning problem-solving, there is literature that would explain or expand the characteristics in other domains of what the three-dimensional task's eye movement have tied up here. Mental rotation is an ability to turn objects in mind and is arguably strongly linked to general intelligence and could even be perceived as entirely independent cognitive domain (Varialle et al. 2018) but to solve a rotational problem people might not even use this ability (Zhao & Della Sala, 2017) in some cases. Truth be told, to successfully solve this kind of problem a great deal of adaptability is needed and the differences in mental rotation performance may reflect strategic differences and not only raw spatial ability. Stieff (2007) argues that flexibility to switch between visuospatial and analytic strategies may be the most important aspect in mental rotation. The article also argues that visuospatial strategies are more default strategy and dominate novices, while analytical heuristics are used to solve the more difficult problem. So, eye movement differences in the present study likely do reflect different cognitive strategies and not just random attentional variations and people most likely sample the visual information differently because they represent that information differently internally and efficiency differences may emerge more from strategic optimization and not just general intelligence or pure spatial ability.

To bring it back to the experiment at hand, it seems that the Systematic verifier, Focused heuristic, and Chaotic explorer profiles may reflect a combination of different strategic elements and their ability to adapt to the task, and not only the pure mechanistic approach of spatial rotation. Johnson (1990) solution of the mental rotation problem is found in five steps – forming a representation, mentally rotating it, comparing the objects, and giving a response – therefore, the current reported strategies most likely contain differences inside these steps, meaning that they may not differ in rotation itself but in decision rules, verifications styles, stopping criteria and comparison strategies, e.g. Systematic verifiers seem to continue comparison for longer times, perform explicit checking, revisit information more often and trade speed for better accuracy, while those fitting in Focused heuristics profile terminate the search earlier, rely on partial matching, use simplifying heuristics and seem to apply those "good enough" thresholds, again, characteristic of anchoring behavior. So, eye-movement difference may externally reflect differences in these internal cognitive organizations. Overall, Systematic verifiers seem exhibit actual genuine visuospatial transformation making with an addition of analytical verification (not pure mental rotation alone), and this is evident by their structured exploration stable through the trials, high revisiting and checking behavior, systematic AOI transition and finally, their highest average accuracy with slower performance. These characteristic fit into the Type 2 control explained before and is also very compatible with deliberate adjustment and verification with frequent comparisons and sequential elimination. The Focused heuristic shows a different strategy of feature-based inspection, creating of mental shortcuts, narrower and more focused gaze and less exhaustive exploration patterns. This hints at only partial rotation of every objects with Type 1 control and strong anchoring.

The last group, the *Chaotic explorers*, don't fit the standards discussed before, although it is the smallest group, only comprised of two participants, they could be representing a mischaracterization but could also the representing a real pattern of thinking that is just more rare than others. The *Chaotic explorers*, hence the name, seem to not successfully apply any stable strategy at all, likely failing at heuristic selection and inefficiently comparing the features. Their broad and disorganized exploration suggests they likely attempt the transformation but lose the internal spatial representation failing to successfully compare it with others. It fits with the research of low-spatial participants struggling to maintain coherent representations of the mental images (Zhao & Della Sala, 2017) or could also demonstrate inability to identify diagnostic features, only a reason for this would still be unknown now. The two participants representing the Chaotic explorers did not solve a single problem correctly but were not grouped based on the accuracy, rather purely on eye-movement patterns, frankly – there was one other participant scoring zero, although they fit the Focused heuristic profile during this task, adding validity to the profiles representing inner mental working rather than scores alone.

4.3.Overlap in cognitive task profiles

Talking about the overlap between strategic groups of both cognitive tasks, one might deduce that the verifier strategies would overlap the strongest, meaning those fitting Systematic verifiers in mental rotation task would maintain Analytical verifier strategy in matrix reasoning, although this was not the case. Contrary, only four people fit both profiles together and the biggest overlap was seen between the Systematic verifiers in mental rotation and Exhaustive eliminators in matrix reasoning, where all ten participants fitting the latter profile actually exhibited strategy of verifying in mental rotation. This could be explained in a few ways, firstly, with adaptation to task demands and, secondly, with those two strategies having an underlying processing structure that is not seen at first glance. The first theory is consistent with Just and Carpenter's account with spatial thinking where the trial's structure, item difficulty, and the stimulus format can elicit a change in strategy depending on the coordinate system and representation adopted. Therefore, the lack of complete overlap between the profiles of reasoning tasks in present study does not necessarily point to instability of visual strategy but could reflect adaptive changes in strategy implementation according to the task demands (Just & Carpenter, 1985). This interpretation is also consistent with more recent EEG evidence suggesting that mental rotation performance highly depends on the flexibility between the motor-stimulation based rotation and analytic strategies. Gardony et al. (2017) have shown that increasing angular disparity is associated with reduced reliance on mental rotation and heightened involvement of working memory suggesting that strategy shifts with task difficulty and type. Also, Hegarty (2010) argues that higher spatial intelligence does involve higher flexibility between mental simulation and analytic strategies, including task decomposition and rule-based reasoning. From this perspective, the same participants may express the same systematic tendency differently depending on whether the task requires object transformation efforts or induction of own's rules. So, the fact that all Exhaustive eliminators in matrix reasoning task are Systematic verifier in mental rotation task, suggests that these participants have a general tendency towards complete systematic problem-solving approach, and, one could claim, weaker anchoring: they do not stop after finding plausible answer and continue comparing options to not miss something, a more Type-2 approach. In mental rotation the person inspects the reference and response options carefully, repeatedly checking those alternatives, while the same person in matrix reasoning inspects all the answers with great caution and eliminate them by comparison, so while the label changes because the task changes the underlying characteristic remain similar – broad, cautious and covering all possible options. The other strategic groups do not show such obvious overlaps, however, there are more seemingly strategic changes seen, e.g. some people who fit in the Focused heuristic profile, characterized by more narrow answer search, selecting a likely candidate quickly and anchoring to it, less exhaustive exploration, they later became Analytic verifier in matrix reasoning. An explanation for this could be that the nature of a matrix reasoning task forces the participant to analyze and induce the rules more than mental rotation tasks. Here, MR requires rule abstraction and analysis of the matrix components, finding the silent logic in the sequences, so the more adaptable cognitive minds should make a switch to at least attempt successful task execution, while still remaining some characteristic focus in exploration and relevant efficiency. Those who fit the Chaotic explorer profile in rotation tasks also switched to Analytic verifier in the following task, hinting that the utter confusion in the rotation task was not a sign of low cognitive capabilities, but rather the inability to solve such an unstable task. R3D is highly open-ended with many possible comparison paths and requires higher order coordinate systems, while matrix reasoning has a more familiar two-dimensional system, that has stability that the rotation lacks. So, people who appear chaotic in R3D task may become more systematic in MR as the task externally organizes the reasoning process, which may be the thing that was lacking beforehand. Overall, the chi-square test did show a near significant overlap of cognitive ability tasks ($\chi 2(4) = 9.14$, $p = .058$), and the stability can be postulated in some aspects from the characteristics of the strategies, but the main finding here is that there is a large gap in the research of the coexistence of all these strategies in one mind. It is evident that there must be an unobserved systematic axis of human consciousness that would tie all these characteristics together and we might be able to describe it by examining these rich relationships between the personal outlooks on different problems. Although, making any definitive conclusions would require a much bigger sample size.

4.4.Painting strategies

In a similar way, painting viewing strategies have been determined, according to similarities in eye movement patterns: the most abundant group, the Central integrative viewers, were characterized by most stable exploration behavior towards the center of the paintings, as well as the most outstanding details in them. Exploratory contextual scanners, on the other hand, showed more evenly distributed attention allocation through the whole composition. Then again, a group that could not be classified within any of the other categories emerged, the Global compositional explorers, that showed the broadest exploration and the least interest in the details of the paintings, utilizing the 30 seconds of viewing time to take in the whole picture. This type of clustering merely suggests tendencies in how the participants distribute attention across paintings, although the actual distinction between the profiles is relatively subtle, as the task is open-ended and unconstrained, with no specific goal in mind. Because of this task distinction it does make sense that the aesthetic viewing profiles make up much weaker and more continuous profiles than the cognitive problem-solving. So, while there is an outstanding profile, Global compositional explorers, the other two groups do partially overlap and the differences are seen in more subtle ways, not necessarily reaching the mathematical significance at this sample size. Here, the results don't show three completely distinct strategies, it has more to do with different degrees and emphasis of visual exploration during aesthetic viewing. One of the main characteristics distinguishing those patterns was the exploration spread along the axes: Global compositional explorers had shown significantly broader horizontal and vertical exploration patterns, indicating a tendency to distribute attention across larger compositional areas of artwork. In contrast, Central integrative viewers together with Exploratory contextual scanners showed similar exploration ranges, this does indicate that distinction between these profiles reflect more subtle differences in attentional organization rather than fundamentally different viewing mechanisms. Although, it is important to consider that the Global compositional explorers profile contained data from only two participant, meaning it should be interpreted with caution. Nevertheless, the underlying reasons of this distinct group emerging is not known and it's equally possible that the outlier group emerged accidently as a result of the experimental process flaws, as it is possible that these participant do actually represent a smaller yet existing group of population.

One of the clearest findings across the aesthetic viewing behavior involved attention allocation towards semantic human elements. Participants who spent greater proportional time focusing on human AOIs also demonstrated substantially narrower exploration patterns, such as reduced horizontal and vertical fixation spread as well as shorter gaze transition distances. This could be interpreted as human figures acting as strong attention anchors during this task, concentrating people's attentions towards it at different levels of strength. On the other hand, broader global exploration was associated with strongly reduced focus on the human elements and greater overall distribution across the whole composition consistent with greater overall distribution of attention. Kozhevnikov et al. (2005) have investigated visual cognitive styles and landed at the conclusion that people can be separated into two groups when visualizing: object visualizer and spatial visualizers. Object visualizers tend to process the images more pictorially and vividly, focusing on shapes colors, scenic contexts, emotional elements, and global perceptual appearance, while spatial visualizers process the same more analytically and relationally, using imagery to represent and transform spatial relations, with this distinction suggesting that both groups encode and process the same mental images in different ways. From this perspective, the painting viewing strategies in this current study could also resemble Kozhevnikov et al. (2005) distinctions. Central integrative viewers demonstrated stronger attention allocation towards semantic human elements and exhibit overall narrower yet more stable exploration patterns. These tendencies seem to resemble object-based visual processing, which emphasizes holistic scene representation and perceptual detail. In contrast, a generally broader composition scanning and reduced focus on human AOIs was noticed in *Global compositional explorer* profile, resembling a pattern of more spatially oriented viewing which could be characterized by more equally distributed attention across the visual scene. The *exploratory contextual scanners* may be an intermediate viewing mode between these extremes. However, these parallels remain speculative, especially considering differing methodologies and the small sample size of Global compositional explorer group. This relationship between semantic AOI focus and exploration width may reflect differing balances between local and global processes during aesthetic viewing. Especially that it is also seen between all groups at a lower level. So, it would mean that some participant prioritize their attention around semantically meaningful points, like human figures, while others automatically focus more broadly on other compositional elements of the artwork. Beelders and Bergh (2020) did a study on paintings composition influencing how the viewers look at landscape art and they found that semantic regions like human figures, faces, eyes, bodies, movement, and socially meaningful content naturally attract attention regardless of the placement, acting like strong anchor point. It would be reasonable to assume that this effect is strongest in the Central integrative viewers profiles, and least to the Global compositional explorers, with the latter moving more continuously through the composition rather than anchoring. Moreover, according to Villani et al. (2015) study this distinction of attention priorities towards semantic social information versus broader compositional information could be explained by differences in top-down processing inclusion that strongly shapes the gaze behavior, especially when humans are present. However, these tendencies appear to be less rigid compared to strategic distinctions that were observed during reasoning tasks and would need to be studied more extensively in the future to make definitive claims. It is an interesting observation that other semantic AOI categories, like nature or objects, were not significantly associated with the identified profiles, although the uniquely strong salience of human features is known and expected (Massaro et al. 2012; Villani et al., 2015; Beelders & Bergh, 2020). Albeit, structural elements were associated with longer fixation durations, which would suggest a more detailed inspection of architectural or more grand and rigid elements in the composition.

All in all, the findings suggest that aesthetic viewing behavior may be characterized less by distinct categorical strategies and more by continuous variation in exploration spread and semantic allocation prioritization. It is a stark contrast to reasoning tasks, where eye movements seem to tell way more about the inner working of the conscious mind. Although, the mental processes in aesthetic viewing may be more complex and multi-dimensional than the methods anticipated, leaving the described profiles only as tendencies in attentional allocation and compositional exploration.

4.5.Overlap in all groups

Given that all the tasks performed involved different processing mechanisms, huge overlap is not to be expected, although some exploration tendencies do remain fairly stable across domains. Significant relationships in vertical exploration spread were found between mental rotation task and painting viewing as well as matrix reasoning and painting viewing. A weak positive trend was found in horizontal exploration spread between matrix reasoning and aesthetic tasks. In addition, it was discovered that ~ 44 % of the differences between people in painting exploration could be statistically explained by exploration tendencies during reasoning tasks, suggesting that some aspects of visual exploration behavior are relatively stable individual tendencies extending between both cognitive and aesthetic tasks, supporting the presence of some level of cross-domain consistency in these domains. However, regression only predicts spatial exploration width and not semantic viewing behavior or performance in problem-solving, as these stable tendencies likely operate at a broader organizational level rather than task-specific strategies. Therefore, the findings suggest that trait-like visual tendencies emerge not necessarily as fixed cognitive strategies, but more akin to broader organizational styles influencing how individuals distribute attention across different visual environments. Another interesting finding was that exploration structure was more persistent, yet semantic interpretations were not, meaning people may consistently explore more broadly or more narrowly but what they allocate attention to depends mostly on the task as cognitive tasks force goal-oriented inspective behavior while paintings allow a freer semantic interpretation. Similar findings were already made by Yarbus (1965) where he mentions the repeated returns of the gaze to important regions, cyclical scan behavior, and individual differences in how observers think and look, this supports the idea that how one views is not only shaped by the task itself, but some broader exploration tendencies may persist across domains. Overall, the current findings suggest that visual exploration behavior comes from a complex interaction between task demands, semantic content and stable observer-specific attentional tendencies. This sentiment is also consistent with numerous newer studies (Andrews & Coppola, 1999; Paterson & Eckstein, 2013) with de Haas et al. (2019) concluding it best by claiming that “visual salience is not just a function of the image, but also of the individual observer”.

4.6.Cognitive style differences

The self-reported cognitive styles (CSI) reported in this study showed some relationship with reasoning tasks, especially the moderate effect size in mental rotation efficiency, however the overall associations between the CSI scores and eye-movement behavior remained relatively weak and inconsistent. Comparing it with the strong cross-domain relationship observed in spatial exploration measures, it would seem that CSI is less predictive of both the task performance and visual exploration organization. This could suggest that consistent visual exploration tendencies are not fully captures with this measurement as it self-reported, therefore – a conscious measure, whereas eye-movement reflect a more subconscious part of the mental inner workings.

A possible explanation for this lack of expected relationship is that the 'self-report' nature of the CSI measurement: Nisbett & Wilson (1979) argue that people lack access to direct introspection of owns judgements, decisions, problem-solving, or other layers of behavior, they merely become aware of the results of cognition, not the processing itself. While discussing this limitation of introspection, they reference Miller's (1962) idea that "it is the result of thinking, not the process of thinking, that appears spontaneously in consciousness". A measure like CSI would reflect broader conscious preferences and understandings of own's identity, whereas eye-movements capture more direct information sampling and active perception during task execution. Therefore, eye-movements could be revealing a relative stability of processing tendencies that participants themselves could not accurately report on. This could theoretically explain why visual exploration measures demonstrate more stability, while CSI associations remained weak, as they are measuring different levels of cognition, although to test this possibility further study would need to be conducted.

4.7.Additional findings

One additional interesting finding in the present study was the relationship between uncertainty-related viewing and unsuccessful problem-solving in mental rotation task. The increased difficulty in separate R3D task trials was associated with longer response times and more importantly – greater proportional viewing time directed towards the "I don't know" response option. Furthermore, increased attention towards this area predicted lower probability of correct solution of the task. These findings suggest that uncertainty during problem solving could be externally visible through such eye-movement behavior. This interpretation is in line with Just & Carpenter (1976) mental rotation study where they found that eye fixations are closely tied to cognitive processes occurring in real time and that people tend to fixate on the stimulus that is actively being processed. They suggest that the processing of such task is done in three stages: 1. Search – searching for corresponding parts between figures; 2. Transformation and comparison – participants look back and forth between corresponding parts while mentally rotating them; 3. Confirmation – visually confirming if the figures truly match by revisiting, checking consistency, verifying. While checking the incorrect trials they found that people often either fixated on incorrect segments or used unsuccessful strategies and their eye movements could reveal where the failure happened. This gives credit to the interpretation of the current study's "I don't know" answer fixations as an active reflection of uncertainty. Longer or repeated inspection of such region's may therefore reflect active reevaluation, reduced confidence or strong confusion of not being able to stabilize the mental image. Similarly, ideas of prolonged or atypical fixation behavior being associated with confusion, increased cognitive load, and potential unsuccess in processing have been discussed in more recent literature on fixations (Bixler & D'mello, 2016; Negi & Mitra, 2020).

At the same time, participants who spent greater proportion of time viewing the reference stimulus or were exploring the AOIs in greater detail, were generally more successful. Such behavior is pointing to the more extensive manifestation of systemic comparison and verification, which would likely lead to better performance in the task. This is consistent with previous research where continuous comparison or reference versus response was interpreted with active transformation of mental images and verification during spatial reasoning, also associated with greater success (Just & Carpenter, 1976). Altogether, the findings support the idea that eye movements do provide insight into the active organization of cognitive processes in real time.

4.8.Limitations

There are a few big limitations in this study, mainly the sample size. Although it is a common excuse, given the exploratory nature of this study, a bigger number of participants would have really solidified the results, mainly, the extremely small profiles Global compositional explorer group and Chaotic explorer, are left with an uncertainty about the validity of their existence and characteristics. The conclusions regarding these groups should be made with extreme caution until further research. Although, the participant in these groups did show internal consistency of eye-movement behavior, it still remains possible that the observed effects reflect only individual variability rather than stable population-level strategy types. The small and unequal subgroup sizes may have prevented detection of some weaker cross-domain relationship, especially in overlap between cognitive and aesthetic viewing strategies.

Another limitation is the exploratory strategic profiling approach itself: the profiles identified were derived from clustering of eye-movement patterns and subsequently interpreted behaviorally and theoretically. While the profiles appear psychologically meaningful and are partially supported by other behavioral performance differences, clustering methods do not necessarily reveal objectively discrete cognitive categories. Human visual exploration behavior might be better describe in a spectrum rather than discrete types, therefore, the identified profiles should be treated as a useful organization tool rather then definitive cognitive classes. Different clustering approaches, variable selections or larger datasets could produce somewhat different profiles structures.

The free-viewing painting paradigm also introduces additional variability. Unlike reasoning tasks with explicit goals, aesthetic viewing is highly open-ended and may be influenced by emotional responses, personal preferences and so on. This might partially explain why painting viewing profiles demonstrated weaker differentiation and overlap compared to the cognitive task profiles.

Finally, the study remains correlational in nature. Although consistent relationships emerged between visual exploration measures across cognitive and aesthetic domains, the study does not allow causal conclusions regarding the origins of stable exploration tendencies. This could only be find out in future studies

5. Conclusions

1. Eye movement patterns varied considerably depending on the task: matrix reasoning, mental rotation, or aesthetic viewing. This shows that different types of tasks lead to unique ways of visualizing information.
2. During mental rotation tasks, people explored more broadly and made larger gaze jumps. In contrast, during aesthetic exploration of paintings, people tended to explore less systematically, also showing longer fixations of semantically significant interest areas
3. Some ways of looking—especially how much people move their eyes up and down—remained consistent across both reasoning and art viewing tasks.
4. Different types of visual exploration strategies were found for reasoning and art tasks. These strategies varied in how efficiently and accurately people processed information, and how they paid attention to different parts of what they saw.
5. The way people moved their eyes depended not just on the task, but also on individual differences in how they organize information and gather details.
6. These results suggest that some ways of looking around are stable habits that apply to both thinking tasks and art viewing.

VILNIUS UNIVERSITY

LIFE SCIENCES CENTER

Marta Purvinytė

Master's Thesis

Visual Strategies Across Mind and Art: Eye Movements in Reasoning Tasks and Aesthetic Viewing

ABSTRACT

There is much that is unknown about how different domains of cognitive processing manifest in people and how stable these features are both inter- and interpersonally. The primary goal of this exploratory study was to determine whether individuals display relative consistency of visual exploration tendencies across different cognitive reasoning and aesthetic viewing tasks, and how these tendencies are linked to problem-solving performance and strategy selection.

Twenty-four participants completed three experimental tasks: a three-dimensional mental rotation task, a matrix reasoning task, and a free-viewing aesthetic task involving 10 different styles of paintings. Eye movements were tracked with an infrared corneal reflection eye-tracking system, the EyeLink1000. Fixation duration, saccade amplitude, fixation spread, proportional attention allocation to areas of interest (AOIs), response times, and performance efficiency were analyzed to group participants into visual exploration strategy profiles.

It was discovered that gaze organization substantially differed between tasks: free-viewing painting has elicited the longest fixations, while cognitive tasks like mental-rotation showed overall broader exploration patterns, especially larger saccades. Some crosstalk stability was observed at an individual level, especially exploration spread and strategic choices, leading to interpretations of innate characteristics that could persist despite a change in task demands. Three novel strategic profiles were found by means of clustering for every task. They were named and defined, each showing a signature behavioral characteristic as well as an association with different success and efficiency tendencies.

The results add merit to eye movements being not only mnemonic attention signatures but also a reflection of broader cognitive processing in real time. Some of the attentional tendencies do persist across domains, even suggesting a trait-like structure. Overall, eye tracking has proved to be useful for studying features of fluid intelligence and aesthetic viewing together.

References

1. Allinson, C. W., & Hayes, J. (1996). The cognitive style index: A measure of intuition-analysis for organizational research. *Journal of Management studies*, *33*(1), 119-135.
2. Allinson, C., & Hayes, J. (2012). The cognitive style index: Technical manual and user guide. *Retrieved January*, *13*, 2014.
3. Andrews, T. J., & Coppola, D. M. (1999). Idiosyncratic characteristics of saccadic eye movements when viewing different visual environments. *Vision research*, *39*(17), 2947-2953.
4. Bardach, L., Schumacher, A., Trautwein, U., Kasneci, E., Tibus, M., Wortha, F., Gerjets, P. and Appel, T., 2024. Taking another look at intelligence and personality using an eye-tracking approach. *npj Science of Learning*, *9*(1), p.41.
5. Beelders, T., & Bergh, L. (2020). The role that composition plays in determining how a viewer looks at landscape art. *Journal of Eye Movement Research*, *13*(2), 19.
6. Bethell-Fox, C. E., Lohman, D. F., & Snow, R. E. (1984). Adaptive reasoning: Componential and eye movement analysis of geometric analogy performance. *Intelligence*, *8*(3), 205-238.
7. Bixler, R., & D'Mello, S. (2016). Automatic gaze-based user-independent detection of mind wandering during computerized reading. *User Modeling and User-Adapted Interaction*, *26*(1), 33-68.
8. Breit, M., Scherrer, V., Tucker-Drob, E. M., & Preckel, F. (2024). The stability of cognitive abilities: A meta-analytic review of longitudinal studies. *Psychological Bulletin*, *150*(4), 399.
9. Brown, S., Gao, X., Tisdelle, L., Eickhoff, S. B., & Liotti, M. (2011). Naturalizing aesthetics: brain areas for aesthetic appraisal across sensory modalities. *Neuroimage*, *58*(1), 250-258.
10. Carpenter, P. A., Just, M. A., & Shell, P. (1990). What one intelligence test measures: a theoretical account of the processing in the Raven Progressive Matrices Test. *Psychological review*, *97*(3), 404.
11. Carroll, J. B. (1993). Human cognitive abilities: A survey of factor-analytic studies. Cambridge University Press.
12. Cattell, R. B. (1963). Theory of fluid and crystallized intelligence: A critical experiment. *Journal of educational psychology*, *54*(1), 1.
13. Chase, W. G., & Simon, H. A. (1973). The mind's eye in chess. In *Visual information processing* (pp. 215-281). Academic Press.
14. Chatterjee, A., & Vartanian, O. (2014). Neuroaesthetics. *Trends in cognitive sciences*, *18*(7), 370-375.

15. Connor, C. E., Egeth, H. E., & Yantis, S. (2004). Visual attention: bottom-up versus top-down. *Current biology*, *14*(19), R850-R852.
16. Cooper, L. A., & Shepard, R. N. (1973). Chronometric studies of the rotation of mental images. In *Visual information processing* (pp. 75-176). Academic Press.
17. Corballis, M. C. (1988). Recognition of disoriented shapes. *Psychological review*, *95*(1), 115.
18. Davitt, L. I., Cristino, F., Wong, A. C. N., & Leek, E. C. (2014). Shape information mediating basic-and subordinate-level object recognition revealed by analyses of eye movements. *Journal of Experimental Psychology: Human Perception and Performance*, *40*(2), 451.
19. de Groot, A. Thought and choice in chess. The Hague: Mouton, 1965.
20. De Haas, B., Iakovidis, A. L., Schwarzkopf, D. S., & Gegenfurtner, K. R. (2019). Individual differences in visual salience vary along semantic dimensions. *Proceedings of the National Academy of Sciences*, *116*(24), 11687-11692.
21. Duncan, J. (1980). The locus of interference in the perception of simultaneous stimuli. *Psychological review*, *87*(3), 272.
22. Duncan, J. (2010). The multiple-demand (MD) system of the primate brain: mental programs for intelligent behaviour. *Trends in cognitive sciences*, *14*(4), 172-179.
23. Duncan, J., Emslie, H., Williams, P., Johnson, R., & Freer, C. (1996). Intelligence and the frontal lobe: The organization of goal-directed behavior. *Cognitive psychology*, *30*(3), 257-303.
24. Duncan, J., Seitz, R. J., Kolodny, J., Bor, D., Herzog, H., Ahmed, A., ... & Emslie, H. (2000). A neural basis for general intelligence. *Science*, *289*(5478), 457-460.
25. Dworak, E. M., Revelle, W., Doebler, P., & Condon, D. M. (2021). Using the International Cognitive Ability Resource as an open source tool to explore individual differences in cognitive ability. *Personality and Individual Differences*, *169*, 109906.
26. Engle, R. W., Kane, M. J., & Tuholski, S. W. (1999). Individual differences in working memory capacity and what they tell us about controlled attention, general fluid intelligence, and functions of the prefrontal cortex. *Models of working memory: Mechanisms of active maintenance and executive control*, *4*, 102-134.
27. Erdogan, G., Chen, Q., Garcea, F. E., Mahon, B. Z., & Jacobs, R. A. (2016). Multisensory part-based representations of objects in human lateral occipital cortex. *Journal of cognitive neuroscience*, *28*(6), 869-881.
28. Frederick, S. (2005). Cognitive reflection and decision making. *Journal of Economic perspectives*, *19*(4), 25-42.

29. Glöckner, A., & Herbold, A. K. (2011). An eye-tracking study on information processing in risky decisions: Evidence for compensatory strategies based on automatic processes. *Journal of Behavioral Decision Making*, *24*(1), 71-98.
30. Hayes, T.R., Petrov, A.A. and Sederberg, P.B., 2011. A novel method for analyzing sequential eye movements reveals strategic influence on Raven's Advanced Progressive Matrices. *Journal of Vision*, *11*(10), pp.10-10.
31. Heil, M., & Jansen-Osmann, P. (2008). Sex differences in mental rotation with polygons of different complexity: Do men utilize holistic processes whereas women prefer piecemeal ones?. *Quarterly Journal of Experimental Psychology*, *61*(5), 683-689.
32. Huang, M., Bridge, H., Kemp, M. J., & Parker, A. J. (2011). Human cortical activity evoked by the assignment of authenticity when viewing works of art. *Frontiers in human neuroscience*, *5*, 134.
33. Jensen, A. R. (1998). *The g factor: The science of mental ability*. Praeger.
34. Jung, R. E., & Haier, R. J. (2007). The Parieto-Frontal Integration Theory (P-FIT) of intelligence: converging neuroimaging evidence. *Behavioral and brain sciences*, *30*(2), 135-154.
35. Just, M. A., & Carpenter, P. A. (1980). A theory of reading: from eye fixations to comprehension. *Psychological review*, *87*(4), 329.
36. Just, M. A., & Carpenter, P. A. (1985). Cognitive coordinate systems: accounts of mental rotation and individual differences in spatial ability. *Psychological review*, *92*(2), 137.
37. Kapoula, Z., Daunys, G., Herbez, O. and Yang, Q., 2009. Effect of title on eye-movement exploration of cubist paintings by Fernand Léger. *Perception*, *38*(4), pp.479-491.
38. Kozhevnikov, M., Kosslyn, S., & Shephard, J. (2005). Spatial versus object visualizers: A new characterization of visual cognitive style. *Memory & cognition*, *33*(4), 710-726.
39. Kozhevnikov, M., Kozhevnikov, M., Yu, C. J., & Blazhenkova, O. (2013). Creativity, visualization abilities, and visual cognitive style. *British journal of educational psychology*, *83*(2), 196-209.
40. Lacey, S., Hagtvedt, H., Patrick, V. M., Anderson, A., Stilla, R., Deshpande, G., ... & Sathian, K. (2011). Art for reward's sake: Visual art recruits the ventral striatum. *Neuroimage*, *55*(1), 420-433.
41. Larsen, A. (2014). Deconstructing mental rotation. *Journal of experimental psychology: Human perception and performance*, *40*(3), 1072.

42. Laurence, P. G., & Macedo, E. C. (2023). Cognitive strategies in matrix-reasoning tasks: State of the art. *Psychonomic Bulletin & Review*, *30*(1), 147-159.
43. Laurence, P.G., Mecca, T.P., Serpa, A., Martin, R. and Macedo, E.C., 2018. Eye movements and cognitive strategy in a fluid intelligence test: Item type analysis. *Frontiers in Psychology*, *9*, p.380.
44. Legg, S. and Hutter, M., 2007. A collection of definitions of intelligence. *Frontiers in Artificial Intelligence and applications*, *157*, p.17.
45. Locher, P., Krupinski, E. A., Mello-Thoms, C., & Nodine, C. F. (2008). Visual interest in pictorial art during an aesthetic experience. *Spatial vision*, *21*(1), 55.
46. Logie, R. H., Pernet, C. R., Buonocore, A., & Della Sala, S. (2011). Low and high imagers activate networks differentially in mental rotation. *Neuropsychologia*, *49*(11), 3071-3077.
47. Massaro, D., Savazzi, F., Di Dio, C., Freedberg, D., Gallese, V., Gilli, G., & Marchetti, A. (2012). When art moves the eyes: a behavioral and eye-tracking study. *PloS one*, *7*(5), e37285.
48. Metzler, J., & Shepard, R. N. (2024). Transformational Studies of the Internal Representation of Three-Dimensional Objects 1. In *Theories in cognitive psychology* (pp. 147-201). Routledge.
49. Miller, G. A., & Buckhout, R. (1973). *Psychology: The science of mental life*. Harper & Row.
50. Moen, K. C., Beck, M. R., Saltzmann, S. M., Cowan, T. M., Burleigh, L. M., Butler, L. G., ... & Greening, S. G. (2020). Strengthening spatial reasoning: Elucidating the attentional and neural mechanisms associated with mental rotation skill development. *Cognitive research: principles and implications*, *5*(1), 20.
51. Mühlenbeck, C., Liebal, K., Pritsch, C. and Jacobsen, T., 2016. Differences in the visual perception of symmetric patterns in orangutans (Pongo pygmaeus abelii) and two human cultural groups: A comparative eye-tracking study. *Frontiers in psychology*, *7*, p.408.
52. Myszkowski, N., & Zenasni, F. (2016). Individual differences in aesthetic ability: The case for an aesthetic quotient. *Frontiers in psychology*, *7*, 750.
53. Nayak, B.K., Karmakar, S., 2019a. Eye Tracking Based Objective Evaluation of Visual Aesthetics: A Review. In: Rebelo, F., Soares, M. (eds) Advances in Ergonomics in Design. AHFE 2018. Advances in Intelligent Systems and Computing, vol 777. Springer, Cham. https://doi.org/10.1007/978-3-319-94706-8_41
54. Nayak, B.K. and Karmakar, S., 2019b. Eye tracking based objective evaluation of visual aesthetics: a review. In *Advances in Ergonomics in Design: Proceedings of the AHFE 2018 International Conference on Ergonomics in Design, July 21-25, 2018, Loews Sapphire Falls*

Resort at Universal Studios, Orlando, Florida, USA 9 (pp. 370-381). Springer International Publishing.

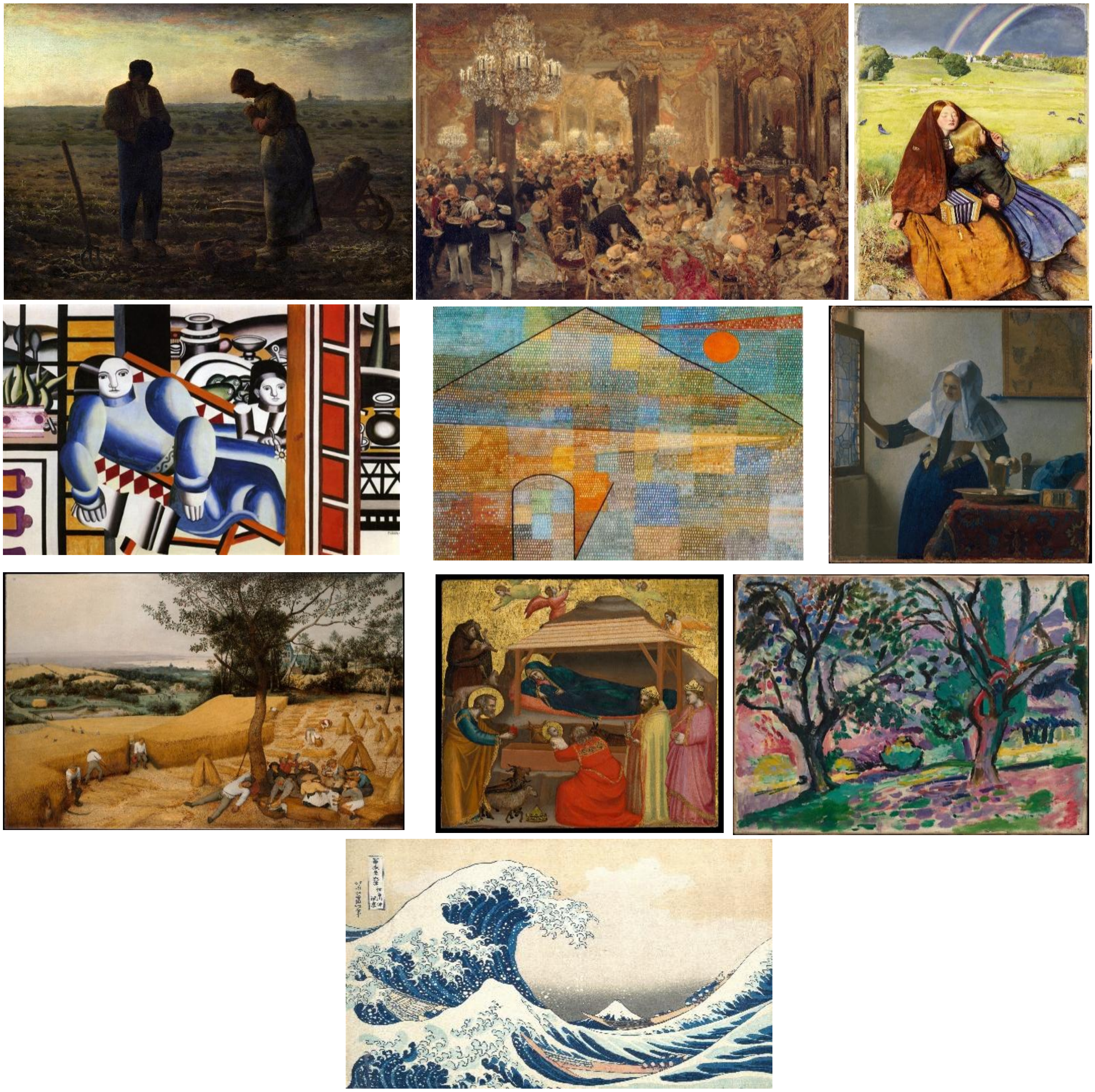
55. Negi, S., & Mitra, R. (2020). Fixation duration and the learning process: An eye tracking study with subtitled videos. *Journal of Eye Movement Research*, *13*(6), 40.
56. Nisbett, R. E., & Wilson, T. D. (1977). Telling more than we can know: Verbal reports on mental processes. *Psychological review*, *84*(3), 231.
57. Peterson, M. F., & Eckstein, M. P. (2013). Individual differences in eye movements during face identification reflect observer-specific optimal points of fixation. *Psychological science*, *24*(7), 1216-1225.
58. Prabhakaran, V., Smith, J. A., Desmond, J. E., Glover, G. H., & Gabrieli, J. D. (1997). Neural substrates of fluid reasoning: an fMRI study of neocortical activation during performance of the Raven's Progressive Matrices Test. *Cognitive psychology*, *33*(1), 43-63.
59. Prabhakaran, V., Smith, J. A., Desmond, J. E., Glover, G. H., & Gabrieli, J. D. (1997). Neural substrates of fluid reasoning: an fMRI study of neocortical activation during performance of the Raven's Progressive Matrices Test. *Cognitive psychology*, *33*(1), 43-63.
60. Pylyshyn, Z. W. (1973). What the mind's eye tells the mind's brain: A critique of mental imagery. *Psychological bulletin*, *80*(1), 1.
61. Raab, M. (2020). *Judgment, decision-making, and embodied choices*. Academic Press.
62. Ramachandran, V. S., & Hirstein, W. (1999). The science of art: A neurological theory of aesthetic experience. *Journal of consciousness Studies*, *6*(6-7), 15-51.
63. Raven, J. C. (1938). Progressive matrices: A perceptual test of intelligence (Vol. 19). *HK Lewis, London*, 20.
64. Shepard, R. N., & Cooper, L. A. (1986). *Mental images and their transformations*. The MIT Press.
65. Shepard, R. N., & Metzler, J. (1971). Mental rotation of three-dimensional objects. *Science*, *171*(3972), 701-703.
66. Snow, R. E. (1980). Aptitude, learner control, and adaptive instruction. *Educational Psychologist*, *15*(3), 151-158.
67. Spearman, C. (1904). " General Intelligence," objectively determined and measured. *The American journal of psychology*, *15*(2), 201-292.
68. Sternberg, R. J. (1977). Intelligence, information processing, and analogical reasoning: The componential analysis of human abilities. *Lawrence Erlbaum Associates*.

69. Sternberg, R.J. (2000) 'The Concept of intelligence', in R.J. Sternberg (ed.) *Handbook of Intelligence*. Cambridge: Cambridge University Press, pp. 3–15.
70. Stieff, M. (2007). Mental rotation and diagrammatic reasoning in science. *Learning and instruction*, *17*(2), 219-234.
71. Teovanović, P. (2019). Individual differences in anchoring effect: Evidence for the role of insufficient adjustment. *Europe's Journal of Psychology*, *15*(1), 8.
72. The International Cognitive Ability Resource Team (2014). https://icar-project.com/.
73. The Metropolitan Museum of Art. (n.d.). *The Met collection*. Retrieved January 2026, from https://www.metmuseum.org/art/collection
74. Thompson, V. A. (2021). Eye-tracking IQ: Cognitive capacity and strategy use on a ratio-bias task. *Cognition*, *208*, 104523.
75. Thomson, G. H. (1916). A hierarchy without a general factor. *British Journal of Psychology*, *8*(3), 271.
76. Thurstone, L.L., 1921. Intelligence and its measurement: A symposium--X. *Journal of Educational Psychology*, *12*(4), p.201.
77. Tversky, A., & Kahneman, D. (1974). Judgment under Uncertainty: Heuristics and Biases: Biases in judgments reveal some heuristics of thinking under uncertainty. *science*, *185*(4157), 1124-1131.
78. Varriale, V., Van Der Molen, M. W., & De Pascalis, V. (2018). Mental rotation and fluid intelligence: A brain potential analysis. *Intelligence*, *69*, 146-157.
79. Vessel, E. A., Starr, G. G., & Rubin, N. (2012). The brain on art: intense aesthetic experience activates the default mode network. *Frontiers in human neuroscience*, *6*, 66.
80. Vessel, E. A., Starr, G. G., & Rubin, N. (2013). Art reaches within: aesthetic experience, the self and the default mode network. *Frontiers in neuroscience*, *7*, 52124.
81. Vigneau, F., Caissie, A. F., & Bors, D. A. (2006). Eye-movement analysis demonstrates strategic influences on intelligence. *Intelligence*, *34*(3), 261-272.
82. Villani, D., Morganti, F., Cipresso, P., Ruggi, S., Riva, G., & Gilli, G. (2015). Visual exploration patterns of human figures in action: an eye tracker study with art paintings. *Frontiers in Psychology*, *6*, 1636.
83. Wallraven, C., Cunningham, D. W., Rigau, J., Feixas, M., & Sbert, M. (2009, May). Aesthetic appraisal of art: from eye movements to computers. In *Computational Aesthetics 2009:*

Eurographics Workshop on Computational Aesthetics in Graphics, Visualization and Imaging (pp. 137-144). Eurographics.

84. Xue, J., Li, C., Quan, C., Lu, Y., Yue, J., & Zhang, C. (2017). Uncovering the cognitive processes underlying mental rotation: An eye-movement study. *Scientific Reports*, *7*(1), 10076.
85. Yarbus, A. L. (2013). *Eye movements and vision*. Springer.
86. Young, S. R., Kim, J., McKee, K., Doyle, D. R., Novack, M. A., Revelle, W., ... & Dworak, E. M. (2025). Validation of International Cognitive Ability Resource (ICAR) Implemented in Mobile Toolbox (MTB). *Journal of Intelligence*, *13*(12), 154.
87. Zhao, B., & Sala, S. D. (2018). Different representations and strategies in mental rotation. *Quarterly Journal of Experimental Psychology*, *71*(7), 1574-1583.

Appendix A.



Appendix A: The ten listed paintings in order of appearance: Top row from left to right: “The Angelus” Jean-François Millet; “The Dinner at the Ball” Adolph von Menzel; “The Blind Girl” John Everett Millais Second row: “The Woman and the Child” Fernand Léger; “Ad Parnassum” Paul Klee; “Young Woman with a Water Pitcher” Johannes Vermeer; Third row: “The Harvesters” Pieter Bruegel the Elder; “The Adoration of the Magi” Giotto di Bondone; “Olive Trees at Collioure” Henri Matisse. Bottom row: “Under the Wave off Kanagawa” Katsushika Hokusai