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Differences in Spatial Visualization Ability and Vividness of Spatial Imagery Between People With and Without Aphantasia

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DIFFERENCES IN SPATIAL VISUALIZATION ABILITY AND VIVIDNESS OF SPATIAL IMAGERY BETWEEN PEOPLE WITH AND WITHOUT APHANTASIA

A dissertation submitted in partial fulfillment of the requirements for the
Doctor of Philosophy in Education, Educational Psychology
at Virginia Commonwealth University

by

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Acknowledgment

Ever since I was a little girl, I have always been curious. I have loved to hear strangers' stories, puzzles, and trying to understand how disparate things can fit together in a cohesive whole. For me, the journey is more important than the destination, which is why I do not believe I will ever stop realizing how much I do not know. Never in a million years did I imagine that I would earn my Ph.D, and there are so many people that I need to thank.

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Abstract

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Mathematics education researchers have examined the relationship between visualization and mathematics for decades (e.g., Arcavi, 2003; Bishop, 1991; Duval, 1999; Fennema & Tartre, 1985; Presmeg, 1986; Rösken & Rolka, 2006). Studies have linked spatial visualization ability, such as measured in mental rotation tasks, directly to mathematics self-efficacy (Pajares & Kranzler, 1995; Weckbacher & Okamoto, 2014), which in turn influences mathematics achievement (Casey, Nuttall, & Pezaris, 1997). With the important role that spatial visualization plays in learning mathematics, the recent identification of congenital aphantasia (Zeman, Dewar, & Della Sala, 2015), which is the lack of mental imagery ability, has raised new questions for mathematics education researchers. This study investigated the differences in mental rotation test performance and vividness of spatial imagery between people who have aphantasia and people who do not as a first step toward examining how aphantasia may affect mathematics learning and education. Results confirmed prior aphantasia research showing that there was no significant difference in mental rotation test performance between people with aphantasia and those without aphantasia, despite people with aphantasia reporting significantly lower vividness of spatial imagery. Results also showed that there was less difference in mental rotation test performance between the genders for people with aphantasia, while gender played a significant role in mental rotation test performance for people without aphantasia. People with aphantasia also reported lower self-efficacy in the arts than people without aphantasia. Implications of these results will be discussed within the context of current research, and possible directions for future research will be offered.

Keywords: mathematics, aphantasia, mental imagery, visualization, spatial imagery

Chapter One: Introduction

With the decrease in the number of students from the United States studying STEM-related subjects, some have predicted that there will be a shortage of qualified Americans to fill the available STEM jobs within the next ten years (Joint Economic Committee Chairman's Staff, Senator Bob Casey, Chairman, 2012). Success in higher level mathematics is considered a critical gateway for students pursuing careers in science, technology, engineering, and mathematics (STEM; Maltese & Tai, 2011; Tyson, Lee, Borman, & Hanson, 2007). The United States Department of Education found a correlation between those who studied higher level mathematics in high school (e.g., trigonometry, pre-calculus, calculus) and those who studied STEM in college. On average, those students had earned at least a "B" in their high school mathematics classes (Chen, NCES, & IES, 2009). Research has also found that the biggest differences in mathematical self-concept are between people who major in STEM fields and those who do not (Sax, 1994). The Sax (1994) results showed that 52% of men and 41.2% of women enrolled in STEM majors rated themselves in the top 10% in mathematics ability, compared to 16.9% of men and 8.6% of women in non-STEM majors. Moreover, the gender gap in mathematical self-concept was smaller in those enrolled in STEM majors than those enrolled in non-STEM majors (Sax, 1994). In contrast, poor performance in mathematics as early as the ninth grade may cause students to discount the possibility of studying further mathematics, engineering, or technology, and lead to choosing "lower prestige" careers (Shapka, Domene, & Keating, 2006). These findings bolster the theory that students tend to choose future study in fields where they have had prior success (Eccles, 2009). The potential shortage of qualified

American STEM professionals and the fact that mathematics is an important part of the STEM pipeline makes research into mathematics learning essential.

For decades, research has delved into the role that visualization plays in mathematics learning and problem-solving (e.g., Arcavi, 2003; Bishop, 1991; Duval, 1999; Fennema & Tartre, 1985; Presmeg, 1986; Rösken & Rolka, 2006). The term visualization has been defined in various ways in the literature, but in this proposed study, visualization means the production of a mental representation of an object not in sight; while the term mental imagery refers to the produced mental representation. In other words, visualization is the process and mental imagery is the product. Cognitive and neuro-imaging research into visualization supports two categories of visualization: object and spatial (e.g., Kosslyn, 1981; Logie & Pearson, 1997). Spatial visualization is the creation of spatial imagery, which is a mental representation of an object that deals with attributes like 3D structure, location, and motion. Object visualization is the creation of object imagery, or a mental pictorial representation of an object dealing with color, shape, and texture (Blazhenkova, 2016). Spatial visualization ability appears to have a direct, positive relationship to both mathematics achievement and mathematics self-efficacy (Casey, Nuttall, & Pezaris, 1997; Pajares & Kranzler, 1995; Weckbacher & Okamoto, 2014), while object visualization ability seems to have a parallel direct, positive relationship to achievement and self-efficacy in the arts (Blazhenkova & Kozhevnikov, 2016). In this context, self-efficacy reflects the "expectations of personal mastery" (Bandura, 1977) of a subject.

Given the apparent relationship between visualization and mathematics, what would happen if a student were given a geometry word problem such as, "Given triangle ABC, with side AB longer than side AC. Which angle is bigger, B or C?" and the student could not "see" the triangle in her mind's eye? How would the student solve the problem? According to Zeman et al. (2015), as many as one in thirty people are unable to create mental imagery, a condition he termed aphantasia. The identification of congenital aphantasia, which has been described as having a “blind mind’s eye,” has led to an interesting new avenue for visualization and mathematics education researchers. Existing research on aphantasia has focused on object rather than spatial visualization and has not yet studied the potential impact this condition could have on education. Studying the spatial visualization abilities of people with aphantasia and how those abilities may affect mathematics learning could lead to important insights into mathematics education.

Statement of the Problem

Because spatial visualization is most closely related to mathematics achievement and self-efficacy, this study aimed to begin to build a connection between the spatial visualization abilities of people with aphantasia and the learning of mathematics. The first step toward that goal was to examine the differences in spatial visualization ability, such as measured by mental rotation tasks, and vividness of spatial imagery between people with aphantasia and those without aphantasia. The study also explored differences in the level of self-efficacy in STEM and arts fields between people with and without aphantasia.

To date, published research on the visualization ability of people with aphantasia has dealt exclusively with object visualization. People with aphantasia score significantly lower than the general population on self-report instruments measuring vividness of object imagery (Zeman et al., 2010; Zeman et al., 2015). No research exists on the vividness of spatial imagery or spatial visualization ability of people identified with aphantasia. In fact, it was not until recently that researchers began to develop instruments meant to specifically target the two types of visualization (e.g., Blazhenkova, 2016; Blazhenkova, Kozhevnikov, & Motes, 2006). In validating the Vividness of Object and Spatial Imagery Questionnaire (VOSIQ), Blazhenkova (2016) found that vividness of object imagery and vividness of spatial imagery appeared to be two independent constructs. She also reported strong correlations between the vividness of object imagery scores and performance tasks that measured object visualization ability, and between the vividness of spatial imagery scores and spatial visualization ability performance tasks. Blazhenkova (2016) found a moderate correlation between the vividness of object and spatial imagery. However, Kozhevnikov, Blazhenkova, & Becker (2010) reported that there may be a trade-off between spatial and object visualization ability because of the brain's use of shared resources to accomplish visualization tasks. Kozhevnikov et al. (2010) found that subjects with high spatial visualization ability had lower object visualization ability, and vice versa. No subjects in the Kozhevnikov et al. (2010) study possessed both high spatial visualization ability and high object visualization ability.

Working from the conceptual framework that spatial visualization ability and vividness of spatial imagery are tightly connected to each other and to mathematics achievement and self-efficacy, the impact of a person having both low object and low spatial visualization ability on mathematics learning could be severe. With so much unknown, however, it is quite possible that people with aphantasia have high spatial visualization ability, which may make them more prone to enter STEM fields. If the estimate that one in 30 people have some level of aphantasia is true (Zeman et al., 2015), this study could have far-reaching effects on understanding the mathematics learning of a large segment of the population.

Context of the Study

Over the past fifty years, a multitude of cognitive and neuroscientific studies have focused on visualization and mathematics, spatial visualization and mathematics, and spatial and object visualization. Direct research on the relationship between object visualization and mathematics is rare and mostly tangential, resulting from examining the differences between spatial and object visualization ability (e.g., Xistouri & Pitta-Pantazi, 2011). Because congenital aphantasia is a recently identified phenomenon, very little published research on the condition exists, and that research has dealt exclusively with object visualization ability. There are no published studies on how aphantasia may affect spatial visualization ability and mathematics learning and education. Figure 1 represents where this study falls in the existing research into mathematics and visualization.

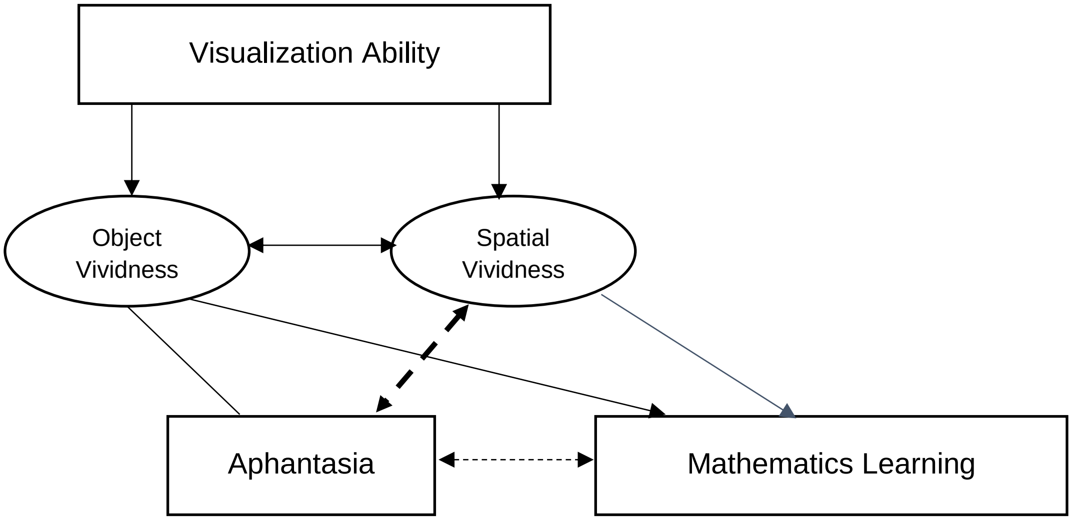

Figure 1: Current research in visualization, aphantasia and mathematics. Solid lines represent the existence of published studies on the relationships. Dotted lines mean that there is currently no published research on the relationships. The bold dotted line represents what the current study addressed.

Study Rationale

The purpose of this study was to examine the visualization characteristics of people with aphantasia. People with aphantasia score significantly lower on the Vividness of Visual Imagery Questionnaire (VVIQ; Marks, 1973; Zeman et al., 2015), which indicates very poor vividness of object imagery. To date, no published data exists on vividness of spatial imagery of people with aphantasia. Further, no research on “normal non-imagers” (Faw, 2009) and their experiences with mathematics has been published. If people with aphantasia have high spatial imagery vividness and high spatial visualization ability, research would suggest that they would perform well in mathematics and tend to choose professions related to STEM. In fact, unpublished research using self-report data from thousands of participants has found that respondents with aphantasia were more likely to have careers in IT or mathematics, while respondents at the other end of the vividness of object imagery scale, those with hyperphantasia, were more likely to have careers in the arts (Winlove, Goddum, Heuerman-Williamson, & Zeman, 2017). This would seem to indicate that people with aphantasia have strong spatial visualization ability. However, because the only data available on people with aphantasia deals with vividness of object imagery and is based on self-report surveys, the level of their spatial visualization ability remains unknown. Tests, such as the Object-Spatial Imagery Questionnaire (OSIQ; Blazhenkova, Kozhevnikov, & Motes, 2006) and the Vividness of Object Spatial Imagery Questionnaire (VOSIQ; Blazhenkova, 2016), as well as performance measures like the Mental Rotation and Paper Folding tasks, must be undertaken with subjects who report they have aphantasia. If results from spatial visualization tests show that people with aphantasia have low spatial visualization ability, along with low object visualization ability, yet are successful in mathematics, they must be compensating with some other representation method. To determine whether spatial visualization ability can be considered “low,” there must be a baseline against which to compare, which is why this study is designed as a comparison study between people with aphantasia and people who do not have aphantasia.

Conceptual Framework

The design of this study aligned with previous research on visualization and mathematics, as well as the existing research on aphantasia. As indicated previously, studies have shown that there are two categories of visualization: spatial and object, corresponding to spatial and object imagery respectively (e.g., Chabris, et al., 2006). Other research has linked performance on spatial visualization ability tasks like the MRT to mathematics performance (e.g., Hegarty & Kozhevnikov, 1999), and performance on object visualization tasks such as the Fragmented Pictures task to object visualization ability (e.g., De Winter & Wagemans, 2004). Object visualization ability has been linked to self-efficacy and ability in the arts, while spatial visualization ability has been linked to self-efficacy and ability in STEM fields (e.g., Kozhevnikov, Kosslyn, & Shephard, 2005). Blazhenkova (2016) found strong correlations between responses on the object items of the VOSIQ and responses to the VVIQ, and between responses to the spatial items of the VOSIQ and performance on the MRT. This would seem to show that vividness of object imagery as measured on the VOSIQ is a satisfactory representation of object visualization ability; while vividness of spatial imagery is a satisfactory representation of spatial visualization ability. Figure 2 represents the conceptual framework of this study.

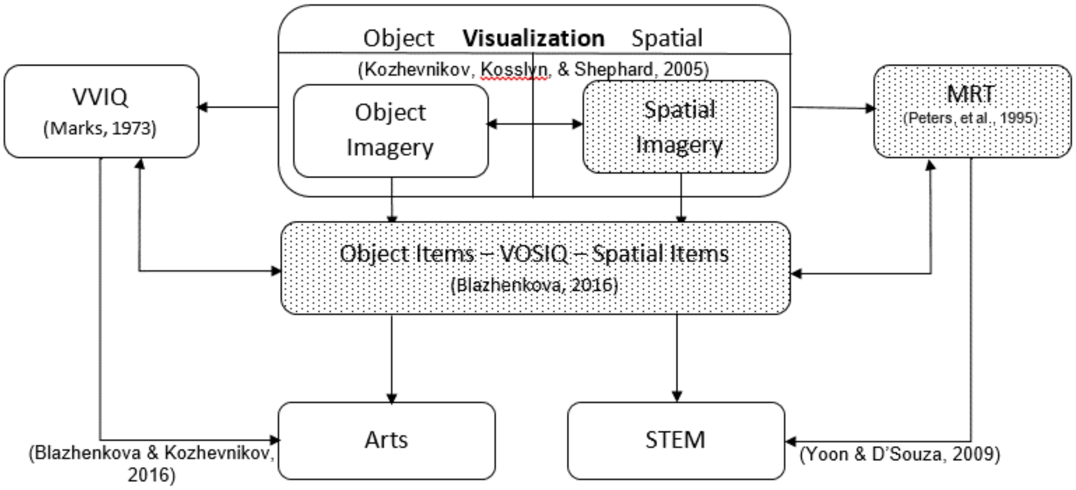

Figure 2. Conceptual framework. Graphic of how this study aligns with current research. Greyed boxes indicate the focus of this study regarding aphantasia.

Research Questions

The study addressed the following research questions:

1. Is the vividness of mental imagery of people with aphantasia significantly lower than the vividness of mental imagery of people without aphantasia?

- **a.** Object Imagery
- **b.** Spatial Imagery

2. Is mental rotation test performance of people with aphantasia significantly lower than mental rotation test performance of people without aphantasia?

- **a.** Accuracy
- **b.** Speed

3. Is there a significant correlation between mental rotation test performance and vividness of mental imagery?

- **a.** Accuracy – Spatial Imagery

  - **b.** Accuracy – Object Imagery
  - **c.** Speed – Spatial Imagery
  - **d.** Speed – Object Imagery

4. Is the level of self-efficacy in Arts/STEM independent of whether a person has aphantasia?

  - **a.** Arts
  - **b.** STEM

Definition of Terms

The definitions of the key terms used throughout this study are listed below:

1) *Ability:* Possessing capacity and/or talent to perform a task.
2) *Aphantasia*: The inability to create mental images of objects not in sight. This condition is characterized by a score of less than 30 on the Vividness of Visual Imagery Questionnaire (VVIQ; Marks, 1973; Zeman et al., 2015).
3) *Arts*: Fields in creative pursuits, such as literature, visual arts, music, dance, theater, etc.
4) *Mental Imagery*: Representation in the mind of an object that is not present.
5) *Object Imagery*: Pictorial representation in the mind dealing with attributes like shape, texture, and color of an object.
6) *Self-efficacy*: Belief in the capability of performing various activities (Bandura, 1982).
7) *Spatial Imagery*: Relational representation in the mind dealing with attributes like 3D structure, location, and motion.
8) *STEM*: Fields in science, technology, engineering, and mathematics; including computer science.

9) *Vividness*: “the quality of the subjective imagery experiences in terms of their clarity and richness, sense of reality, and resemblance of actual perceptual experiences” (Blazhenkova, 2016, p. 491).
10) *Visualization*: The creation of a mental representation of an object when the object is not present (Presmeg, 2006).

Chapter Two: Literature Review

This section of the paper will give a broad overview of the history of research on visualization and how it has been broken down into object and spatial. The review will then delve into visualization research from the perspectives of cognitive psychology and neuroscience. Next, the section will outline the theorized relationship between object and spatial visualization ability and the vividness of visualization will be outlined. Finally, the review will discuss current research on aphantasia.

Summary of Search Methodology

Literature for this review was gathered from both internet and in-print sources. Internet sources included Google Scholar, PsychINFO, ERIC, and JSTOR, while in-print sources included reprints of journal articles that were unavailable online and books from the VCU Libraries system. The search began with the keywords “aphantasia mathematics” using the VCU Libraries website, restricting results to peer-reviewed articles. This initial search returned no relevant results. The term was then shortened to just “aphantasia,” which returned four dissertations and three articles. The dissertations were conceptual in nature and none dealt directly with aphantasia. Of the three articles, two focused on aphantasia, while the third article was a review of the second. To widen the search, the single word “aphantasia” was used as a Google Scholar search term, which returned two further conceptual articles. Because of the lack of results, references from the aphantasia articles were then examined. I expanded the electronic and in-print searches to include the keyword visualization, which resulted in an overwhelming amount of historical research, much of which did not meet this study's definition of the term as the production of mental imagery. Therefore, the search was narrowed by using more specific terms like mental imagery and linking visualization and mathematics. Using these search terms revealed decades of research on visualization and mathematics, as well as books and articles focused on visualization as a cognitive process to create mental imagery and conceptual works on mental imagery itself. This line of research documented the bifurcation of object and spatial visualization, and the term "object spatial visualization" became the new keyword to continue the search. This term resulted in articles about the relationship each type of visualization had with preference, achievement, and career choice. Following along this path also led to ongoing neuroscientific research into object and spatial visualization as a neurological process that could be measured using methods such as functional magnetic resonance imaging (fMRI).

Visualization

Visualization is a complicated concept. In the research literature, the word visualization has had many definitions. The term visualization has been defined as the perception of concrete images, the use of images to illustrate or solve problems, and the creation of mental imagery of an object in the mind when the object is not present (Presmeg, 2006). In their exhaustive research into the concept of visualization in the context of educational research, Phillips, Norris, & Macnab (2010), grouped the various definitions into categories like those of Presmeg: visualization objects (concrete images); introspective visualization (mental imagery); and interpretive visualization (use of images to solve problems; p. 26). When the word visualization is used in terms of perception, it could mean the pictures in a storybook created to represent the author's words that the reader sees. When used in terms of mental imagery, visualization could mean the creation of pictures in the reader's imagination to represent the author's words sans visual stimuli. In this proposal, the term visualization will refer to the production of mental imagery of an object that is not in sight, as defined by Presmeg (2006) and Phillips, et al. (2010).

Because the very act is not observable, the study of mental imagery was the domain of philosophers for much of history, starting with Aristotle's view that all thought was accompanied by pictures, or visual mental imagery (Faw, 2009). Many researchers attribute the start of the formal study of mental imagery to Sir Francis Galton. In 1880, Galton published an article detailing his inquiry into the vividness of individual mental imagery ability (Burbridge, 1994; Galton, 1880). Vividness of mental imagery refers to how clearly a person can "see" representations in their mind's eye without a visual stimulus. Galton explained that the reason for his imagery research was his own curiosity. After reading articles describing people who could "present mental pictures that may be scrutinised with nearly as much ease and prolonged attention as if they were real objects" (Galton, 1883, p. 83), and what he saw as his own "dim" mental imagery ability, he decided to investigate the phenomenon. Galton developed an open-ended questionnaire that was meant to measure three properties of a person's vividness of mental imagery: illumination, definition, and colouring (Galton, 1880, p. 301). He asked 100 adult men, including 19 scientists, as well as 172 students, to complete the questionnaire. An example item from Galton's instrument was, "think of some definite object -- suppose it is your breakfast-table as you sat down to it this morning -- and consider carefully the picture that rises before your mind's eye" (1880, p. 302). Galton created the instrument and chose his subjects with the assumption that the more educated, most notably the scientists, would possess the most vivid imagery ability and would be best able to explain the experience. Instead, his data collection revealed that the scientists he questioned seemed to have little to no idea what he meant by mental imagery. Given his preconceptions, he was quite surprised at the results he received when polling people from what he called the “general society.” He wrote, “On the other hand, when I spoke to persons whom I met in general society, I found an entirely different disposition to prevail. Many men and a yet larger number of women, and many boys and girls, declared that they habitually saw mental imagery, and that it was perfectly distinct to them and full of colour” (Galton, 1880, p. 303). The results of this inquiry led Galton to posit that lower vividness of mental imagery was a characteristic of scientists and those with higher intelligence.

When discussing the obstacles to research on mental imagery, Shepard (1978) wrote, “What makes a mental image such a difficult thing to study empirically or even to clarify conceptually is that it is inherently internal” (p. 128). In fact, the study of mental imagery became a risky proposition in the scientific world after the rise of behaviorism as a psychological philosophy. According to Bower (1972), “many experimental psychologists cannot entertain thoughts about imagery without some deep sense of guilt associated with some forbidden taboos” (p. 51). However, over one hundred years after Galton, researchers in the fields of cognitive psychology, neuroscience, and education began to take a renewed and intense interest in the concept of mental imagery and published a copious amount of research on the topic. As an example, because of conflicting accounts of scientists claiming to actively use visualization in their work, Brewer & Schommer-Aikins (2006) set out to test Galton’s conclusions about the relationship between low vividness of mental imagery and scientists. Brewer & Schommer-Aikins (2006) believed that Galton was not testing vividness of mental imagery, but vividness of recall memory, which they proposed was an entirely different process. In their report, the authors include a quote from Albert Einstein where he denied that words played any role in his thought processes. Instead, Einstein said, “The psychical entities which seem to serve as elements in thought are certain signs and more or less clear images which can be ‘voluntarily’ reproduced and combined" (Brewer & Schommer-Aikins, 2006, p. 133). As further examples, the authors cited quotes from scientists like J.J. Thompson. Thompson wrote that when thinking of mechanical models, "an attempt is made to form an idea of something concrete, a model, for example, which will supply us with a mental picture of what may be taking place in the physical phenomena under consideration" (Brewer & Schommer-Aikins, 2006, p. 133). This evidence of scientists appearing to use mental imagery as a core part of their thinking and problem-solving led Brewer & Schommer-Aikin to use Galton's original open-ended instrument on a group of scientists and a group of undergraduate students. Two raters then scaled the answers from one to five, where one represented no imagery at all and five represented the highest vividness of imagery. Analyzing this newly collected data, Brewer & Schommer-Aikins (2006) found that only 6% of the scientist subjects appeared to have "feeble imagery," much different from what Galton concluded. However, the scientists in Brewer & Schommer-Aikins (2006) did show lower vividness of mental imagery on average when compared to the undergraduate subjects. The researchers suggested that it was possible that Galton's conclusions were biased by his own belief in his theory (Brewer & Schommer-Aikins, 2006).

Object and Spatial Visualization

Research on visualization has also led to the proposition that there are two types of visualization: object and spatial. Object visualization refers to the generation of pictorial images and includes being able to clearly visualize shape, color, and texture, such as measured by Galton's instrument. Spatial visualization refers to the generation of a schema that represents an object's three-dimensional structure, motion, and location (Chabris, et al., 2006), which arguably could describe the type of visualization used by the scientists quoted by Brewer & Schommer-Aikins (2006). Spatial visualization ability has been strongly associated with mathematics learning via psychological and neurological experiments. Table 1 offers a brief overview of terms used in the literature that describe two separate types of imagery and visualization.

Table 1

Overview of Terms in the Literature

Author	Object	Spatial
Bower, 1972	what	how
Kosslyn, Brunn, Cave, & Wallach, 1984	surface representation	deep representation
Presmeg, 1986	concrete imagery	pattern imagery
Van Garderen, 2006	pictorial	schematic
Blazhenkova & Kozhevnikov, 2009, p. 640	"objects and scenes in terms of their shape, colour information and texture"	"object location, movement, spatial relationships and transformations and other spatial attributes"
Clements, 2014	holistic (as strategy)	analytic (as strategy)
Blazhenkova, 2016	color, texture, shape	3D structure, location, mechanism

Cognitive psychology

The natural assumption when discussing mental imagery is that it is visual, that humans are creating pictures in their minds to study and manipulate for some purpose, be it recall or problem-solving. However, cognitive researchers have offered the theory that visualization is both pictorial and propositional. In 1972, Bower posed the idea that mental imagery is used to describe both the "how" and the "what." This idea means that while there may indeed be visual pictures generated in the mind (the "what"), mental imagery can also be structural and represent the "how" of an object. In other words, some mental imagery is less of a picture of an object than a verbal or spatial depiction of the object and how it behaves or relates to its context. The words “propositional” and “structural” may refer to what is known as spatial reasoning. Many researchers have made the argument for this idea of propositional or spatial mental imagery, either instead of, or in addition to, visual or object mental imagery.

Pylyshyn (1973) was another one of the first cognitive researchers to discuss the possibility of non-visual mental imagery existing alongside visual mental imagery (object). As evidence of this, Pylyshyn wrote of a hypothetical experiment where a subject learns a paired word association such as “boy-play” after looking at an image of a boy playing. In his example, the subject would later be given the stimulus “boy,” recall the image of the boy, and immediately associate the word “play.” Pylyshyn wrote, “The problem remains, however, to explain why the subject in this case chooses to respond play and not throw or ball or catch or any of an unlimited number of words equally appropriate to that image. Presumably it is because he remembers more than is contained in the image” (1973, p. 7). Pylyshyn also believed that the activity of generating mental imagery was separate from the processing of information. Shepard (1978), however, believed that object, or pictorial, imagery was a crucial actor in creativity and invention. As examples, he wrote of scientists who created theories that could have only been based on some sort of mental imagery or internal visualization, such as Faraday and his depiction of how electromagnetic fields exist in space (Shepard, 1978). It could be argued that the imagery Shepherd described as being used by Faraday could be placed into the “spatial” category of imagery because the depiction of electromagnetic fields deals with location, motion, and structure more than a realistic pictorial image.

Anderson (1978) wrote a review of the disagreement between what he referred to as “image theorists” who believed that mental imagery was strictly visual and “propositional theorists” who believed that mental imagery was only descriptive or spatial. By examining the existing proposed cognitive models of visualization at the time, Anderson found that none of them were able to adequately explain the phenomenon of mental imagery and its processing. Anderson (1978) even suggested the use of multiple information processing models, each to fit a specific mental imagery task or tasks. In one of the bullet points of his conclusion, Anderson wrote, “The frequent criticisms made of the picture metaphor are not valid. One can have a viable dual-code model involving picture and verbal representations” (1978, p. 275).

Cognitive psychologist and neuroscientist Stephen Kosslyn has been working on a model of mental imagery since the 1970’s. Kosslyn viewed mental imagery and its manipulation as a logical system. He used the theories of computer science to create a computer model of mental imagery composed of data and processes (Kosslyn, Brunn, Cave, & Wallach, 1984). The “data” for this model were very similar to the idea of spatial and object mental imagery. Kosslyn (1981) theorized that mental imagery was made up of two components: a surface representation and a deep representation. The surface representation was described as “a quasi-pictorial representation that occurs in a spatial medium; this representation depicts an object or scene and underlies the experience of imagery” (p. 49), while the deep representation “is the information in long-term memory that is used to generate a surface representation” (p. 49). In Kosslyn’s (1981) model, both the surface and deep representations could be acted upon by various processes: image generation, image inspection, and image transformation. The representations were theorized to be used for image retrieval and transfer between the long- and short-term memory stores by using the deep representation to construct the surface representation. Other systems-thinking cognitive psychologists described mental imagery processing in terms of the activities of perception, manipulation, storage, and retrieval in the context of working memory (e.g., Baddeley, 1988; Logie, 2014; Logie & Pearson, 1997, Pearson, 2001). Baddeley (1988) theorized that mental imagery is stored by a visuo-spatial sketchpad. In Baddeley's theory, the sketchpad is the storage place in working memory that contains the necessary object and spatial information to set up and manipulate mental visual images, which is very like Kosslyn's definition of surface and deep representation. Baddeley (2007) offers further evidence of the dissociation of visual and spatial information in working memory from a Logie & Marchetti (1991) study which showed that recall of a sequential series of colors was disrupted by showing the subjects images, and the ability to recall sequential order was disrupted by movement of the subject's arm.

In their 1997 experiment on the development of the visuo-spatial sketchpad (VSSP) in working memory, Logie & Pearson found that there was evidence that both object and spatial representations are stored in the VSSP for use in working memory. The researchers tested groups of children on their recall and recognition of pattern and motion. The children were separated into three age range groups: five to six; eight to nine; and 11 to 12 years old. The results showed that the subjects' ability to recall and recognize patterns increased rapidly with age, while the ability to recall and recognize motion seemed to develop more slowly. This led to the conclusion that visual and spatial skills developed at different rates, meaning that these skills were independent. More recent cognitive psychology experiments have used different types of instruments and tests that target either object (pictorial) or spatial (structural or propositional) visualization. These instruments will be discussed in the Measurement section of this paper. Results from these experiments have provided even more evidence of the two styles of visualization (e.g., Blazhenkova & Kozhevnikov, 2010; Burton & Fogarty, 2003).

Neuroscience

Before the availability of reliable neuro-imaging, researchers had to rely on subjective self-report, supposition, or inferences from observable experiments to collect data on visualization. Recent neuroscientific research has allowed scientists to analyze brain activation patterns and locations, supporting the distinction between object and spatial visualization that cognitive psychologists have theorized. Studies have found that there are two types of brain activation for these two different components of mental imagery (e.g., Botez, Olivier, Vézina, Botez, & Kaufman, 1985; Carlesimo, Perri, Turriziani, Tomaiuolo, & Caltagirone, 2001; Kosslyn, Ganis, & Thompson, 2001; Mishkin & Ungerleider, 1982). fMRI and ERP studies have discovered that there are two separate visual pathways in the brain, the dorsal and the ventral, which process spatial and object imagery respectively (e.g., Wang, et al., 1999). Studies have also found spatial visualization and mental rotation task ability differences between genders. In most research over the past three decades, males have shown a higher level of spatial visualization and mental rotation task ability than women (Casey, Nuttall, & Pezaris, 1997; Debelak, Gittler, & Arendasy, 2014; Fennema & Sherman, 1977; Fennema & Tartre, 1985), even manifesting in differing areas of brain activation during visualization tasks (Jordan, Wüstenberg, Heinze, Peters, & Jäncke, 2002; Logie, Pernet, Buonocore, & Della Sala, 2011; Weiss et al., 2003). However, Moè (2009) wrote that self-efficacy plays a large part in mental rotation task performance for females. In their meta-analysis of the research on the gender differences in mental rotation task ability, Maeda & Yoon (2013) reported that the mental rotation test performance gap between males and females increases when the task is timed, which may indicate that the two genders may be using different strategies.

Object vs. Spatial Visualization Ability

Currently, most of the existing literature points to visualization being both object and spatial. Research on object-spatial visualization reveals that people prefer one or the other type of visualization, each of which has its own connection to education and preferred profession (e.g., Blazhenkova & Kozhevnikov, 2016; Yoon & D'Souza, 2009). Blazhenkova & Kozhevnikov (2016) found that people with stronger, more vivid object imagery tended to select professions related to the arts, while people with stronger vividness of spatial imagery preferred STEM fields. Of course, visualization ability is not the sole predictor of career or chosen field of study. Wai, Lubinski, & Benbow (2009) found that females with high spatial ability more often enter creative fields in the arts, in contrast to males with high spatial ability who more often enter STEM fields. So, even when both genders display the same level of spatial ability, affect, attitudes, and societal norms may play a part in education and career planning.

Research has also found that people with higher vividness of object imagery are better with autobiographical memory than those with low vividness of object imagery (Sheldon, Amaral, & Levine, 2017). Vannucci, Pelagatti, Chiorri, & Mazzoni (2016) found a significant correlation between high vividness of object imagery, fantasy proneness, and the frequency of specific types of video game play; a correlation that was not found in those with high vividness of spatial imagery. Yoon & D'Souza (2009) studied college students enrolled in design and architecture and found that object visualizers preferred to work in two dimensions and use familiar materials, while spatial visualizers preferred working in three dimensions with less concern about materials. In their comparison between college students majoring in interior design and those majoring in architecture, Yoon & D'Souza wrote, "it was also found that architecture students scored significantly higher in spatial visualization." Because architecture is considered a STEM field (Wai, et al., 2009), these results would seem to lend credence to the connection between spatial visualization ability and mathematics self-efficacy and achievement.

Measurement

While the study of mental imagery was once considered impossible because of the lack of observability, the subject has become increasingly important because of the possible implications for psychology and education. Most measurement of mental imagery ability has been based upon statistical analyses of the results of self-report surveys or the evaluation of performance tasks. Survey instruments have mostly focused on vividness of object mental imagery. Galton's (1880) visualization questionnaire was intended to measure vividness, which included sharpness and brightness (or definition and illumination); color; "extent of field of mental view" (p. 310); ability to project an image onto a surface; and the size of mental images compared to the actual object. Of his purpose, he wrote, "I desire to define the different degrees of vividness with which different persons have the faculty of recalling familiar scenes under the form of mental pictures, and the peculiarities of the mental visions of different persons" (p. 302). He categorized the responses he received on his instrument into high, mediocre, and low faculty. While Galton focused on voluntary imagery, Betts (1909) used the work of Galton and Titchener (1909) to create a 150-item instrument to study the vividness of imagery that takes place during mental processes, or what he called "spontaneous imagery." Sheehan (1967) created and validated the results from a shortened form of the Betts instrument. Sheehan explained that the Betts questionnaire measured the vividness of seven types of imagery: "Visual, auditory, cutaneous, kinaesthetic, gustatory, olfactory, and organic" (p. 387). Marks (1973) created the Vividness of Visual Imagery Questionnaire (VVIQ) that is still in frequent use today (e.g., Blazhenkova, 2016; Campos, 1995; McKelvie, 1995; Zeman et al., 2015). The VVIQ is a self-report questionnaire that asks respondents to describe how vividly they "see" described images in their minds using a Likert-type scale. The original VVIQ (Marks, 1973) grouped items after a prompt such as, "Visualize a rising sun. Consider carefully the picture that comes before your mind's eye" (p. 24). The prompt was then followed by items asking the respondent to visualize certain aspects of the prompt. For example, one item following the prompt was, "Clouds. A storm blows up, with flashes of lightning" (p. 24). The response options were numbered from one to five, from most vivid to least vivid. Marks (1973) wrote the options as follows: 1) Perfectly clear and as vivid as normal vision; (2) Clear and reasonably vivid; (3) Moderately clear and vivid; (4) Vague and dim; and (5) No image at all, you only "know" that you are thinking of the object" (p. 18). The VVIQ relies exclusively on a person's own opinion of what they are seeing with their mind's eye.

With the distinction between two key varieties of mental imagery, object and spatial (Mishkin & Ungerleider, 1982), researchers developed other scales to measure object-spatial visualization ability and preference, as well as vividness of object-spatial visualization. Blazhenkova, Kozhevnikov, & Motes (2006) developed the Object-Spatial Imagery Questionnaire (OSIQ) in response to cognitive and neuroscientific research that "emphasized a key distinction in visual information processing, namely, that there is a distinction between processing object properties and processing spatial relations" (p. 242). The items on the OSIQ target object or spatial visualization ability, and the response options are a scale from one to five, from total disagreement to total agreement respectively. As explained previously, object visualization is when one imagines pictorial representations dealing with attributes like shape, texture, and color. Spatial visualization is associated with relational representations like 3D structure, location, and motion. An example of an object-related OSIQ item is, "My images are colourful and bright," while an example of a spatial-related OSIQ item is, "My images are more schematic than colourful and pictorial" (Pitta-Pantazi & Christou, 2010, p. 106). Keogh & Pearson (2017) used the OSIQ, VVIQ, and the spontaneous use of imagery scale (SUIS) in conjunction with the binocular rivalry task to compare the physical response and subject perception of visualization between people with aphantasia and a control group. Keogh & Pearson found that participants with aphantasia "were not impaired on their spontaneous use of spatial imagery" (2017, p. 6).

While the OSIQ was created to measure ability and preference, the Vividness of Object-Spatial Imagery Questionnaire (VOSIQ) was developed to measure the vividness of spatial and object imagery (Blazhenkova, 2016). The VOSIQ used the same response options as the VVIQ (Marks, 1973). An example VOSIQ item that targets the vividness of object imagery is, "Fine details of a zebra's skin," while "Mechanism of a door handle" targets vividness of spatial imagery (Blazhenkova, 2016, p.499). Results from validation studies of the VOSIQ show that (1) Marks' VVIQ (1973) almost exclusively measures object imagery and (2) there is a trade-off between object and spatial visualization (Blazhenkova, 2016). Psychological and neuroscientific research has revealed that people have a natural preference and aptitude for either object or spatial visualization and are better at one than the other (Kosslyn & Thompson, 2012; Pitta-Pantazi & Christou, 2010).

A 1971 factor analysis of tests used in mental imagery research revealed that while spatial and image representation appear to be independent, results from subjective imagery measures were significantly affected by the social desirability factor. This suggests that subjective reports on imagery may not be enough to stand on their own without some objective measure (Di Vesta, Ingersoll, & Sunshine, 1971). In their exhaustive review of instruments used to measure object and spatial visualization ability and imagery vividness, Pearson, Deeprose, Wallace-Hadrill, Heyes, & Holmes (2013) evaluate performance task measures as well as subjective survey instruments that have been used extensively in research on mental imagery in psychological disorders. The authors separate the measures into the domains of image generation, image maintenance, image inspection, mental rotation, restructuring and reinterpretation, and mental synthesis. Pearson et al. (2013) state that objective performance tasks and subjective self-report instruments should be used together. As an example of that approach, when Blazhenkov (2016) validated the VOSIQ, she used alternative performance tasks to obtain concurrent validity for the results. For object imagery, she used the VVIQ, as well as Fragmented Pictures and Camouflage Pictures tasks. The Fragmented Pictures task gives subjects five minutes to discern objects from images of fragmented outlines (De Winter & Wagemans, 2004). The Camouflage Pictures task presents subjects with images of nature. The subjects are then given five minutes to find hidden objects in the pictures. Both tasks are meant to measure the ability of a person to perceive and recognize pictorial representations of whole objects.

To validate the spatial imagery portion of the VOSIQ, Blazhenkov (2016) added the Mental Rotation and Paper Folding tasks. Many variations of the mental rotation task have been developed, but one of the most used is from Vandenberg & Kuse (1978). The design of their task asks subjects to look at an irregularly shaped figure made of cubes. Subjects are then presented with what appear to be several images of the original figure rotated, but only two of the options are feasible rotations of that figure. The subjects have three minutes to select the options that are correct rotated representations. The Paper Folding task (Ekstrom, French, Harman, & Dermen, 1976) requires subjects to look at an image of folded paper and determine how it would look unfolded. These tasks measure the subject's ability to mentally manipulate objects in space. Blazhenkov (2016) correlated the results from the object imagery tasks and VVIQ with the responses on the VOSIQ object items, and the results from the spatial imagery tasks with the responses on the VOSIQ spatial items for concurrent validity of her scale. The VOSIQ may be a much more helpful measure than the VVIQ because it is measuring the vividness of both types of visualization.

Neuroscience has also lent its voice to objective measurement of the vividness of mental imagery. Cui, Jeter, Yang, Montague, & Eagleman (2007) first administered the VVIQ and then had the subjects perform a color naming task where they had to identify colors when they were flashed briefly in either color or word form. The researchers then used fMRI while their eight subjects were asked to create mental images of themselves either lifting weights or climbing stairs. Cui et al. (2007) found that there was a significant correlation between the results on the subjective measures and the measured relative activity (blood flow) in the early visual cortex of the brain. Their article states, "This finding is conceptually interesting because it shows that aspects of mental thought can be studied objectively with current technology (e.g., fMRI)" (p. 477). Another recent fMRI study found that a smaller primary visual cortex surface area was negatively correlated to the strength of mental imagery, and positively correlated with detail and location imagery (Bergmann, Genç, Kohler, Singer, & Pearson, 2016). This suggests that the trade-off hypothesized by object-spatial visualization researchers may be a factor of the size of the primary visual cortex. To quantify spatial visualization, neuroscientists have captured fMRI data while subjects are performing tasks like the Vandenberg & Kruse Mental Rotation test (1978). To measure object visualization, researchers have asked subjects to generate mental images based upon non-visual stimuli (Ganis, Thompson, & Kosslyn, 2004) during fMRI scans.

To date, the main purpose of fMRI implementation of visualization tests is less to measure ability than to determine which parts of the brain are activated when different subsets of the population are performing the tasks. Neuroscientific measurement allows for objective imagery testing but can also lend validity to the results of subjective self-report scales. Further, brain scans can be used to draw inferences on the relationship between brain activation patterns and measures like mathematics tests (de Hevia, Vallar, & Girelli, 2008).

Visualization and Mathematics

Even though the relationship between spatial ability and mathematics is acknowledged by most mathematics education researchers, there is no concrete explanation for this relationship. In her book about individual differences in mathematics, Dowker (2005) posited that verbal ability is a more important factor in mathematics than spatial ability, but she did write that spatial ability does have a direct relationship to geometry. Dowker also wrote that the relationship between spatial ability and types of mathematics other than geometry has not been proven. In a 1981 study, researchers found that high spatial visualization ability had less influence on mathematical performance than verbal-logical ability (Lean & Clements, 1981). However, Skagerlund & Träff (2016) used a mental rotation task to measure spatial transformation ability and found that mental rotation ability served as a predictor of overall mathematics ability.

Lean & Clements (1981) defined spatial ability as “the ability to formulate mental images and to manipulate these images in the mind.” This is slightly different from how other studies have defined spatial ability. For instance, Blazhenkova (2016) defined spatial ability as “visualizing spatial relations and movements of objects and their parts, and spatial transformations” (p. 492). The latter definition strips the creation of mental images from spatial ability, a view that is more aligned with the preponderance of research on mathematics and spatial visualization. It has been theorized that spatial ability is used when dealing with the capacity of numbers on a number line, using information for complex mental calculations, or being able to understand mathematics facts in a deeper way (Booth & Thomas, 1999; Presmeg, 1986). An example of how intertwined spatial visualization and mathematics has been in the research is the van Hiele model of geometric thinking (Fuys, Geddes, & Tischler, 1988; Hershkowitz, 1989). In the van Hiele model, the very first level of geometric thinking is visualization (van Hiele, 1984). In his article on the role of visualization in mathematics learning, Arcavi (2003) described visualization in terms of seeing what is not seen, of using the mind's eye to imagine, rotate, and transform objects that may or may not be within physical sight. He wrote that visualization is being able to see "what we are unable to see because of the limitations of our visual hardware" (p. 55). Applying this to mathematics, Arcavi (2003) meant that visualization allows humans to, among other tasks, see patterns in data, represent objects symbolically, and abstract information for problem-solving.

In his review of the research on spatial abilities and mathematics, Bishop (2008) identified and discussed four different categories of researchers that have been engaged to provide evidence of the spatial-mathematical relationship: factor analysts; developmental psychologists; those focused on individual differences; and teaching experimenters. Clements (2014), in his own literature review on visualization and mathematics, also pointed out that the word visualization has had several meanings depending on the research focus. Clements wrote that psychologists have used the term in the context of factor analysis, meaning that psychological researchers tend to study the acts of perception and mental imagery to identify the underlying structure of the behavior. In this definition, visualization has been broken down into the types of strategies people use to visualize; for instance, analytic and holistic. Analytic strategy corresponds to the idea of spatial visualization, where items are viewed in the mind's eye by their structure and the way the parts of the item fit together. Holistic strategy refers to object visualization, where an item is viewed as more of a concrete, whole pictorial representation. In a 1996 study on spatial visualization ability and mathematics, Skemp (1996) studied girls with high and low spatial visualization ability. While both groups of girls performed their mathematics tasks successfully, Skemp found that, when dealing with multiplication facts, girls with higher spatial visualization ability had what was called a "relational" understanding, meaning that they understood the concepts beneath the multiplication facts. Girls with lower spatial visualization ability had a more surface understanding and performed their mathematics tasks using rote memorization. The girls with lower spatial visualization ability were not able to translate the memorized mathematics facts to concrete representations, unlike the girls with higher spatial visualization ability (Skemp, 1996).

Given spatial visualization's apparent role in mathematics learning, it is not surprising that this ability also appears to have an important relationship to participation in STEM fields (Wai, et al., 2009). Wai et al. wrote a review of spatial ability in STEM fields because "relatively little implementation of spatial ability is found for selection, curriculum, and instruction in educational settings— even in STEM domains, where it appears to be highly relevant" (p. 817). These researchers outlined what they referred to as "cumulative" psychological knowledge from studies on spatial ability and STEM subjects over the last half-century. In fact, some studies have recommended that spatial ability be measured outside of the mathematics domain as a means of recognizing potential talent for STEM fields (Shea, Lubinski, & Benbow, 2001; Wai, et al., 2009; Webb, Lubinski, & Benbow, 2007).

Researchers have also found that the different types of visualization ability have different relationships to mathematics domains. In her investigation of visualization in high school mathematics, Presmeg (1986) utilized the Mathematical Processing Instrument (MPI), which consisted of different types of math problems intended to promote the use of some type of visual representation for solving. Presmeg identified five types of imagery: concrete; pattern; memory images of formulae; kinesthetic; and dynamic. Concrete imagery is pictorial in its representation of objects as contrasted to pattern imagery, which, like spatial imagery, strips pictorial details away and uses patterns between and among objects as representations. In this study, the highest performing student, who was classified as a "visualizer," consistently used pattern imagery to solve problems. This result led Presmeg (1986) to cite a study by de Groot, where researchers flashed an image of a chess game situation for five seconds in front of different chess players. Only the ex-world champion chess player was able to recall perfectly where the chess pieces were placed on that image. However, this exact recall did not happen when chess pieces were placed randomly on a chessboard. This implied that the chess player's familiarity with game play and his strategic expertise helped him to recognize the patterns on the board in the "real-life" situation, as opposed to the randomly placed pieces which would never happen during a match. A different study on expert chess players cited by Presmeg (1986) found that expert chess players in blindfolded matches did not use concrete, or object, visualization, they used pattern imagery, or spatial visualization. The data from her own study of high school mathematics, along with the studies described above, led Presmeg to the conclusion that spatial imagery is the optimal visualization strategy for mathematics problem-solving. She reported that concrete imagery could impede mathematics problem-solving for some visualizers because they may be unable to abstract the concrete image into pattern form. This also had negative implications on the use of realistic pictures in mathematics textbooks to illustrate problems.

Supporting Presmeg's (1986) work, another group of researchers studied the relationship of abstraction to mathematics problem-solving (Campbell, Collis, & Watson, 1995). Campbell, et al. investigated the link between vividness of object imagery, logical, or spatial, operation ability, and problem-solving ability. They found no correlation between problem-solving ability and vividness of object imagery, but a positive correlation between spatial operation and problem-solving abilities. This suggests that the ability to create images "rich" in detail and realism is not as important to mathematics problem-solving as the ability to abstract those images into logical constructs. In 1999, Hegarty & Kozhevnikov attempted to classify types of visual-spatial representations and their relationships to mathematical problem-solving. In their study, 33 young male participants completed mathematics problems from the MPI, as well as several spatial and verbal skills measures. These researchers found a positive correlation for what they called schematic imagery – equivalent to Presmeg's pattern imagery or spatial imagery - and successful problem-solving, and a negative correlation between the use of pictorial imagery and problem-solving (Hegarty & Kozhevnikov, 1999).

Van Garderen (2006) published a study on visualization and spatial ability using young participants of different levels of academic ability (gifted, average, and students with learning disabilities). Participants in this study completed two spatial ability scales and used the MPI to solve word problems by drawing representations. The representations were then classified as "pictorial" or "schematic." She found significant positive correlations between the use of schematic imagery and performance on the MPI and two spatial measurement instruments, and a negative correlation between pictorial imagery and spatial skills. This seemed to indicate that students with low spatial visualization skills tended to use pictorial imagery, while students with higher spatial visualizations skills used schematic imagery. Using fMRI in this context, O'Boyle, Cunnington, Silk, Vaughan, Jackson, Syngeniotis, & Egan (2005) compared the brain activation patterns of males identified as gifted in mathematics as they completed mental rotation and matching tasks with the brain activation patterns of males who had not been identified as mathematically gifted. O'Boyle et al. (2005) found significant differences in areas and strength of brain activation patterns between the two groups, but only during the mental rotation task. During the mental rotation task, the gifted subjects showed significantly greater activation in areas of the brain associated with "spatial attention [15], working memory [14], the parsing of executive processes into strategic and evaluative error detection, conflict resolution, and the online monitoring of performance" (O'Boyle et al., 2005, p. 585). This objective measure of the difference in brain activity during the mental rotation task between those with high talent in mathematics versus those with average mathematics skill lends weight to the spatial-mathematics dynamic.

Khooshabeh & Hegarty (2010) studied how color and shape are used by high and low spatial visualizers during a mental rotation task of irregular shapes comprised of cubes. In one of their studies, the researchers used eye-tracking and participant verbalization during the task to find that low spatial visualizers used color cues to rotate shapes, while high spatial visualizers did not. This was very apparent when the researchers used consistent and inconsistent color blocks. When the color blocks were consistent with rotation, the speed and accuracy of the low spatial visualizers increased, while the high spatial visualizer speed and accuracy was not affected (Khooshabeh & Hegarty, 2010). In another interesting finding, Weckbacher & Okamoto (2014) report a positive correlation between mental rotation ability and student achievement in geometry but found no correlation between mental rotation ability and student achievement in algebra. However, students with high mental rotation ability had positive perceptions of their ability to do well in both geometry and algebra. Cheng & Mix (2014) tested whether improvement in spatial skills would lead to improved mathematics achievement in students from six to eight years old. Furthering the ties between spatial ability and mathematics, Cheng & Mix (2014) found that there was significant improvement in mathematics performance for students who had received spatial training versus a control group who had done crossword puzzles instead. In their investigation into possible processing overlap between three domains of spatial ability (spatial visualization, form perception, and spatial scaling) and mathematics, Mix, Levine, Cheng, Young, Hambrick, Ping, & Konstantopoulos (2016) found the strongest relationship between spatial visualization and mathematics.

Studies on children and adults with specific genetic disorders like Williams Syndrome (WS; e.g., Ansari, 2010; Ansari & Karmiloff-Smith, 2002; O'Hearn & Luna, 2009) have provided further evidence on the issue of limited spatial visualization ability and mathematics learning. People with WS have poor spatial ability and poor number skills that manifest themselves over time, while still possessing normal verbal ability. O’Hearn & Luna report that spatial representation in infants with WS is indistinguishable from spatial representation in infants without WS. However, as children with WS mature, their visuospatial deficits become apparent. fMRI studies on people with WS confirm that there appears to be disruption in the development of the dorsal stream, which is associated with spatial visualization (Farran, Jarrold, & Gathercole, 2001; O’Hearn & Luna, 2009). When it comes to mathematics, this lack of spatial ability appears to most seriously affect the development of number sense and magnitude. O’Hearn & Luna wrote, “The most frequently proposed WS profile includes impaired representation of magnitudes and approximate number, and relatively strong memory for math facts" (p. 15). Vicari & Carlesimo (2006) studied the effects of WS and Down Syndrome (DS) on visuospatial working memory. The researchers tested the subjects using object and spatial visualization performance tasks. Results showed that subjects with WS had specific difficulty with spatial visualization and none with object visualization, while the subjects with DS had difficulty with both types. This supported the idea of two independent visualization abilities: object and spatial (Vicari & Carlesimo, 2006).

In summary, cognitive and neuroscience researchers have found a positive correlation between spatial visualization ability (e.g., mental rotation) and mathematics problem-solving. Conversely, high object visualization ability may have a negative, or impeding, effect on mathematics problem-solving.

Aphantasia

The inability to create mental images has appeared in research articles published as far back as the 19th century (e.g., Galton, 1880). More recently, in reference to a 1965 mental imagery study by McKellar where 500 British respondents were asked to complete an imagery survey, Bower (1972) wrote the following about respondents who reported that they lacked any sort of mental imagery, "Smith (1966) lists three alternatives: they are liars, they have only propositional memory, or they have misunderstood the reference of the question. I prefer the misunderstanding account" (p. 58).

In a review of the literature on mental imagery and his own experience as a "wakeful non-imager," Faw (2009) cited several philosophers and researchers, as far back as Aristotle, who have expressed the idea that thought is always accompanied by pictorial mental imagery and that the absence of imagery indicated either psychological abnormality or physical impairment of the brain. In 1988, Farah, Levine, & Calvanio described the case of a patient who had lost the ability to form pictorial mental images but had retained his spatial visualization after surgery to remove a brain aneurism. Wilson, Baddeley, & Young (1999) reported their research on a sculptress who, before the loss of her “mind’s eye” from the effects of lupus, created true-to-life sculptures. After losing the ability to create pictorial mental images, the sculptress’s style became abstract.

In 2010, a neurological study was published documenting a patient’s loss of the ability to form mental images after complications during heart surgery (Zeman, Della Sala, Torrens, Gountouna, McGonigle, & Logie, 2010). Using brain scans, the researchers found significant differences in brain activation between the patient and control subjects. Both the injured patient and the control subjects showed the same activation in the fusiform gyrus and the posterior region of the brain during the perception of photos of famous faces. Participants were then asked to create their own mental images, and fMRI scans showed that control subjects still showed major activation in the same posterior region of the brain that was activated during perception. However, the injured patient showed very low activation in that area and higher activation in the frontal cortex, where reasoning is thought to occur. This revealed that while both the controls and the injured subject showed no difference in perception, there was a biological difference in how the subjects processed visual imagery in their mind’s eye.

After the Zeman et al. study was published in 2010, thousands of people from all over the world contacted the researchers claiming that they had never been able to create mental images. Some cried with relief after spending their lives believing there was something “wrong” with them. Others expressed disbelief and a feeling of being “cheated” when they realized that others could actually “see” pictorial representations in their minds (Winlove et al., 2017). Even though the symptoms of the condition had been identified in the late 1800's (e.g., Galt, 1880), it did not have a name until Zeman, Dewar, & Della Salla published a later article and called the condition congenital aphantasia (2015). Zeman et al. (2015) posit that aphantasia exists at the lowest end of a sliding scale of vividness of visualization, with hyper-visualizers – or "hyperphantasia" (Winlove, et al., 2017) - at the other end who visualize with extreme vividness and detail.

In their neurological study on aphantasia and spatial visualization, Keogh & Pearson (2017) found a significant difference in brain activation patterns between people with aphantasia and a control group, even though the two groups did not differ in performance of a spatial task. This led the researchers to posit that people with aphantasia "may have a severe deficiency with the ventral or 'what' pathway, or components of the pathway such as early visual or temporal cortex, but not the where pathway" (Keogh & Pearson, 2017, p. 6). The researchers also suggested that because it is theorized that visual imagery in the visual cortex is driven by feedback from the frontal cortex, people with aphantasia may have differing activity levels in either – or both – of those areas of the brain.

Summary of Literature

Research in education, cognitive psychology, and neuroscience shows that there are two types of visualization: object and spatial. Each type of visualization is related to distinct abilities and preferences in education and career choice. Spatial visualization ability is linked to STEM and mathematics ability and self-efficacy, while object visualization ability is linked to arts self-efficacy and preference. Both object and spatial visualization abilities can be measured by performance tasks, fMRI, and self-report questionnaires on vividness of imagery. Aphantasia, which is defined as the inability to create mental imagery, is a recently identified condition, and research on aphantasia has focused solely on object visualization ability. This study extends the

Blazhenkova (2016) study by using the VOSIQ and other existing instruments to measure spatial visualization ability and vividness of spatial imagery of people with aphantasia. This research adds to the existing knowledge about aphantasia, spatial visualization, and potential impacts on mathematics learning and education.

Chapter Three: Research Method

This quantitative study was designed to be a preliminary step in the investigation of how people with aphantasia learn mathematics by examining whether there are significant differences in the vividness of spatial visualization and mental task rotation ability between people with aphantasia and those without aphantasia. Further, the study sought to determine whether there was a significant difference in preference for STEM or arts between people with aphantasia and people without aphantasia. This study was essentially a partial replication of Blazhenkova (2016). This study extends Blazhenkova (2016) by specifically targeting participants with aphantasia to compare with participants from the general population. All instruments used in this study were piloted before implementation.

Because the target population of participants was not easily identified, widely dispersed geographically, and existed in a virtual environment, online implementation of the instruments was found to be a suitable method of data collection (Kraut, Olson, Banaji, Bruckman, Cohen, & Couper, 2004). The online approach allowed the study to have a wider geographical reach, as well as minimized the cost for data collection.   Although the risks associated with anonymous internet-based surveys include sample bias and questionable participant integrity, Kraut, et al. (2004) write that these risks may be partially overcome by collecting a larger sample and analyzing data to identify outliers.

Research Design

This proposal was designed as a pseudo-replication of Blazhenkova's 2016 VOSIQ instrument validation study, with the addition of comparing results from two distinct populations: people with aphantasia and people without aphantasia.   Participants were grouped based on their VVIQ scores. Participants who selected the option representing the least vividness (“No image at all, you only “know” that you are thinking of the object”) for all 16 questions on the VVIQ scored a 16 on the instrument and were categorized as having aphantasia. The independent and dependent variables, as well as the hypotheses, are listed with the corresponding research questions below.

1. Is the vividness of mental imagery of people with aphantasia significantly lower than the vividness of mental imagery of people without aphantasia?

- **a.** Object imagery

  Independent variable: VVIQ score; dependent variable: average score on VOSIQ object items.

    - a. $H1_{a0}$: The vividness of object imagery of people with aphantasia is greater than or equal to the vividness of object imagery of people without aphantasia.
    - b. $H1_{aa}$: The vividness of object imagery of people with aphantasia is significantly less than the vividness of object imagery of people without aphantasia.

- **b.** Spatial imagery

  Independent variable: VVIQ score; dependent variable: average score on VOSIQ spatial items.

    - a. $H1_{b0}$: The vividness of spatial imagery of people with aphantasia is greater than or equal to the vividness of spatial imagery of people without aphantasia.

   b. $H1_{ba}$: The vividness of spatial imagery of people with aphantasia is significantly lower than the vividness of spatial imagery of people without aphantasia.

2. Is the mental rotation test performance of people with aphantasia significantly lower than the mental rotation test performance of people without aphantasia?

- **a.** Accuracy

  Independent variable: VVIQ score; dependent variable: percentage of correctly answered items on the MRT.

  a. $H2_{a0}$: The mental rotation test accuracy of people with aphantasia is greater than or equal to the mental rotation test accuracy of people without aphantasia.

  b. $H2_{aa}$: The mental rotation test accuracy of people with aphantasia is significantly lower than the mental rotation test accuracy of people without aphantasia.

- **b.** Speed

  Independent variable: VVIQ score; dependent variable: ratio of number of answered items to number of allotted time blocks in period.

  a. $H2_{b0}$: The mental rotation test speed of people with aphantasia is greater than or equal to the mental rotation test speed of people without aphantasia.

  b. $H2_{ba}$: The mental rotation test speed of people with aphantasia is significantly lower than the mental rotation test speed of people without aphantasia.

3. Is there a significant correlation between mental rotation test performance and vividness of mental imagery?

- **a.** Accuracy – Spatial Imagery

  Independent variable: average score on VOSIQ spatial items; dependent variable: percentage of correctly answered items on the MRT.

  - a. $H3_{a0}$: There is no significant correlation between mental rotation test accuracy and vividness of spatial imagery.
  - b. $H2_{aa}$: There is a significant correlation between mental rotation test accuracy and vividness of spatial imagery.
- **b.** Accuracy – Object Imagery

  Independent variable: average score on VOSIQ object items; dependent variable: percentage of correctly answered items on the MRT.

  - a. $H3_{b0}$: There is no significant correlation between mental rotation test accuracy and vividness of object imagery.
  - b. $H3_{ba}$: There is a significant correlation between mental rotation test accuracy and vividness of object imagery.
- **c.** Speed – Spatial Imagery

  Independent variable: average score on VOSIQ spatial items; dependent variable: ratio of number of answered items to number of allotted time blocks in period.

  - a. $H3_{c0}$: There is no significant correlation between mental rotation test speed and vividness of spatial imagery.

        b. $H3_{ca}$: There is a significant correlation between mental rotation test speed and vividness of spatial imagery.

- **d.** Speed – Object Imagery

  Independent variable: average score on VOSIQ object items; dependent variable: ratio of number of answered items to number of allotted time blocks in period.

    a. $H3_{d0}$: There is no significant correlation between mental rotation test speed and vividness of object imagery.

    b. $H3_{da}$: There is a significant correlation between mental rotation test accuracy and vividness of object imagery.

4. Is the level of reported self-efficacy in Arts/STEM independent of whether a person has aphantasia?

- **a.** Arts

  Independent variable: aphantasia group; dependent variable: Arts self-efficacy score.

    a. $H4_{a0}$: Reported self-efficacy in the arts is independent of whether a person has aphantasia.

    b. $H4_{aa}$: Reported self-efficacy in the arts is not independent of whether a person has aphantasia.

- **b.** STEM

  Independent variable: aphantasia group; dependent variable: STEM self-efficacy score.

a. $H4_{a0}$: Reported self-efficacy in STEM is independent of whether a person has aphantasia.

b. $H4_{aa}$: Reported self-efficacy in STEM is not independent of whether a person has aphantasia

Instruments

Participants were asked to complete a brief demographic survey, two self-report imagery instruments (VVIQ and VOSIQ), and one timed performance task (MRT) meant to measure mental rotation task ability. The VVIQ and the MRT were chosen because they showed the highest correlation with the VOSIQ in the 2016 Blazhenkov study. Participants took a maximum of 30 minutes to complete the instruments.

Demographic survey

The demographic survey (Appendix A) asked participants the gender and the ethnicity with which they most closely identify, their age, and to rate their self-efficacy, or confidence in their own ability, in STEM and the arts. The self-efficacy rating items were modified from the Motivated Strategies for Learning Questionnaire (MSLQ; Pintrich, Smith, Garcia, & McKeachie, 1991). Items were worded as “Compared with others, I think I'm good at STEM subjects (science, technology, engineering, mathematics, etc.).” and “Compared with others, I think I'm good at the arts (visual arts, dance, literary arts, theater, music, etc.).” The responses were on a Likert-type scale ranging from one (not at all true of me) to seven (very true of me). The self-efficacy items were used to answer research question four. The purpose of collecting the demographic information was to compare the two groups and analyze any differences that could relate to demographic characteristics.

VVIQ

The Vividness of Visual Imagery Questionnaire (VVIQ) can be found in Appendix B. The VVIQ was developed in the early 1970's (Marks, 1973). Researchers have modified and validated results from this instrument many times over the last few decades (Eton, Gilner, & Munz, 1988). In an analysis of this instrument, the VVIQ was found to have acceptable internal consistency (.88) and construct validity. However, there were concerns about the impact of social desirability on response (McKelvie, 1995), which is why in later implementations like the one listed in Appendix B, an introductory paragraph was added to let respondents know that there are no wrong answers. I used the instrument as it was in Zeman et al. (2015), with a few modifications for language differences (e.g., replacing "colour" with "color"). The responses for each item were scored from 1 to 5, from least vivid (1 - No image at all, you only "know" that you are thinking of the object) to most vivid (5 - Perfectly clear and vivid as real seeing). Scores were computed by totaling the responses, as it was in Zeman et al. (2015). In that study, distinct groups were identified. The first group had a median score of 16, which differed significantly from the median score of 58 for control participants. The researchers then divided the participants into subgroups: no imagery (scores of 16 and below) and minimal imagery (scores ranging from 17-30). For purposes of this study, participants who scored 16 points were categorized as having aphantasia.

VOSIQ

The Vividness of Object Spatial Imagery Questionnaire (VOSIQ; Blazhenkova, 2016) was chosen because it measures vividness of both object and spatial visualization. People with aphantasia have very low vividness of object imagery (Zeman, et al., 2015), which should translate to lower scores on both the VVIQ (Zeman et al., 2015) and the object items of the

VOSIQ (Blazhenkova, 2016). The items for this instrument are listed in Appendix C. The object and spatial scales showed satisfactory internal consistency (.88 and .85 respectively), and criterion-related validity was demonstrated by correlating VOSIQ results with other instruments and tasks designed to measure the same constructs. For this study, some of the wording on the instrument has been changed from Blazhenkova (2016) for clarity (e.g., “aquarelle painting” is replaced with “watercolor painting”). The VOSIQ was scored as in the literature (Blazhenkova, 2016), by averaging the responses to the object and spatial items separately. Responses were on the Likert-type scale described in the Measures section of this paper, worded exactly like the VVIQ, and have values from 1 to 5, from least vivid (1 - No image at all, you only “know” that you are thinking of the object) to most vivid (5 - Perfectly clear and vivid as real seeing).

MRT

The Vandenberg-Kuse Mental Rotation Test (MRT) - Redrawn (Peters, Laeng, Latham, Jackson, Zaiyouna, & Richardson 1995; Vandenberg & Kuse, 1978) is used to measure spatial transformation ability and has shown satisfactory internal consistency (KR-20 = .88). The original version of the MRT consists of 24 items which participants have seven minutes to answer. Permission was granted from the authors (Peters, et al.) to implement this test online for the first time. This study, modeled after Blazhenkova (2016), used 12 of the 24 items (Appendix D) and gave participants three and a half minutes to answer as many as they can. Each item on the MRT is a target shape – a computer-rendered line drawing of an irregular shape comprised of cubes. For each item, four possible rotations of the target shape are presented, only two of which are feasible rotations of the target. The maximum score for this test is 12 points. To score a point, the participant must select both correct responses.

Implementation

According to Andrews, Nonnecke, & Preece (2003), a well-designed electronic survey instrument must meet several criteria including, but not limited to, the following: usable on multiple browsers; detects multiple submissions; presents questions in a logical way; allows user to save responses before completion; gives feedback on completion; automatically saves to database; follows paper survey conventions; and quickly displays questions (p. 187). The implementation for this study has been designed to meet the criteria.

For example, to be usable on multiple browsers, the surveys were tested on Google Chrome, Mozilla Firefox, Safari, and Internet Explorer. Because the responses were linked to a specific user_id, multiple submissions per user_id were not allowed. Questions for the three self-report surveys have been ordered exactly as in the paper versions of the instruments, which have been piloted and tested for validity and reliability as discussed in the Instruments section. To allow the user to save responses before completion, the design kept the three self-report surveys separate, each with its own set of instructions as they appear in the paper versions. The respondents were able complete the three short surveys one at a time and save them independently. Designing the implementation in this way allowed the data collection to meet the requirement of simplicity of instructions (Andrews, Nonnecke, & Preece, 2003). Upon completion of each instrument, the link to the instrument on the Tests page was replaced with a message noting the time and date of completion, fulfilling the feedback on completion requirement. The system used PHP and Javascript to save all responses immediately to a password-protected mySQL database. Because the web surveys were based on established instruments, they were designed to mimic the paper surveys and thus follow paper survey design principles.

To protect the integrity of the MRT, all reasonable measures were taken to protect the images used on the instrument. All images were stored in a database instead of on a server to prevent direct download, keys were disabled to keep users from accessing the source code, and all images were watermarked with the title of this study. Finally, because the MRT was the only instrument that was not text-based and required time to load images, the system pre-loaded all images before the timed test began and did not contact the server again until the test was completed. This kept all activity on the client machine and mitigated the possibility of slow internet connections and image load times during the test affecting performance.

Piloting and Testing

Andrews, et al. (2003) outline four steps to successfully piloting an electronic survey. The first step is an expert review of survey questions. Because all questions were based on existing instruments, this first step was completed by the instrument developers. The second step has pilot participants evaluate question clarity, survey ease of use, and logical question sequencing. The third step to piloting an electronic survey is to conduct a mini-replication of the intended study to test the actual implementation and procedures designed for the study. The researcher combined the second and third steps. Students from the VCU School of Education were invited to become pilot participants via e-mail that included an explanation of the study and a link to the instruments. Because this data collection was completely anonymous, observation, as suggested by Andrews, et al. (2003) was not feasible. Therefore, open-ended questions addressing the issues listed in step two were placed at the end of each survey to allow participants to reflect on their testing experience. Fifty-two respondents participated in this step of the piloting process. To reduce the effects of survey fatigue, respondents were randomly assigned to one of three groups that determined the order of completion for the MRT, VOSIQ, and VVIQ was randomized, with the demographic survey last for all users. The assigned group also determined the order of the MRT items to help reduce any practice effects.

The self-efficacy items were evaluated for internal consistency and congruent validity with results from the VVIQ, VOSIQ, and MRT. Further, the timing of testing was examined to ensure that the estimated time frame for testing was valid. The results from this phase of piloting showed that MRT performance was adversely affected the later the MRT appeared in the order of surveys. Therefore, users were assigned to one of two groups and the MRT was set to be completed first for both groups, the order of the VOSIQ and VVIQ was randomized, and the demographic survey was last for both groups. Finally, the instruments and instructions were checked for any errors made during the revisions from the prior steps (Andrews, et al., 2003).

Procedure

After obtaining approval from the Institutional Review Board, all participants accessed the instruments via web link that was either posted to social media or printed on a flyer. The link took participants to a website program developed by the researcher using a combination of PHP, Ajax, JavaScript, and MySQL. The site was best accessible via computer using Google Chrome or Mozilla Firefox. The first page of the website offered the participants the option to log in if they were returning. If this was their initial visit, this page informed participants about the study, asked the participants to certify that they were over the age of 18 years old, and required agreement to participate by clicking on an “I Agree” button before proceeding. Once the participant agreed, the program created a unique, randomly generated user_id and randomly assigned the user to one of two groups controlling the order of completion of the surveys. Each instrument had to be completed in one sitting, but the user_id allowed participants to log in and complete each instrument separately for exactly one week after the user_id was created. It took a maximum total of 30 minutes to complete the instruments.

The user_id and its expiration date were displayed prominently at the top of the site once the user logged in. A user_id became invalid if any of the following occurred: participant quit before completing the demographic survey, VVIQ, or the VOSIQ; quit the MRT before the given time has elapsed; or failed to complete all instruments within the week timeframe. A progress indicator was visible on all instruments (Couper, Traugott, & Lamias, 2001). The order of the items on the MRT were based upon the randomly assigned group to help reduce the practice effect. There was no connection between the randomly generated user_id and the identity of the participant. Neither e-mails nor IP addresses were captured during data collection, which allowed for complete anonymity of participants. The user_id was used to link the results from the demographic survey and the three instruments during analysis. All responses were saved in a password-protected database on a server that could only be accessed by the researcher.

The data collected from the MRT entailed a different implementation than the other instruments, which are self-report surveys. As in Blazhenkova (2016), each participant was allowed just three and one-half minutes to complete twelve items. Therefore, after completing four untimed warm-up items to become familiar with the format of the test, a countdown timer was visible on the screen when the actual test began. The instructions for the test clearly stated that both accuracy and speed would be considered, which was meant to help mitigate the compulsion to rush through the test at the expense of accuracy. To discourage participants from attempting the test multiple times to improve their score, participants were not given any feedback on their performance on individual items. When the time elapsed, the test was automatically submitted, capturing the answers the participant had given up to that point. The program then displayed a message informing the participant that they completed the test. The participant could score a maximum of 12 points, one point for each time the participant selected both correct options for an item (Vandenberg & Kuse, 1978).

Upon completion of the MRT, three scores for each participant were calculated for analysis: number correct; accuracy; and speed. MRT accuracy was measured by the number of correct items divided by the number of attempted items. This means that if one person completed six items in three and a half minutes and got all six correct, she would have 100% accuracy. If another person completed 10 items in three and a half minutes and got six correct, he would have 60% accuracy.

Speed was measured by the ratio of number of items completed to the time it took to complete the items. To keep the scale the same for this ratio, “time” was the number of 17.5 second time blocks (time allotted to each item - 210 seconds divided by 12 items) used to answer the items. For example, if participant 1 completed four items in three and a half minutes, her speed would be four divided by the 12 (the number of 17.5 second time blocks needed to complete the items), or 1/3. If participant 2 completed all 12 items in three and a half minutes, his score would be 12 divided by 12, or one. Participant 3 may have completed all 12 items in 2 minutes, which would make her score = 12/(120/17.5) ~ 1.75. While there may be no difference in accuracy on the MRT (Appendix D) between people with aphantasia and the general population, as reported by Zeman, et al. (2010), there may be a difference in speed, or the number of items answered in the time given to complete the test (e.g., Debelak, Gittler, & Arendasy, 2014).

Participants

To determine whether people with aphantasia differed in spatial visualization ability from the general population, members of two English-speaking online aphantasia support communities with over 800 members between them were recruited via social media. The members of this community have self-identified as having congenital aphantasia, voluntarily joined the community, are primarily native English speakers, and reside predominantly in the United Kingdom and North America. A control group consisting of participants from the general population was recruited by distributing flyers in certain undergraduate and graduate classes at the VCU School of Education, as well as displaying flyers in public spaces, like the library, on the VCU campus. The only constraint on participation was that participants had to be over 18 years of age.

Because of the strict definition of aphantasia used for this study (VVIQ score of exactly 16), there were a low number of participants classified into the aphantasia group after social media recruitment. Therefore, further recruitment via e-mail to a pre-existing list of people self-identified as having aphantasia was pursued. In the e-mail, interested participants were directed to the study website. After two months of recruitment, the system identified 124 usable responses out of 208 responses that were attempted. Further data analysis of responses of participants who scored zero on the MRT showed that those participants spent significantly less than the mean time per MRT item, suggesting that these participants clicked through the instrument without making a true effort to determine correct answers. This led to the exclusion of five participants, one classified into the aphantasia group and four from the non-aphantasia group. These exclusions made the total number of usable responses 119. The aphantasia group, those with a VVIQ score of 16, contained 40 participants, while the non-aphantasia group (VVIQ score > 16) contained 79 participants. The age of the aphantasia group ranged from 18 to 65 years old (*M* = 43.20, *SD* = 13.82), while the non-aphantasia group age ranged from 18 to 66 years old (*M* = 28.32, *SD* = 13.61). The demographic characteristics of each group are displayed in Table 2.

Table 2

Demographic Descriptive Statistics by Group

Demographic Variable	Level	Aphantasia (*N* = 40)		Non-Aphantasia (*N* = 79)	
Gender	Female	23	56%	54	69%
	Male	16	41%	25	31%
	Other	1	3%	0	0%
Ethnicity	African or Black	0	0%	15	19%
	Caucasian or White	36	90%	58	73%
	Asian	1	2%	4	5%
	Native American	0	0%	0	0%
	Other	3	8%	2	3%
Education Level	Some High School	3	8%	0	0%
	High School Diploma	0	0%	5	6%
	Some College	14	36%	46	59%
	Bachelor's Degree	9	21%	12	16%
	Some Graduate School	3	8%	4	5%
	Graduate Degree	11	28%	12	14%

Data Analysis Steps

Chi square goodness of fit tests were performed on demographic variables to identify any significant differences between the two participant groups. Comparisons of the means within groups based on demographic variables were also performed.

The following statistical analyses were used to answer the study's research questions:

1. Is the vividness of mental imagery of people with aphantasia significantly lower than the vividness of mental imagery of people without aphantasia?

a. Object imagery

This study used the independent samples *t*-test to measure the difference in the mean scores on the VOSIQ object items between people with aphantasia and people without aphantasia.

b. Spatial imagery

This study used the independent samples *t*-test to measure the difference in the mean scores on the VOSIQ spatial items between people with aphantasia and people without aphantasia.

2. Is mental rotation test performance of people with aphantasia significantly lower than mental rotation test performance of people without aphantasia?

a. Accuracy

This study used the independent samples *t*-test to measure the difference in the mean percentage of correct items on the MRT between people with aphantasia and people without aphantasia.

b. Speed

This study used the independent samples *t*-test to measure the difference in the mean number of correctly answered MRT items in three and a half minutes between people with aphantasia and people without aphantasia.

3. Is there a significant correlation between mental rotation test performance and vividness of mental imagery?

a. Accuracy – Spatial Imagery

This study used Pearson correlation analysis to examine the relationship between the average score on VOSIQ spatial items and percentage of correctly answered items on the MRT.

b. Accuracy – Object Imagery

This study used Pearson correlation analysis to examine the relationship between average score on VOSIQ object items and percentage of correctly answered items on the MRT.

c. Speed – Spatial Imagery

This study used Pearson correlation analysis to examine the relationship between average score on VOSIQ spatial items and number of correctly answered items in three and a half minutes.

d. Speed – Object Imagery

This study used Pearson correlation analysis to examine the relationship between average score on VOSIQ object items and number of correctly answered items in three and a half minutes.

4. Is the level of reported self-efficacy in Arts/STEM independent of whether a person has aphantasia?

a. Arts

This study used the Chi square test of independence to determine whether there is a significant difference in reported self-efficacy in the arts between people categorized with aphantasia and those categorized as not having aphantasia.

b. STEM

This study used the Chi square test of independence to determine whether there is a significant difference in reported self-efficacy in STEM between people categorized with aphantasia and those categorized as not having aphantasia.

Chapter Four: Results

The purpose of this study was to explore the possible differences in vividness of spatial imagery and mental rotation task performance between people with aphantasia and people without aphantasia. Participants were grouped by VVIQ score. A VVIQ score of 16 placed participants into the aphantasia group, while a VVIQ score of greater than 16 placed participants in the non-aphantasia group. Vividness of object imagery was measured using the responses to the VOSIQ-object items, and vividness of spatial imagery was measured using the responses to the VOSIQ-spatial items. Mental rotation task performance was measured using the MRT. This chapter will present the results of the data analyses as they pertain to each of the study's research questions.

Descriptive Statistics

Table 3 displays the descriptive statistics of MRT performance and self-report survey responses for the 119 participants. As shown in the table, the average MRT score was 6.76 (*SD* = 2.97) out of 12, with an average accuracy of approximately 70% and the average speed close to the allotted 17.5 seconds per item (*M* = 1.01, *SD* = .75). The mean VVIQ score was approximately 40 out of 80 possible points (*M* = 40.18, *SD* = 23.89). The average reported vividness of spatial imagery (*M* = 30.39, *SD* = 16.83) was lower than the mean reported vividness of object imagery (*M* = 34.89, *SD* = 20.72). In contrast, participants rated their self-efficacy marginally higher in STEM (*M* = 4.61, *SD* = 1.83) than in the arts (*M* = 4.28, *SD* = 1.87).

Table 3

Descriptive Statistics of Dependent Variables

	N	Minimum	Maximum	Mean	Std. Deviation
MRT Score	119	1.00	12.00	6.76	2.97
MRT Accuracy	119	.08	1.00	.71	.24
MRT Speed	119	.17	5.71	1.01	.75
VVIQ	119	16.00	80.00	40.18	23.88
VOSIQ-Object	119	14.00	70.00	34.89	20.73
VOSIQ-Spatial	119	14.00	70.00	30.29	16.83
Arts Self-efficacy	119	1.00	7.00	4.28	1.87
STEM Self-efficacy	119	1.00	7.00	4.61	1.83
Valid N (listwise)	119				

Table 4 shows the descriptive statistics broken down by the two groups: aphantasia and non-aphantasia. As discussed previously, the aphantasia group was identified by a VVIQ score of 16, the minimum number of points possible on the instrument. The aphantasia group rated itself lower in arts self-efficacy and higher in STEM self-efficacy than the non-aphantasia group. The aphantasia group had lower MRT scores, higher MRT accuracy, slower MRT speed, and reported lower vividness of both spatial and object imagery.

Table 4

Descriptive Statistics of Dependent Variables by Group

Aphantasia		N	Minimum	Maximum	Mean	Std. Deviation
Non-Aphantasia	MRT Score	79	1.00	12.00	6.94	3.01
	MRT Accuracy	79	.08	1.00	.69	.25
	MRT Speed	79	.25	5.71	1.10	.87
	VVIQ	79	17.00	80.00	52.43	20.28
	VOSIQ-Object	79	14.00	70.00	45.71	17.93
	VOSIQ-Spatial	79	14.00	70.00	38.74	15.17
	Arts Self-efficacy	79	1.00	7.00	4.48	1.75
	STEM Self-efficacy	79	1.00	7.00	4.56	1.79
	Valid N (listwise)	79				
Aphantasia	MRT Score	40	1.00	12.00	6.43	2.88
	MRT Accuracy	40	.25	1.00	.73	.23
	MRT Speed	40	.17	1.88	.83	.37
	VVIQ	40	16.00	16.00	16.00	.00
	VOSIQ-Object	40	14.00	19.00	14.30	.99
	VOSIQ-Spatial	40	14.00	24.00	14.45	2.00
	Arts Self-efficacy	40	1.00	7.00	3.88	2.05
	STEM Self-efficacy	40	1.33	7.00	4.73	1.92
	Valid N (listwise)	40				

Group Demographic Differences

The demographic descriptive statistics are displayed in Table 2. An independent samples *t*-test performed on the continuous independent variable of participant age showed that the aphantasia group (*M* = 43.20, *SD* = 13.82) was significantly older than the non-aphantasia group (*M* = 28.32, *SD* = 13.61); *t*(117) = 5.61, *p* < .001. Because of the significant difference in age between the groups, a Pearson correlation analysis was performed to ensure that age would not significantly affect MRT accuracy and MRT speed, the dependent variables used to represent MRT performance. The results showed that there were nonsignificant negative correlations between age and MRT accuracy for the non-aphantasia group (*r*(79) = -.02, *p* = .85) and for the aphantasia group (*r*(40) = -.17, *p* = .30), and between age and MRT speed in both the non-aphantasia (*r*(79) = -.17, *p* = .14) and aphantasia groups (*r*(40) = -.25, *p* = .12). An ANCOVA on

MRT accuracy [between-subjects factor: aphantasia; covariate: age] revealed no main effects of aphantasia, $F(1, 115) = 1.27$, $p = .26$, $\eta_p^2 = .011$, or age, $F(1, 115) = .54$, $p = .47$, $\eta_p^2 = .005$. There were no main effects of aphantasia ($F(1, 115) = 3.49$, $p = .39$, $\eta_p^2 = .007$) or age ($F(1, 115) = .54$, $p = .06$, $\eta_p^2 = .029$) on MRT speed.

Chi square tests of goodness-of-fit determined that there was no significant difference between the aphantasia group and the non-aphantasia group on the categorical independent variables of gender representation (χ^2 (2, $N = 119$) = 3.00, $p = .22$). Because of the low number of respondents in the “Some High School” and the “High School Diploma” groups, these two categories were combined to perform the chi square test on education level. This test showed that there was no significant difference in education level between the two groups (χ^2 (2, $N = 119$) = 6.05, $p = .20$). However, the aphantasia group was significantly more Caucasian (χ^2 (2, $N = 119$) = 10.50, $p = .02$) than the non-aphantasia group. To verify that the difference in ethnicity would not adversely skew the results, all between group statistical analyses were performed matching participants on ethnicity, as well as without matching participants on ethnicity, and the results did not change significantly. Therefore, the statistics discussed in this paper are from analyses run without regard to ethnicity.

Vividness of Mental Imagery

To answer the first research question, whether the vividness of mental imagery of people with aphantasia was significantly lower than the vividness of mental imagery of people without aphantasia, an independent samples *t*-test was used. The independent variable for this question was whether a participant had aphantasia, which was determined using the participant’s VVIQ score. If the participant scored 16 on the VVIQ, this meant that they reported the minimum vividness for all 16 items (Zeman, et al., 2015). The VVIQ had good reliability in this study, with a Cronbach's alpha of .989 for all participants.

Object Imagery

To determine vividness of object imagery, I calculated each participant's total responses on the 14 VOSIQ-Object items. Reliability analyses were performed for all participants, as well as separately for each group. For this study, the VOSIQ-Object items had good reliability for all participants ($\alpha = .986$). The scale showed acceptable reliability for both the non-aphantasia ($\alpha = .974$) and aphantasia ($\alpha = .696$) groups. Analysis of the lower reliability of this scale for the aphantasia group revealed that 10 of the 14 items on the scale had a mean of 1.03 and a standard deviation of .158. Two other items showed no variance at all. The variance of the responses was related to two items. The first item, "Splashes of colors in fireworks," had a slightly higher mean ($M = 1.05$) and twice the standard deviation ($SD = .32$) than nine of the 10 items that showed variance. A second item on the scale, "Fine details and shape of a jellyfish," also had a mean of 1.05 and a slightly higher standard deviation of .22 than the remaining items on the scale. Further examination showed that, because of the small size and homogeneity of the aphantasia group responses, the reliability was strongly affected by divergent responses.

Results of the independent samples *t*-test showed that the aphantasia group ($M = 14.30$, $SD = .99$) reported significantly lower vividness of object imagery than the non-aphantasia group ($M = 45.32$, $SD = 17.93$). Levene's test for equality of variances indicated unequal variances ($F = 93.70$, $p < .001$), so degrees of freedom were adjusted from 117 to 78.94; $t(78.94) = -15.33$, $p < .001$, $d = -2.44$.

Spatial Imagery

To determine vividness of spatial imagery, I calculated each participant’s total responses on the 14 VOSIQ-Spatial items. The VOSIQ-Spatial items also showed good reliability for all participants ($\alpha = .974$), as well as for the non-aphantasia ($\alpha = .953$) and aphantasia ($\alpha = .957$) groups. Results of an independent samples *t*-test showed that the aphantasia group ($M = 14.45$, $SD = 2.00$) reported significantly lower vividness of spatial imagery than the non-aphantasia group ($M = 38.47$, $SD = 15.17$). Levene’s test for equality of variances indicated unequal variances ($F = 83.08$, $p < .001$), so degrees of freedom were adjusted from 117 to 83.25; $t(83.25) = -13.84$, $p < .001$, $d = -2.24$.

Mental Rotation Test Performance

The second research question asked if the mental rotation test performance of people with aphantasia was significantly lower than mental rotation test performance of people without aphantasia. The independent variable was whether the participant was in the aphantasia or non-aphantasia group, which was determined by the participant’s VVIQ score. A VVIQ score of 16 placed a participant in the aphantasia group. A VVIQ score of greater than 16 placed a participant in the non-aphantasia group. The dependent variables for this question were MRT accuracy and MRT speed. The results of the independent samples *t*-test on MRT accuracy showed that the aphantasia group ($M = .73$, $SD = .23$) had higher accuracy than the non-aphantasia group ($M = .69$, $SD = .25$), although not significantly higher; $t(117) = .72$, $p = .237$, $d = .17$. However, the aphantasia group ($M = .82$, $SD = .37$) was significantly slower on the MRT than the non-aphantasia group ($M = 1.10$, $SD = .87$); $t(117) = -1.94$, $p = .027$, $d = -.42$. Looking at the MRT score variable, there was no significant difference between the two groups, although the non-aphantasia group (*M* = 6.94, *SD* = 3.01) had higher MRT scores on average than the aphantasia group (*M* = 6.43, *SD* = 2.88).

Gender Differences in MRT Performance

This section of the results section will briefly discuss the analysis of the gender differences in MRT score, MRT speed, and MRT accuracy. Overall, males performed more accurately and earned higher scores on the MRT, while there appeared to be no difference between males and females in the speed with which they completed the test.

MRT Speed

Overall, no significant difference was found in MRT speed between male (*M* = 1.02, *SD* = .85) and female (*M* = 1.00, *SD* = .70) participants using an independent samples *t* test. Because the MRT speed data were highly skewed, a log10 transformation was applied to normalize the data. The test for homogeneity of variance was not significant, with Levene $F(3, 114) = .832$, $p > .05$, indicating that the assumptions underlying the application of the two-way ANOVA were met. The ANOVA yielded a main effect for aphantasia, $F(1, 114) = 5.20$, $p = .024$, such that the average transformed MRT speed was significantly slower for people with aphantasia (*M* = - .13, *SD* = .21) than for people without aphantasia (*M* = -.03, *SD* = .24). The main effect of gender was non-significant, $F(1, 114) = .02$, $p > .05$, and there was non-significant interaction effect of gender*aphantasia as shown in Figure 3 ($F(1, 114) = .25$, $p > .05$).

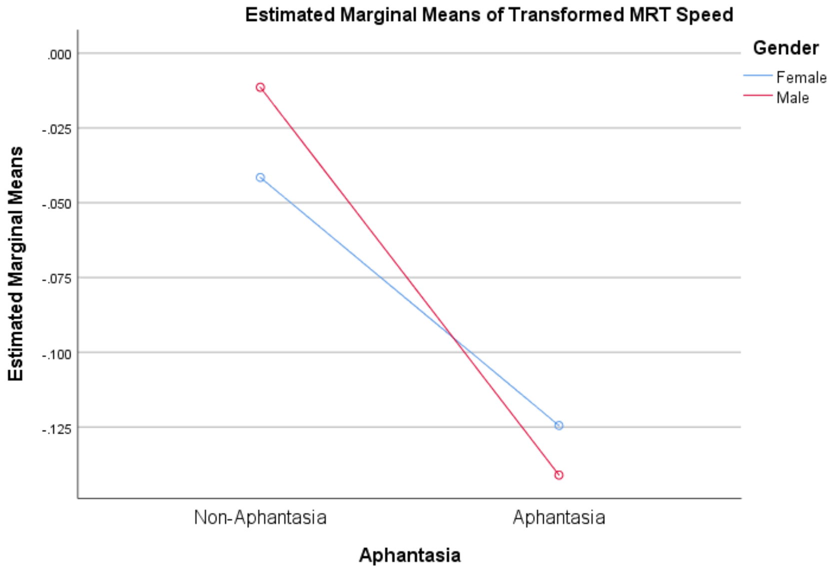

Figure 3. Two-way ANOVA means plot on transformed MRT speed with gender and aphantasia as main effects.

MRT Score

For all subjects, males had significantly higher MRT scores (*M* = 7.93, *SD* = 2.50) than females (*M* =6.18, *SD* = 3.03); *t*(116) = 3.16, *p* < .001, *d* = .63. Data for MRT scores were approximately normal and the test for homogeneity of variance was not significant, with Levene *F*(3, 114) = .868, *p* > .05, meeting the assumptions needed to perform the two-way ANOVA. The ANOVA yielded a main effect for gender, *F*(1, 114) = 8.68, *p* = .004, meaning that the average MRT score was significantly higher for males (*M* = 7.93, *SD* = 2.49) than for females (*M* = 6.18, *SD* = 3.03). The main effect of aphantasia was non-significant, *F*(1, 114) = 1.432, *p* > .05, and there was a non-significant interaction effect of gender*aphantasia as shown in Figure 4 (*F*(1, 114) = .289, *p* > .05).

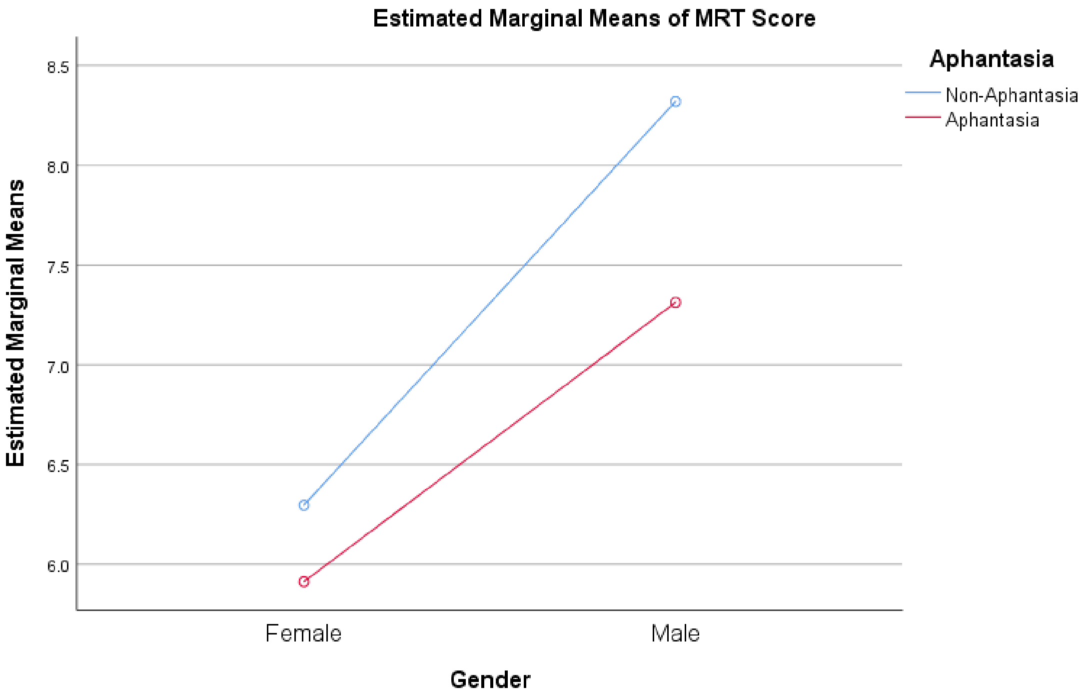

Figure 4. Two-way ANOVA means plot on transformed MRT speed with gender and aphantasia as main effects.

MRT Accuracy

Although the accuracy data were approximately normal, with satisfactory skewness and kurtosis (Jones, 1969), the assumption of homogeneity of variances was violated ($F(3, 114) = 5.478$, $p < .001$), making the results from the two-way ANOVA less valid (Wobbrock, Findlater, Gergle, & Higgins, 2011) and, when sample sizes are unequal, reducing the power (Ananda & Weerahandi, 1997). Nevertheless, a two-way ANOVA was performed, and the results led to further investigation. The ANOVA showed a main effect for gender, $F(1, 114) = 12.88$, $p < .001$, meaning that the average MRT accuracy was significantly higher for males ($M = .82$, $SD = .15$) than for females ($M = .65$, $SD = .26$). The main effect of aphantasia was non-significant, $F(1, 114) = .43$, $p > .05$, and there was a non-significant interaction effect of gender*aphantasia as shown in Figure 5 ($F(1, 114) = .450$, $p > .05$).

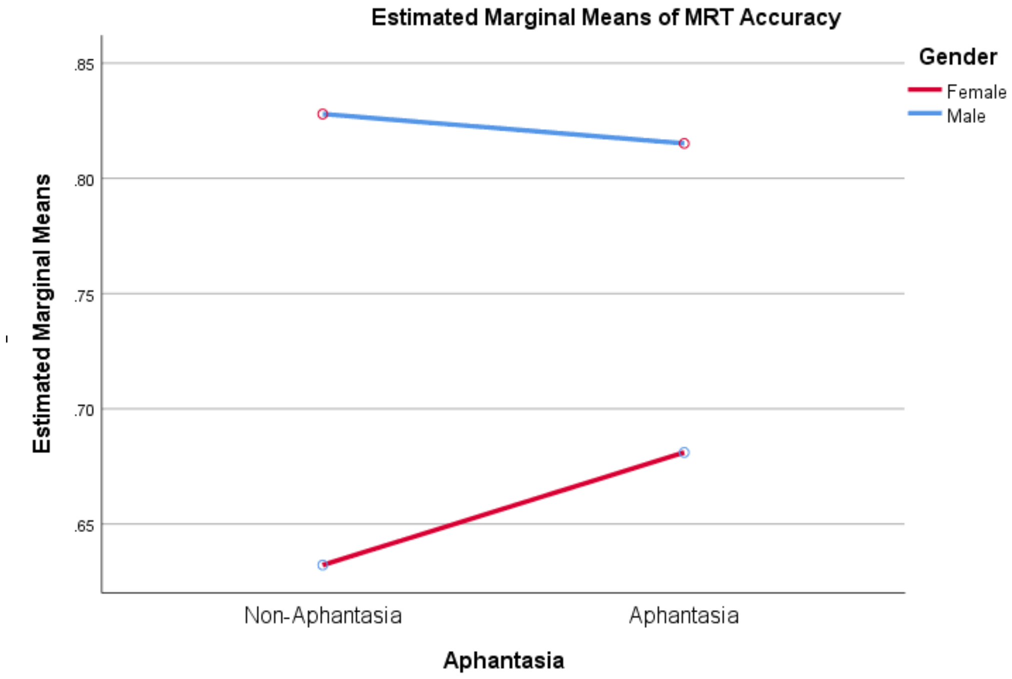

Figure 5. Two-way ANOVA means plot on MRT accuracy with gender and aphantasia as main effects.

Because of the issues with the unequal sample sizes and variances, the gender differences for accuracy were further analyzed by comparing the results of independent samples *t* tests. Based on these results, males performed with higher accuracy on the MRT (*M* = .82, *SD* = .15) than females (*M* = .65, *SD* = .26). Levene's test for equality of variances indicated unequal variances (*F* = 14.81, *p* < .001), so degrees of freedom were adjusted from 116 to 114.90; *t*(114.90) = 4.70, *p* < .001, *d* = .84. When the aphantasia and non-aphantasia groups were examined separately, results showed less difference between the genders in MRT performance for the aphantasia group than the non-aphantasia group (Table 5). In fact, for the aphantasia group there was no significant difference between males (*M* = .77, *SD* = .28) and females (*M* = .86, *SD* = .44) in speed. Levene's test for equality of variances indicated unequal variances (*F* = 5.32, *p* = .027), so degrees of freedom were adjusted from 37 to 36.79; *t*(36.79) = .78, *p* = .221, *d* = .24. The aphantasia group results also showed no significant difference between males (*M* =

7.31, $SD = 2.80$) and females ($M = 5.91$, $SD = 2.88$) in MRT score ($t(37) = 1.32$, $p = .093$, $d = .49$). However, the aphantasia group did show a significant difference between males ($M = .82$, $SD = .17$) and females ($M = .68$, $SD = .24$) in accuracy ($t(37) = 1.92$, $p = .032$, $d = .64$). Like the aphantasia group, the non-aphantasia group results revealed no significant difference between males ($M = 1.18$, $SD = 1.04$) and females ($M = 1.07$, $SD = .79$) in MRT speed ($t(77) = -.53$, $p = .300$, $d = .12$) and a significant difference between males ($M = .83$, $SD = .14$) and females ($M = .63$, $SD = .26$) in accuracy. For accuracy, Levene's test for equality of variances indicated unequal variances ($F = 12.22$, $p = .001$), so degrees of freedom were adjusted from 77 to 75.00; $t(75.00) = -4.286$, $p < .001$, $d = .93$. The non-aphantasia group results also showed a significant difference between males ($M = 8.32$, $SD = 2.25$) and females ($M = 6.30$, $SD = 3.12$) in MRT score ($t(77) = -2.91$, $p = .0025$, $d = .74$).

Table 5

*MRT Accuracy * Gender - By Group*

			Levene's Test for Equality of Variances		t-test for Equality of Means						
										95% Confidence Interval of the Difference	
Aphantasia			F	Sig.	T	Df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Non-Aphantasia	MRT Accuracy	Equal variances assumed	12.22	.001	3.49	77.00	.001	.20	.06	.08	.31
		Equal variances not assumed			4.29	75.00	.000	.20	.05	.10	.29
Aphantasia	MRT Accuracy	Equal variances assumed	1.88	.178	1.54	38.00	.131	.11	.07	-.034	.25
		Equal variances not assumed			1.60	37.85	.117	.11	.07	-.029	.25

Relationship between Vividness of Mental Imagery and Mental Rotation Test Performance

The third research question addressed the possible relationships between vividness of mental imagery (object and spatial), with MRT performance (accuracy and speed). Bivariate correlation analyses were performed. Where appropriate, to minimize the risk of Type I error due to multiple comparisons in these analyses, alpha levels were adjusted using the Bonferroni correction (Abdi, 2007). Using a Bonferroni adjusted alpha level of .005, the results for all of the participants showed a moderate negative correlation between MRT accuracy and MRT speed ($r(119) = -.23$, $p = .011$), a moderate positive correlation between MRT speed and vividness of object imagery ($r(119) = .25$, $p = .006$) and a significant positive correlation between MRT speed and vividness of spatial imagery ($r(119) = .28$, $p = .002$). Analyses also revealed a weak negative correlation between MRT accuracy and vividness of object imagery ($r(119) = -.14$), and little to no correlation between MRT accuracy and vividness of spatial imagery ($r(119) = -.03$). Additionally, results showed a significant positive correlation between vividness of object and vividness of spatial imagery ($r(119) = .91$, $p < .001$).

When the data were analyzed by group using the Bonferroni adjusted alpha of .005, the results were slightly different (Table 6). Both the aphantasia group ($r(40) = .78$, $p < .001$) and the non-aphantasia group ($r(79) = .84$, $p < .001$) showed significant correlations between vividness of object imagery and vividness of spatial imagery. The non-aphantasia group responses showed a weak negative correlation between MRT speed and MRT accuracy ($r(79) = -.25$, $p = .030$), a weak positive correlation between MRT speed and vividness of object imagery ($r(79) = .19$), and very little correlation between vividness of spatial imagery and MRT accuracy ($r(79) = .03$) or between MRT speed and MRT score ($r(79) = .03$).

For the aphantasia group, there were weak negative correlations between MRT accuracy and MRT speed ($r(40) = -.17$), between MRT accuracy and vividness of object imagery ($r(40) = -.11$), and between MRT accuracy and vividness of spatial imagery ($r(40) = -.11$). The aphantasia group results showed a moderate positive correlation between MRT score and MRT speed ($r(40) = .46$, $p = .003$).

Table 6

Correlations by Group

Aphantasia		MRT Score	MRT Accuracy	MRT Speed	VOSIQ-Object	VOSIQ-Spatial
Non-Aphantasia	MRT Score	1	.81 **	.03	-.00	.12
	MRT Accuracy	.81 **	1	-.25	-.16	.03
	MRT Speed	.03	-.25	1	.19	.24
	VOSIQ-Object	-.00	-.16	.19	1	.84 **
	VOSIQ-Spatial	.12	.03	.24	.84 **	1
Aphantasia	MRT Score	1	.70 **	.46	.04	.00
	MRT Accuracy	.70 **	1	-.17	-.11	-.11
	MRT Speed	.46	-.17	1	.09	-.02
	VOSIQ-Object	.04	-.11	.09	1	.78 **
	VOSIQ-Spatial	.00	-.11	-.02	.78 **	1

**. Correlation is significant at the 0.005 level (2-tailed).

Arts and STEM Self-efficacy and Aphantasia

The final research question addressed whether having aphantasia affected how participants rated their self-efficacy in STEM or the arts. In this study, the three STEM self-efficacy items showed very good reliability for both the non-aphantasia group ($\alpha = .920$) and the aphantasia group ($\alpha = .922$). The three arts self-efficacy items also proved to be reliable for both the non-aphantasia ($\alpha = .900$) and aphantasia groups ($\alpha = .938$). For both arts and STEM, self-efficacy ratings (from one to seven) were averaged across the three arts and three STEM items respectively.

Chi square tests of independence were performed to answer this research question. First, scores for arts and STEM self-efficacy were recoded into new variables representing “low,” “medium,” and “high” reported self-efficacy rating by means of K-means ($k = 3$) clustering. K-means clustering has been used for decades in machine learning and has been proven both a stable and reliable way to group data via the nearest neighbor algorithm (Jain, Murty, & Flynn, 1999). As can be seen in the frequencies cross-tabulated in Table 7, there seems to be no relationship between having aphantasia and arts self-efficacy (χ^2 (2, N = 119) = 5.42, p = .066). Meanwhile, the frequencies in Table 8 show that there appears to be no relationship between having aphantasia and STEM self-efficacy (χ^2 (2, N = 119) = 2.18, p = .337). *Table 7*

*Arts Self-efficacy * Aphantasia*

			Aphantasia		
			Non-Aphantasia	Aphantasia	Total
Arts Self-efficacy	Low	Count	34.0	16.0	50.0
		Expected Count	33.2	16.8	50.0
		Residual	.8	-.8	
	Medium	Count	17.0	16.0	33.0
		Expected Count	21.9	11.1	33.0
		Residual	-4.9	4.9	
	High	Count	28.0	8.0	36.0
		Expected Count	23.9	12.1	36.0
		Residual	4.1	-4.1	
Total		Count	79.0	40.0	119.0
		Expected Count	79.0	40.0	119.0

Table 8

*STEM Self-efficacy * Aphantasia*

			Aphantasia		
			Non-Aphantasia	Aphantasia	Total
STEM Self-efficacy	Low	Count	17.0	8.0	25.0
		Expected Count	16.6	8.4	25.0
		Residual	.4	-.4	
	Medium	Count	27.0	9.0	36.0
		Expected Count	23.9	12.1	36.0
		Residual	2.7	-2.7	
	High	Count	35.0	23.0	58.0
		Expected Count	38.5	19.5	58.0
		Residual	-3.5	3.5	
Total		Count	79.0	40.0	119.0
		Expected Count	79.0	40.0	119.0

The non-aphantasia group rated itself higher (*M* = 4.48, *SD* = 1.75) than the aphantasia group (*M* = 3.88, *SD* = 2.05) in arts self-efficacy, while the aphantasia group rated itself higher in STEM self-efficacy (*M* = 4.72, *SD* = 1.92) than the non-aphantasia group (*M* = 4.56, *SD* = 1.79). However, neither of those differences were statistically significant.

Gender and STEM/Arts Self-efficacy

Just as in the literature discussed in chapter 2, females from both groups reported lower STEM self-efficacy than males based on the results of independent samples *t*-tests (Table 9). Females in the non-aphantasia group reported a significantly lower mean STEM self-efficacy of 4.09 (*SD* = 1.76), while the males in that group reported a mean STEM self-efficacy of 5.57 (*SD* = 1.43); *t*(77) = -3.70, *p* < .001, *d* = .92.   However, in the aphantasia group, there was no significant difference found between males and females in reported STEM self-efficacy. Females had a mean STEM self-efficacy score of 4.42 (*SD* = 1.78) compared to the mean male STEM self-efficacy score of 5.35 (*SD* = 1.94); *t*(37) = -1.55, *p* = .065, *d* = .50. There was no significant difference in arts self-efficacy ratings between the genders in either the aphantasia or non-aphantasia groups.

Table 9

*Arts/STEM Self-efficacy * Gender – by Group*

			Levene's Test for Equality of Variances		t-test for Equality of Means						
										95% Confidence Interval of the Difference	
Aphantasia			F	Sig.	t	Df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Non-Aphantasia	Arts Self-efficacy	Equal variances assumed	.02	.878	-.55	77.00	.586	-.23	.43	-1.08	.61
		Equal variances not assumed			-.55	47.05	.586	-.23	.42	-1.09	.62
	STEM Self-efficacy	Equal variances assumed	2.22	.141	-3.70	77.00	.000	-1.49	.40	-2.29	-.69
		Equal variances not assumed			-4.00	56.84	.000	-1.49	.37	-2.23	-.74
Aphantasia	Arts Self-efficacy	Equal variances assumed	.55	.465	-1.02	37.00	.31	-.69	.67	-2.06	.68
		Equal variances not assumed			-1.04	34.46	.31	-.69	.66	-2.03	.65
	STEM Self-efficacy	Equal variances assumed	.02	.897	-1.54	37.00	.13	-.93	.60	-2.15	.25
		Equal variances not assumed			-1.53	30.61	.14	-.93	.61	-2.18	.31

STEM Self-efficacy and MRT Performance

Although not a specific research question for this study, Blazhenkova (2016) found relationships between arts self-efficacy and vividness of object imagery and between STEM self-efficacy, vividness of spatial imagery, and MRT performance, therefore these relationships were examined in this study using the Bonferroni adjusted alpha level of .003. In the non-aphantasia group (Table 10), tests showed moderate positive correlations between arts self-efficacy and vividness of object imagery (*r*(79) = .266, *p* = .018), between arts self-efficacy and vividness of spatial imagery (*r*(79) = .25, *p* = .026), and between STEM self-efficacy and MRT accuracy (*r*(79) = .29, *p* = .011). No correlation was shown between STEM self-efficacy and vividness of spatial imagery (*r*(79) = .09). As in Blazhenkova (2016), there was a weak negative correlation between arts self-efficacy and STEM self-efficacy (*r*(79) = -.11) for the non-aphantasia group.

Table 10

Correlations Between Dependent Variables and Arts/STEM Self-efficacy – Non-Aphantasia Group

Aphantasia		MRT Accuracy	MRT Speed	VOSIQ-Object	VOSIQ-Spatial	Arts Self-efficacy	STEM Self-efficacy
Non-Aphantasia	MRT Accuracy	1	-.25	-.16	.03	.01	.29
	MRT Speed	-.25	1	.19	.24	-.07	.05
	VOSIQ-Object	-.16	.19	1	.84 **	.27	-.08
	VOSIQ-Spatial	.03	.24	.84 **	1	.25	.09
	Arts Self-efficacy	.01	-.07	.27	.25	1	-.11
	STEM Self-efficacy	.29	.05	-.08	.09	-.11	1

**. Correlation is significant at the 0.003 level (2-tailed).

The aphantasia group (Table 11) showed a stronger positive correlation between STEM self-efficacy and MRT accuracy (*r*(40) = .42, *p* = .006) than the non-aphantasia group. The aphantasia group showed weak negative correlations between STEM self-efficacy and vividness of spatial imagery (*r*(40) = -.16), and between STEM self-efficacy and vividness of object imagery (*r*(40) = -.17). There was a weak positive correlation between STEM self-efficacy and MRT speed for the aphantasia group (*r*(40) = .25), as well as between arts self-efficacy and vividness of object imagery (*r*(40) = .21), between arts self-efficacy and vividness of spatial imagery (*r*(40) = .27), and between arts self-efficacy and MRT accuracy (*r*(40) = .11).

Table 11

Correlations Between Dependent Variables and Arts/STEM Self-efficacy – Aphantasia Group

Aphantasia		MRT Accuracy	MRT Speed	VOSIQ-Object	VOSIQ-Spatial	Arts Self-efficacy	STEM Self-efficacy
Aphantasia	MRT Accuracy	1	-.17	-.11	-.11	.11	.42
	MRT Speed	-.17	1	.09	-.02	-.39	.25
	VOSIQ-Object	-.11	.09	1	.78 **	.21	-.17
	VOSIQ-Spatial	-.11	-.02	.78 **	1	.27	-.16
	Arts Self-efficacy	.11	-.39	.21	.27	1	-.02
	STEM Self-efficacy	.42	.25	-.17	-.16	-.02	1

**. Correlation is significant at the 0.003 level (2-tailed).

Further Analysis by Cluster

For this study, the definition of people with aphantasia was very strict. Participants who reported the minimum vividness of imagery on every item of the VVIQ, resulting in a score of 16, were put into the aphantasia group. However, this strict categorization meant that even participants who scored a 17 were placed into the non-aphantasia group, which could have diluted any real differences between those with aphantasia and those without aphantasia. Because it seems reasonable to assume that a participant who scored a 17 or 18 on the VVIQ would be more like a participant who scored a 16 than a participant who scored a 70, further analysis was deemed necessary. Toward that end, participants were placed into three different visualization groups using K-means clustering on 16 dimensions (each of the VVIQ items). This created three different vividness levels: low (N = 59), medium (N = 22), and high (N = 38). Table 12 displays the descriptive statistics of age, VVIQ score, and the dependent variables for the different vividness levels.

Table 12

Descriptive Statistics of Dependent Variables by Vividness Cluster

Vividness		N	Minimum	Maximum	Mean	Std. Deviation
Low	Age	59	18.00	66.00	41.29	14.82
	MRT Accuracy	59	.17	1.00	.74	.23
	MRT Speed	59	.17	1.88	.84	.36
	VVIQ	59	16.00	32.00	17.83	3.58
	VOSIQ-Object	59	14.00	25.00	15.63	2.84
	VOSIQ-Spatial	59	14.00	38.00	16.36	4.96
	Arts Self-efficacy	59	1.00	7.00	3.91	1.88
	STEM Self-efficacy	59	1.33	7.00	4.87	1.80
	Valid N (listwise)	59				
Medium	Age	22	18.00	63.00	25.64	12.46
	MRT Accuracy	22	.08	1.00	.62	.31
	MRT Speed	22	.25	5.53	1.22	1.11
	VVIQ	22	34.00	59.00	49.55	6.94
	VOSIQ-Object	22	24.00	62.00	45.32	9.63
	VOSIQ-Spatial	22	19.00	59.00	36.32	10.19
	Arts Self-efficacy	22	1.00	6.67	3.95	1.81
	STEM Self-efficacy	22	1.00	7.00	4.27	1.86
	Valid N (listwise)	22				
High	Age	38	18.00	58.00	25.39	10.85
	MRT Accuracy	38	.25	1.00	.69	.20
	MRT Speed	38	.33	5.71	1.15	.90
	VVIQ	38	61.00	80.00	69.47	6.48
	VOSIQ-Object	38	42.00	70.00	58.76	7.88
	VOSIQ-Spatial	38	23.00	70.00	48.76	11.14
	Arts Self-efficacy	38	1.00	7.00	5.04	1.68
	STEM Self-efficacy	38	1.00	7.00	4.41	1.84
	Valid N (listwise)	38				

As shown in the table above, the low vividness group had a mean VVIQ score of 17.83 (*SD* = 3.58), with a maximum score of 32. The medium vividness group had a mean VVIQ score of 49.55 (*SD* = 6.94), ranging between 34 and 59. Finally, the high vividness group had a mean VVIQ score of 69.47 (*SD* = 6.48), with a minimum score of 69 and a maximum score of 80.

Vividness Groups and Spatial/Object Vividness

Because homogeneity of variances was violated for VOSIQ-spatial and VOSIQ-object responses, Kruskal-Wallis tests were performed on those variables using vividness group as the factor. The test showed that there was a significant difference in means of reported vividness of object imagery between vividness groups (H = 97.40, p < .001). Post hoc tests to test pairwise comparisons found significant differences between low and medium vividness groups (H = -5.39, p < 0.001) and between the low and high vividness groups (H = -9.57, p < .001). The medium and high vividness groups also differed significantly, but at a level of p = .016 (H = -2.40). For reported vividness of spatial imagery, a Kruskal-Wallis test revealed a significant difference in means between vividness groups (H = 91.45, p < .001). Post hoc tests to test pairwise comparisons found significant differences between low and medium vividness groups (H = -5.45, p < 0.001) and between the low and high vividness groups (H = -9.21, p < .001). The medium and high vividness groups did not differ significantly in reported vividness of spatial imagery. These results helped verify that using K-means (k = 16) clustering to group on vividness created clearer, more logical separation of the participant responses.

Vividness Groups and Dependent Variables

The MRT accuracy and MRT speed variables violated the homogeneity of variances required for a one-way ANOVA when analyzed by vividness group, so the Kruskal-Wallis test was performed. Results of that test showed no significant difference between vividness clusters for MRT accuracy or MRT speed. One-way ANOVA tests using Bonferroni an adjusted alpha level of .017 were performed on arts self-efficacy and STEM self-efficacy using the vividness groups as the factor. As shown in Table 13 below, the vividness groups differed significantly on arts self-efficacy.

Table 13

*Vividness Clusters * Dependent Variables*

		Sum of Squares	Df	Mean Square	F	Sig.
Arts Self-efficacy	Between Groups	32.60	2	16.30	4.98	.008
	Within Groups	379.40	116	3.27		
	Total	411.99	118			
STEM Self-efficacy	Between Groups	7.98	2	3.99	1.20	.306
	Within Groups	386.69	116	3.33		
	Total	394.66	118			

Post hoc comparisons using the Tukey HSD test showed that the significant difference in arts self-efficacy existed only between those in the low (*M* = 3.91, *SD* = 1.88) and high (*M* = 5.04, *SD* = 1.68) vividness levels.

Relationships and Vividness Clusters

Pearson correlation analyses using a Bonferroni adjusted alpha level of .003 were performed on the dependent variables and analyzed by vividness cluster. Table 14 displays the correlations for the low vividness cluster. As seen in the table, participants in the low vividness group showed a strong positive correlation between object and spatial vividness (*r*(59) = .76, *p* < .001), a moderate positive correlation between STEM self-efficacy and MRT accuracy (*r*(59) = .40, *p* = .002), and a moderate negative correlation between arts self-efficacy and MRT speed (*r*(59) = -.33, *p* = .012).

Table 14

*Correlations: Low Vividness Cluster * Dependent Variables*

Vividness		MRT Accuracy	MRT Speed	VOSIQ-Object	VOSIQ-Spatial	Arts Self-efficacy	STEM Self-efficacy
Low	MRT Accuracy	1	-.10	.03	.15	.10	.40 **
	MRT Speed	-.10	1	.16	.13	-.33 **	.18
	VOSIQ-Object	.04	.16	1	.76 **	.01	.07
	VOSIQ-Spatial	.15	.12	.76 **	1	.12	.09
	Arts Self-efficacy	.10	-.33 **	.01	.12	1	-.02
	STEM Self-efficacy	.40 **	.18	.07	.09	-.02	1

**. Correlation is significant at the 0.003 level (2-tailed).

Table 15 shows the correlations between dependent variables for the medium vividness cluster. Unlike the low and high vividness groups, there was no significant positive correlation for this cluster between reported vividness of spatial and object imagery (r(22) = .53, p = .011). Results showed a moderate positive correlation between MRT speed and vividness of spatial imagery (*r*(22) = .47, *p* = .027). Although there was a moderate positive correlation between STEM self-efficacy and MRT accuracy, it was not significant (*r*(22) = .28, *p* =.204) , in contrast to the low vividness cluster.

Table 15

*Correlations: Medium Vividness Cluster * Dependent Variables*

Vividness		MRT Accuracy	MRT Speed	VOSIQ-Object	VOSIQ-Spatial	Arts Self-efficacy	STEM Self-efficacy
Medium	MRT Accuracy	1	-.24	-.19	-.01	-.00	.28
	MRT Speed	-.24	1	.28	.47	-.15	.13
	VOSIQ-Object	-.19	.28	1	.53	.23	.32
	VOSIQ-Spatial	-.01	.47	.53	1	.20	.14
	Arts Self-efficacy	-.00	-.15	.23	.20	1	-.14
	STEM Self-efficacy	.28	.13	.32	.14	-.14	1

**. Correlation is significant at the 0.003 level (2-tailed).

Results of the correlation analyses for the high vividness cluster are shown in Table 16. As in the low vividness group, there was a significant positive correlation between reported vividness of spatial and object imagery (*r*(38) = .58, *p* < .001). The high vividness group also showed non-significant positive correlations between STEM self-efficacy and reported vividness of spatial imagery (*r*(38) = .47, *p* = .003) and between STEM self-efficacy and MRT accuracy (*r*(38) = .22, *p* = .175).

Table 16

*Correlations: High Vividness Cluster * Dependent Variables*

Vividness		MRT Accuracy	MRT Speed	VOSIQ-Object	VOSIQ-Spatial	Arts Self-efficacy	STEM Self-efficacy
High	MRT Accuracy	1	-.28	-.05	.30	-.01	.22
	MRT Speed	-.28	1	.08	.09	-.04	.07
	VOSIQ-Object	-.05	.08	1	.58 **	.06	.12
	VOSIQ-Spatial	.30	.09	.58 **	1	.01	.47
	Arts Self-efficacy	-.01	-.04	.06	.01	1	-.09
	STEM Self-efficacy	.22	.07	.12	.47	-.09	1

**. Correlation is significant at the 0.003 level (2-tailed).

Chapter Five: Discussion

The results of this study led to interesting insights and questions about how people with aphantasia complete mental rotation tasks, the relationship between vividness of spatial imagery and mathematics, and the very definition of spatial "imagery." Results showed that people with aphantasia reported very low vividness of spatial imagery yet did not differ significantly in MRT accuracy or MRT score from those who do not have aphantasia and who report better vividness of spatial imagery. This section of the paper will delve deeper into those questions within the context of the results of this study and existing literature. This study's limitations will also be examined. Finally, this section will offer potential directions for future research into aphantasia, STEM, and education.

Aphantasia and Vividness of Mental Imagery

The first research question in this study asked whether people with aphantasia reported significantly lower vividness of mental imagery than people without aphantasia. According to responses on both the VOSIQ-Object and VOSIQ-Spatial items, people with aphantasia report little to no vividness of either type of imagery. The object imagery results were not surprising given that in many studies, like Blazhenkova (2016), the correlation between the VVIQ scores and the VOSIQ-Object scores was significant, most likely because the VVIQ appears to have been designed to measure only object imagery. The unknown was how people with aphantasia experienced vividness of spatial imagery. Given the reported lack of vividness of spatial imagery in this study, people with aphantasia seem to be completely "blind" in the mind's eye.

Kosslyn & Thompson (2012) and Pitta-Pantazi & Christou (2010) proposed that strengths of object and spatial imagery abilities were inversely proportional. Based upon results from this study, people with aphantasia do not fit within that proposed framework. In this study, mean scores on the VOSIQ spatial and object items were significantly and positively correlated for both the aphantasia (VVIQ = 16) and non-aphantasia (VVIQ > 16) groups. However, for the aphantasia group, the VOSIQ spatial item scores had more variance (*M* = 14.45, *SD* = 2.00) than the VOSIQ object item scores (*M* = 14.30, *SD* = .99) because of a few outliers as explained in the prior section. This slightly higher reporting of vividness of spatial imagery held true when the participant responses were placed into low, medium, and high vividness groups via K-means (*k* = 16) clustering, with the low vividness group reporting a mean vividness of object imagery score of 15.63 (*SD* = 2.84), and a slightly higher mean vividness of spatial imagery score of 16.36 (*SD* = 4.96).

Vividness versus Imagery

Keogh & Pearson (2017) used the OSIQ (Blazhenkova, Kozhevnikov, & Motes, 2006) to measure object and spatial imagery, and interpreted the OSIQ spatial items as a measure of "spontaneous use of spatial imagery." The OSIQ asks respondents to rate how much they agree or disagree with statements about their creation of mental imagery, from one (strongly disagree) to five (strongly agree). In Keogh & Pearson (2017), people with aphantasia reported significantly lower agreement with statements about creation of object imagery than the control group, which aligns with results from the present study. However, the aphantasia group in Keogh & Pearson (2017) reported higher agreement with statements focused on creation of spatial imagery than the control group, although not significantly higher. Keogh & Pearson (2017) also reported that people with aphantasia had double the scores on the OSIQ spatial items than they did on the OSIQ object items. Spatial imagery ratings may be different in the present study because this study measured vividness of mental imagery with the VOSIQ while the OSIQ measures visualization ability. Vividness of imagery is a fundamentally different construct than visualization ability (Blazhenkova, 2016). Visualization ability is the ability to create mental imagery, while vividness “refers to the quality of the subjective imagery experiences in terms of their clarity and richness, sense of reality, and resemblance of actual perceptual experiences (Blazhenkova, 2016, p. 491). Therefore, it may be possible that people with aphantasia do experience some form of spatial imagery, but it is not “vivid” in the pictorial sense.

VOSIQ and Aphantasia

One important finding from this study was that participants in the aphantasia group reported significantly lower vividness of spatial imagery than the non-aphantasia group, unlike the results of the OSIQ reported in Keogh & Pearson (2017) or the participants in Blazhenkova (2016). As discussed previously, the VVIQ is currently the instrument used to evaluate whether a person has aphantasia (e.g., Keogh & Pearson, 2017; Winlove, et al., 2017; Zeman, et al., 2010). However, there are two types of mental imagery (object and spatial). Therefore, the VOSIQ could serve as an indicator of aphantasia. Because people with aphantasia did report that they created some sort of spatial mental imagery in Keogh & Pearson (2017), vividness - or the lack thereof - may be the construct that is most associated with the visualization experiences of people with aphantasia.

Aphantasia and Arts/STEM Self-efficacy

This study found differences between how the aphantasia and non-aphantasia groups rated their self-efficacy in arts and STEM. In general, the non-aphantasia group rated themselves higher in the arts, while the aphantasia group rated themselves higher in STEM. This difference was more pronounced when the participants were grouped using K-means (*k* = 16) clustering than when they were grouped using the strict definition of aphantasia, which was a VVIQ score of 16. Gender played a part in STEM self-efficacy ratings in both the aphantasia and the non-aphantasia groups, reflecting the prevailing literature on gender and STEM, and perhaps playing a part in MRT performance results (Moè, 2009).

Arts Self-efficacy

Just as in Blazhenkova (2016), vividness of object imagery had a non-significant, positive relationship with the arts for both the non-aphantasia (*r*(79) = .27, *p* = .018) and the aphantasia group (*r*(40) = .21, *p* = .201). The difference in reported arts self-efficacy was significant when the participants were classified into three vividness groups via K-means (*k* = 16) clustering. Tests using the vividness groups as the independent variable showed that people reporting low vividness of object imagery had notably lower arts self-efficacy scores than either the medium or high vividness groups. These results align with Winlove et al. (2017), who found that people with aphantasia were less likely to have careers in the arts than people with high vividness of mental imagery based on responses to the VVIQ.

STEM Self-efficacy

Participants in the aphantasia group rated themselves slightly higher in STEM self-efficacy (*M* = 4.73, *SD* = 1.92) than those in the non-aphantasia group (*M* = 4.56, *SD* = 1.79). In Blazhenkova (2016), there was a significant positive relationship between science self-efficacy and VOSIQ-spatial items (*r*(205) = .33, *p* < .01). However, results were different in the present study. The aphantasia group’s VOSIQ-spatial scores showed a small negative correlation with STEM self-efficacy ratings (*r*(40) = -.16), while the non-aphantasia group had a very little correlation between STEM self-efficacy and VOSIQ-spatial scores (*r*(79) = .09). The negative correlation between STEM self-efficacy and vividness of spatial imagery was expected for the aphantasia group because of their low VOSIQ-spatial scores, but higher STEM self-efficacy ratings. When the data were analyzed by vividness cluster, the correlation between STEM self-efficacy and vividness of spatial imagery increased with vividness (Tables 14, 15, and 16). Participants with the highest VVIQ scores showed the strongest relationship between vividness of spatial imagery and STEM self-efficacy ($r(38) = .47$) when compared to the medium ($r(22) = .14$) and low ($r(59) = .09$) vividness clusters.

Conversely, only those in the low vividness cluster showed a significant relationship between STEM self-efficacy and MRT performance based on accuracy ($r(59) = .40$, $p < .003$). Although positive correlations existed between STEM self-efficacy and MRT accuracy for all the clusters, the correlations decreased as reported vividness increased. The correlations between STEM self-efficacy and MRT accuracy were not significant for the medium ($r(22) = .28$) or the high ($r(38) = .22$) vividness group. These results would seem to indicate that people with low vividness of mental imagery had a stronger understanding of their own STEM self-efficacy, which was later reflected in performance. This could be because of the metacognition that may be required to solve a visualization task without imagery. Couthino (2008) wrote that the "most successful students are those with strong metacognitive skills who monitor and evaluate their performance, and have confidence in their abilities to perform successfully" (p. 170).

Gender

In both the aphantasia and non-aphantasia groups, females rated themselves lower than their male counterparts in STEM self-efficacy. However, females without aphantasia rated themselves significantly lower than their male counterparts, while the aphantasia group showed no significant difference between males and females on STEM self-efficacy. Moè (2009) found that self-belief could play an important part in spatial ability task performance for women; if women believe in their spatial ability, they will perform spatial ability tasks better. In this study, females in the aphantasia group had lower scores, but marginally higher accuracy and slower speed on the MRT than females in the non-aphantasia group. Females in the aphantasia group also rated themselves higher in STEM self-efficacy (*M* = 4.42, *SD* = 1.78) than women in the non-aphantasia group (*M* = 4.09, *SD* = 1.76), but not at a significant level (*t*(75) = -.76, *p* = .225, *d* = .19). Meanwhile, men in the aphantasia group rated themselves slightly lower in STEM self-efficacy (*M* = 5.35, *SD* = 1.94) than males in the non-aphantasia group (*M* = 5.57, *SD* = 1.43) and performed with about the same accuracy (*M* = .82, *SD* = .17) on the MRT as males in the non-aphantasia group (*M* = .83, *SD* = .14). The smaller difference in STEM self-efficacy between men and women in the aphantasia group may be due to the tendency of people with aphantasia to rate themselves as less artistically inclined, which in turn could push them to pursue different interests, like STEM.

Aphantasia, Mental Rotation, and Mathematics

Existing literature has used mental rotation as a proxy for spatial visualization ability and has found a positive correlation between reported spatial visualization and mental rotation abilities (e.g., Blazhenkova & Kozhevnikov, 2010; Keogh & Pearson, 2017), as well as between spatial visualization ability and mathematics achievement (e.g., Cheng & Mix, 2014). As in previously published research on aphantasia (e.g., Zeman et al., 2010), people with aphantasia in this study were at least as accurate on the MRT than people without aphantasia. Results also revealed that the aphantasia group was slower at the MRT than the non-aphantasia group. The discussion around differences in MRT performance have traditionally centered around the processing differences between those who create an image of the object and rotate it in their mind's eye and those who use analytical strategies to map the object characteristics to a rotated location. Some studies have posited that this difference in cognitive strategy helps to explain the variance in reaction speed and brain activation patterns during mental rotation tasks (e.g., Fennema & Tartre, 1985; Jordan, et al., 2002).

MRT Performance

Overall, the aphantasia group had higher accuracy and slower performance in the mental rotation test. The non-aphantasia group had higher scores on the MRT, but much of the difference in scores between the aphantasia and non-aphantasia groups could reasonably be explained by the fact that the aphantasia group was slower, meaning that they were unable to complete as many items. Although the VOSIQ-spatial results showed that people with aphantasia reported significantly lower vividness of spatial imagery, Keogh & Pearson (2017) found that there was no significant difference in reported spatial visualization ability, or spontaneous use of spatial imagery, between their aphantasia group and their control group. If, as Keogh & Pearson (2017) suggested, there is some sort of physical disruption in the ventral pathway that prevents them from "seeing" with their mind's eye, but no issues with the dorsal (spatial) stream, this would explain why people with aphantasia are able to complete spatial tasks on a par with people who do not have aphantasia. People with aphantasia appear to be accessing spatial information without an imagery component.

Gender

In much of the existing literature on spatial visualization ability and mental rotation, significant differences in task performance have been found between males and females, where males perform significantly better than females (e.g., Fennema & Sherman, 1977; Maeda & Yoon, 2013). Therefore, the gender differences found in this study between participants who identified themselves as male or female were not unexpected. Past studies have found differences in approach to mental rotation between genders, with males using the holistic rotation strategy and females using the analytical strategy (e.g., Debelak, Gittler, & Arendasy, 2014). Additionally, Maeda & Yoon (2013) found that timed tests affect female performance on mental rotation tasks more than males, which may be an effect of the design of this study. There are also differences in brain activation during mental rotation tasks between the genders that some researchers believe show that males take a more holistic approach to mental rotation, and females take a more analytical approach to mental rotation (e.g., Gootjes, Bruggeling, Magnée, & Van Strien, 2008; Hugdahl, Thomsen, & Ersland, 2006; Weiss et al., 2003).

While both the aphantasia and non-aphantasia groups showed a difference in MRT accuracy between males and females, the gender difference was only significant for the non-aphantasia group. When the participant who identified as non-binary was included in the aphantasia group analysis, there was no statistically significant difference found in MRT accuracy between male and non-male participants. For MRT score, there was no significant difference between males and females in the aphantasia group, but women in the non-aphantasia group scored significantly lower than the males. Females with aphantasia were more accurate (M = .68, SD = .24) on the MRT than females without aphantasia (M = .63, SD = .26), although not significantly (t(75) = -.76, p = .224, d = .20), and had lower MRT scores than females without aphantasia. Males with aphantasia (M = .82, SD = .17) were nearly as accurate as males without aphantasia (M = .83, SD =.14) on the MRT, but had lower scores.

If people with aphantasia are not able to create the image of the object in the mind's eye, both males and females with aphantasia may be using an analytical strategy that does not depend on imagery. This may help explain the smaller difference in MRT accuracy and MRT score between genders for the aphantasia group in this study. It is also possible that people with aphantasia are using completely different, and not yet identified, cognitive strategies to perform mental rotation.

Mental Rotation and Mathematics

This study could have interesting implications for mathematics education. According to Winlove et al. (2017), the most common careers reported for people with aphantasia were STEM fields, specifically mathematics and information technology. In this study, people with aphantasia had a much higher correlation between their ratings of STEM self-efficacy and their MRT score than the non-aphantasia group, suggesting that the perceptions of STEM and actual spatial abilities for people with aphantasia are more closely linked.

In much of the mental rotation and mathematics literature, use of the holistic strategy for mental rotation has been associated with mathematics achievement, particularly geometry (e.g., Dowker, 2005) and in basic number representation (Thompson, Nuerk, Moeller, & Cohen Kadosh, 2013). Although people with aphantasia reported little vividness of spatial imagery in this study, Keogh & Pearson (2017) found that there was no significant difference in OSIQ-spatial responses between those with aphantasia and the control group. In fact, the researchers wrote that participants with aphantasia reported higher scores on the OSIQ-spatial items than the control group. Therefore, people with aphantasia may possess spatial ability that has little to no relation to spatial imagery. These results raise a question about the very definition of spatial “visualization.”

It is quite possible that mental imagery is not necessary for mental rotation or other spatial tasks, and the holistic strategy that has been studied in mental rotation research is neither the optimal strategy nor represents the only strategy with a strong relationship with mathematics achievement. Results from studies on the congenitally blind suggest that mental imagery is not a necessary component to successfully complete spatial tasks (e.g., Knauff & May, 2006; Marmor & Zaback, 1976). Marmor & Zaback found that when performing mental rotation tasks, congenitally blind participant reaction times were linearly related to the angle of rotation from the target, just like sighted participants. In contrast, responses from the aphantasia patient during mental rotation tasks in the Zeman, et al. (2010) study showed no such linear relationship. The results from this study replicated the results of Zeman, et al. (2010), with the aphantasia group showing equivalent accuracy but slower speed on the mental rotation test than the non-aphantasia group, suggesting alternative spatial representations.

Practical Implications

This study could have practical implications in the mathematics classroom for both students and educators. Being aware that one in 30 students in a classroom could have little ability to create mental imagery should change how an educator explains concepts, demonstrates problem-solving strategies, and assesses content knowledge. Although this study demonstrated that people with aphantasia performed just as well as those without aphantasia in mental rotation test performance, it also showed that people with aphantasia were significantly slower. This could indicate that students with aphantasia need extended time for tasks that require spatial transformation.

According to Winlove, et al. (2017) people with aphantasia reported not only low vividness of mental imagery, but also rated their memory as worse than people with higher vividness of mental imagery. If there is a relationship between poor memory and low vividness of mental imagery, which has been reported in some previous research (e.g., Faw, 2009), this may help explain the strong relationship between STEM self-efficacy and MRT performance.

For instance, if students have a difficult time with rote memorization, it may be that they must build a better understanding of the underlying concepts to apply them appropriately. Educators might help these students find new strategies for memorization and recall. Simply asking a student to memorize a formula may not be enough for a student with aphantasia, who may require more concept-based ways to remember, such as derivation. It may also be helpful to provide physical manipulatives or images to students with aphantasia so that they do not have to rely on mental imagery that does not exist. However, any recommendations for classroom approaches for teachers and students should wait until more concrete research on aphantasia is available.

Limitations

As discussed at length in previous chapters, the VVIQ, VOSIQ, and the MRT have been shown to have satisfactory internal consistency in prior research and had good reliability for this study. Therefore, most of the limitations of this study are direct consequences of the chosen research design, specifically the method of data collection.

Sample

Using anonymous participants for online data collections poses several risks to study validity (Kraut, et al., 2004; Lefever, Dal, & Matthiasdottir, 2007). Because of anonymity, there was no way to observe participants or judge their motives for participating in the research. Participants could answer the survey multiple times if an IP address or e-mail address is not collected – and even if the IP address or e-mail address is captured, a participant could easily get around the restriction by simply logging off and logging back on to the network or creating a new e-mail address. While online data collection does offer the benefits of lower cost and wider geographical reach, it also limits the type of responders to people who (1) have access to the internet and (2) have the time and interest to respond. These limitations make the results less generalizable to the general population.

Motivation

Motivation played a large factor in this study. Self-selection will always pose a risk to internal validity, but for this study, people who have self-identified as having aphantasia were specifically recruited to participate. These people may be different from those with aphantasia who do not participate in online support groups or do not self-identify as having aphantasia. The aphantasia group was highly enthusiastic and had a great desire to learn more about their condition, which may have led to exaggerated responses to items meant to measure vividness of imagery. To minimize this motivation factor, it would be ideal to recruit from the general population and objectively identify people with aphantasia. However, to accomplish this could be impractical and expensive. Potentially, hundreds of participants would have to be screened to find a large enough sample of people with aphantasia, and there is currently no instrument designed to do identify the condition.

Group Differences

Demographic differences between the groups, particularly age, ethnicity, and education level, were most likely related to the recruitment strategy used for this study. The non-aphantasia group was recruited on a college campus, which would indicate a younger, more diverse population still completing their education, while the aphantasia group was recruited via social media groups with no such underlying common characteristic. Further, it is safe to assume that much of the non-aphantasia group was recruited via classes at the School of Education. The control group would have been more representative of STEM self-efficacy if participants were also recruited specifically from STEM majors.

Demographics

The participants in this study did not reflect the general population. They were overwhelmingly Caucasian and had at least some college education, which made the results less applicable to the public at large. It would be informative to have a more diverse sample to determine whether there is any difference in the distribution of aphantasia across ethnicities.

Technology

While online surveys have been used for many years, to date, there had been no online implementation of the timed MRT as of this writing. This introduced another level of unknown to the study. For example, older participants may have shown slower response rates simply because younger participants are more comfortable using a computer (Van Selm, & Jankowski, 2006).

Lack of prior research

As mentioned throughout this paper, aphantasia as a named condition is a relatively new phenomenon. Because of the lack of studies focused on this condition, it would be difficult, if not impossible, for results from this study to be compared with existing research to check validity. However, results from the study do align with results from Blazhenkova (2016) on correlation of STEM self-efficacy and mental rotation test performance (accuracy) for the aphantasia group, as well as with VVIQ scores as reported in Zeman et al., 2015. What is new from this research is the comparison of vividness of spatial imagery between people with aphantasia and people without aphantasia.

Future Research

The research on aphantasia is still in its infancy, and there is not much known about how this condition could affect students or teachers' practices in the mathematics classroom. If students are unable to visualize, but are still able to achieve in mathematics, it is important to understand the types of strategies they are using. Learning about those strategies may not only help educators deliver content to maximize the skills of students who have aphantasia but could be useful for students without aphantasia as well.

Identification

Development of a self-report instrument or performance task to help screen individuals for aphantasia would be an important research direction. Currently, the VVIQ has been used to identify aphantasia. However, the VVIQ seems to mostly measure vividness of object imagery, as evidenced by the high correlation between VVIQ and VOSIQ-object items (Blazhenkova, 2016). Even though people with aphantasia reported low object imagery on the OSIQ in Keogh & Pearson (2017), they reported higher spatial imagery than the control group in that study. Because of the lack of difference in spatial responses between the aphantasia and the control group, the OSIQ would not be an appropriate means of identifying people with aphantasia. However, the present study showed that people with aphantasia reported low vividness of both object and spatial imagery using the VOSIQ, which could mean that the spatial imagery people with aphantasia reported in Keogh & Pearson was not “imagery” at all, but rather some other sensory experience that does not lend itself to properties of vividness. Therefore, it is possible that lack of vividness could serve as a proxy for the lack of imagery ability as defined in persons with aphantasia.

Instrumentation

Just as in the present study, results from the VVIQ (Marks, 1973) and the MRT-Redrawn (Peters, et al., 1995) have historically shown good reliability and validity. However, one potential issue with this study was the correlation of self-report instruments like the VVIQ and the VOSIQ (Blazhenkova, 2016) with a performance task like the MRT. Blazhenkova (2016) found significant, but weak, correlations between the performance tasks and self-report instruments, while the correlations between the self-report instruments were moderate. This would seem to indicate that while self-report instruments may be measuring the same construct, the performance tasks are measuring something different than the self-report instruments. It may be useful in future studies examining the spatial abilities of people with aphantasia to ask participants to complete several different spatial performance tasks and then examine the relationships between them. For example, as in Blazhenkova, future studies could use the Paper Folding Test (Ekstrom, French, Harman, & Dermen, 1976) and the MRT, with the addition of spatial performance tasks from the French Kit (French, Ekstrom, & Price, 1963). People with aphantasia have consistently reported low vividness of mental imagery ability (e.g., Keogh & Pearson, 2017; Winlove, et al., 2017; Zeman, et al., 2010), despite performing well on spatial performance tasks. It may be this apparent dichotomy between self-report and ability that best clarifies the difference between those with aphantasia and those without aphantasia.

Qualitative Studies

The best way to truly understand the cognitive strategies used by people with aphantasia during spatial tasks and mathematics is to get their personal insights via interviews and/or observations. While there are many individual reflections of people with aphantasia publicly available on the internet, to identify common strategies and patterns of cognitive styles, it would be optimal to conduct “think-aloud” studies as participants complete different spatial performance tasks like the MRT or the paper-folding task. Further, because this study lacked diversity based on ethnicity and educational background, it would be informative to recruit a sample of participants from different cultural, ethnic, and socio-economic backgrounds. If people from divergent backgrounds use the same types of strategies for mathematics problem-solving and spatial tasks, qualitative analysis of those strategies could be recorded, analyzed, and generalized into quantitative instruments to help others. Many people with congenital aphantasia report that they never realized that they were thinking in a different way than others until they learned about the condition. Gathering information about experiences with mathematics content and in the mathematics classroom via interviews could lead to valuable insights for both educators and students.

STEM and Aphantasia

Another important area for educational research is to investigate mathematics achievement and self-efficacy of people with aphantasia. According to the small amount of research available, people with aphantasia report mathematics and information technology as their most common career field (Winlove et al., 2017). While people with aphantasia did not report significantly higher STEM self-efficacy than people without aphantasia in this study, their perceptions of their STEM ability were more highly correlated to their mental rotation test performance than people without aphantasia. If it is true that people with aphantasia propense toward STEM careers, which research says is closely related to mathematics achievement and self-efficacy, studying the mathematics abilities of people with aphantasia could lead to powerful insights about the characteristics of those who decide to enter STEM fields. The results of this study also show that females with aphantasia reported a higher STEM efficacy than females without aphantasia. It is possible that females with aphantasia also propense to STEM careers more than females without aphantasia, which suggests further studies on the visualization abilities of females in STEM careers.

Other Content Areas

Although this study was focused on spatial visualization ability and mathematics, aphantasia most likely impacts other content areas, especially if there is a relationship between memory and aphantasia (Winlove, et al., 2017). Given that people with aphantasia rated themselves significantly lower in arts self-efficacy in this study, one of the natural next steps would be to examine how having aphantasia may affect student attitudes, self-perceptions, and achievement in content like literary and visual arts. If one in thirty students truly have a blind mind’s eye, what sort of tools would an elementary art educator need to best engage those students?

Conclusion

To date, this study was the first to examine the possible effects of aphantasia on mental rotation ability, vividness of spatial imagery, and STEM/arts self-efficacy. The study added to existing research on aphantasia and on spatial visualization by using established instruments to create a baseline comparison between people with aphantasia and those without aphantasia. This study also helped to confirm the reliability of the VOSIQ and the VVIQ as measures of vividness of mental imagery. High vividness of object imagery as reported on the VOSIQ correlated positively with arts self-efficacy for people without aphantasia, while people who reported low vividness on the VVIQ rated themselves significantly lower on arts self-efficacy, buttressing previous findings on the relationship between object imagery and the arts (e.g., Blazhenkova & Kozhevnikov, 2016; Winlove et al., 2017). Results further replicated the slight negative correlation between arts and STEM self-efficacy for both the aphantasia and non-aphantasia groups (Blazhenkova, 2016). Results from this study can help further research on aphantasia and mathematics education by establishing that people with aphantasia report very little vividness of spatial imagery yet perform just as well on the mental rotation test, which has been used as a proxy for spatial visualization and transformation ability for nearly 30 years.

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Appendix A

Demographic Survey Questions

With what gender do you most identify?

Female Male Other __________________

With what ethnicity do you most identify?

Option to specify Latino/Hispanic

African or Black

Caucasian

Asian

Native American

Other ________________________________

Within what age range do you fall?

18-25 26-35

36-45 46-55

56-65 Over 65

I am confident in my abilities in STEM (science, technology, engineering, mathematics, etc.).

I am confident in my abilities in the arts (visual arts, dance, literary arts, theater, music, etc.).

Compared with others, I think I'm good at STEM subjects (science, technology, engineering, mathematics, etc.).

Compared with others, I think I'm good at the arts (visual arts, dance, literary arts, theater, music, etc.).

I'm certain I can understand ideas involving STEM (science technology, engineering, mathematics, etc.).

I'm certain I can understand ideas involving the arts (visual arts, dance, literary arts, theater, music, etc.).

1 – Not at all true of me to 7 – Very true of me

Appendix B

Vividness of Visual Imagery Questionnaire (Marks, 1973)

For each item on this questionnaire, try to form a visual image, and consider your experience carefully. For any image that you do experience, rate how vivid it is using the five-point scale described below. Please note that there are no right or wrong answers to the questions, and that it is not necessarily desirable to experience imagery or, if you do, to have more vivid imagery.

5 - Perfectly clear and vivid as real seeing
4 - Clear and reasonably vivid
3 - Moderately clear and lively
2 - Vague and dim
1 - No image at all, you only "know" that you are thinking of the object

For items 1-4, think of some relative or friend whom you frequently see (but who is not with you at present) and consider carefully the picture that comes before your mind's eye.

1. The exact contour of face, head, shoulders and body
2. Characteristic poses of head, attitudes of body etc.
3. The precise carriage, length of step etc., in walking
4. The different colours worn in some familiar clothes

Visualize a rising sun. Consider carefully the picture that comes before your mind's eye.

5. The sun rising above the horizon into a hazy sky
6. The sky clears and surrounds the sun with blueness
7. Clouds. A storm blows up with flashes of lightning
8. A rainbow appears

Think of the front of a shop to which you often go. Consider the picture that comes before your mind’s eye.

9. The overall appearance of the shop from the opposite side of the road

10. A window display including colors, shapes and details of individual items for sale

11. You are near the entrance. The color, shape and details of the door

12. You enter the shop and go to the counter. The counter assistant serves you. Money changes hands.

Finally think of a country scene which involves trees, mountains and a lake. Consider the picture that comes before your mind’s eye.

13. The contours of the landscape

14. The color and shape of the trees

15. The color and shape of the lake

16. A strong wind blows on the trees and on the lake causing waves in the water.

Appendix C

Vividness of Object and Spatial Imagery Questionnaire (Blazhenkova, 2016)

For each item on this questionnaire, try to form a visual image, and consider your experience carefully. For any image that you do experience, rate how vivid it is using the five-point scale described below. Please note that there are no right or wrong answers to the questions, and that it is not necessarily desirable to experience imagery or, if you do, to have more vivid imagery. *

5 - Perfectly clear and vivid as real seeing
4 - Clear and reasonably vivid
3 - Moderately clear and lively
2 - Vague and dim
1 - No image at all, you only "know" that you are thinking of the object

O1. Play of colors in a bubble

O2. Splashes of colors in fireworks

O3. Shape of cloud in the sky

O4. Shape and color of an autumn leaf

O5. Pictorial details of the best friend's face

O6. Appearance of a candle fire

O7. Color mixing in a watercolor painting of a floral bouquet

O8. Fine details of zebra's skin

O9. Patterns on a peacock tail

O10. Play of colors of the sun reflecting on the water

O11. Fine details and shape of a jellyfish

O12. Color pattern on a butterfly wing

O13. Shapes and colors of a bonfire

O14. Texture of your favorite clothes

S1. Orthographic drawing of a tractor from the three sides

S2. Schema (plan) of a computer connection to a printer

S3. Technical instruction for assembling a kitchen appliance (e.g., blender, food processor)

S4. Mechanism of a door handle

S5. 3D structure of a toilet flushing system

S6. Construction plan (three-dimensional schema) of a roller coaster

S7. Motion of the planets on a model of the solar system

S8. Plan of a multilevel road junction

S9. Mechanism of a mechanical wall clock

S10. Finding the exit path in a paper maze

S11. Trajectory of an object moved by a force (e.g., billiard ball)

S12. Cutting out and folding paper to create a 3D cube

S13. Rotation of 3D Tetris piece (3D shape) to fit a particular slot

S14. Location of your house on a map of your city

* Items preceded by “O” represent object imagery and items preceded by “S” represent spatial imagery.

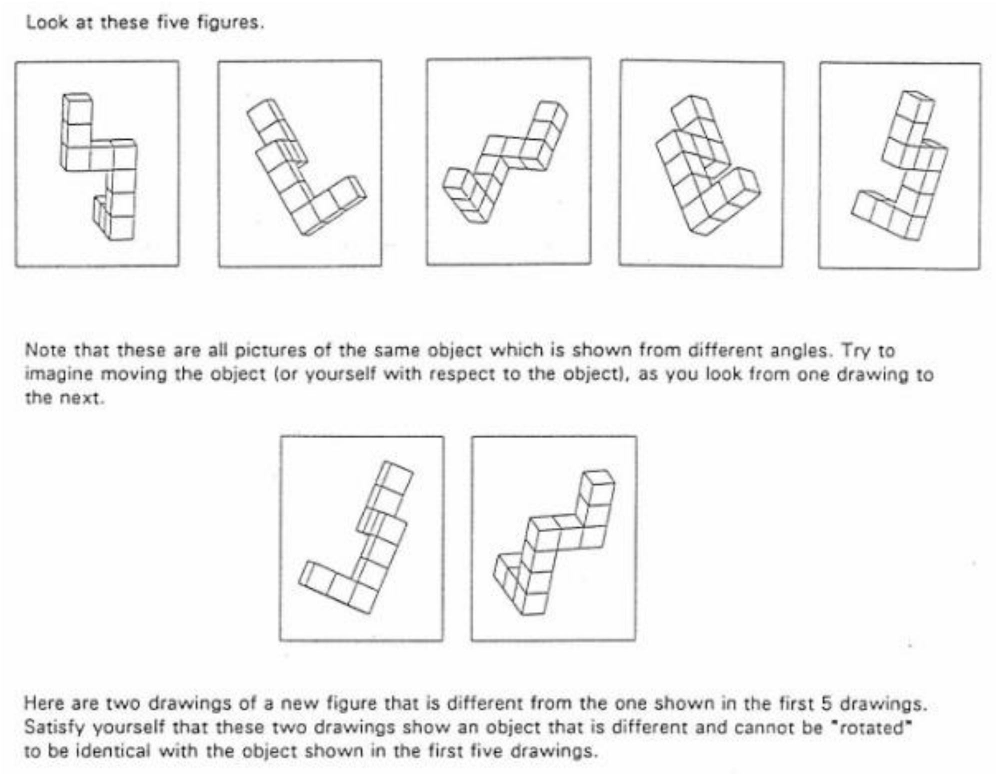
Appendix D

Vandenberg & Kuse Mental Rotation Test – Redrawn Sample Items

(Peters, Laeng, Latham, Jackson, Zaiyouna, & Richardson 1995; Vandenberg & Kuse, 1978)

Please note that these images are copied directly from the PDF of the MRT. When implemented online, the order of the items will be randomized.

Warm-up items will follow the pattern and instructions as illustrated in the images below.



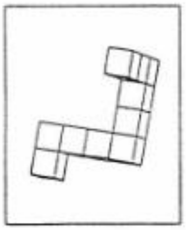
Look at these five figures.

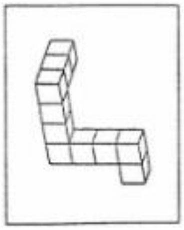
Note that these are all pictures of the same object which is shown from different angles. Try to imagine moving the object (or yourself with respect to the object), as you look from one drawing to the next.

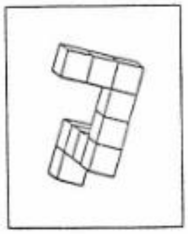
Here are two drawings of a new figure that is different from the one shown in the first 5 drawings. Satisfy yourself that these two drawings show an object that is different and cannot be "rotated" to be identical with the object shown in the first five drawings.

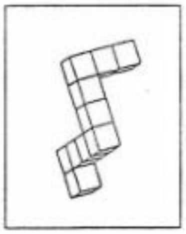
Now look at
this object:

Two of these four drawings show the same object.
Can you find those two ? Put X's in the lower right
corner.



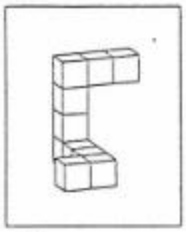


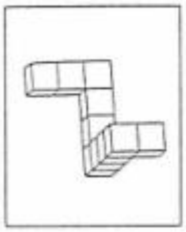


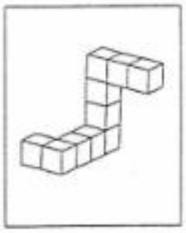


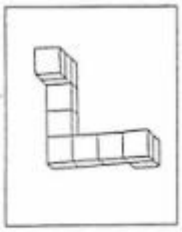
If you marked the first and the third drawings, you made the correct choice.

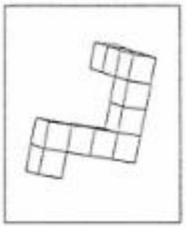
Here are three more problems. Again, the target object is shown <u>twice</u> in each set of four alternatives from which you choose the correct ones.

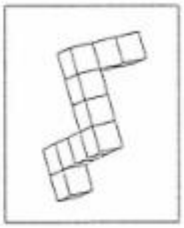


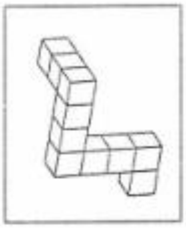


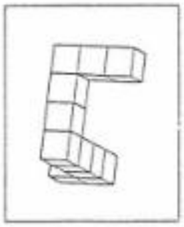


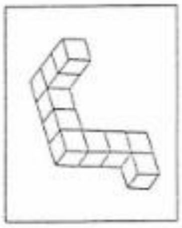


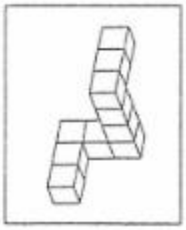


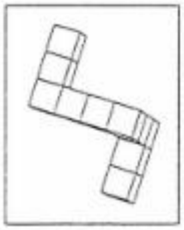


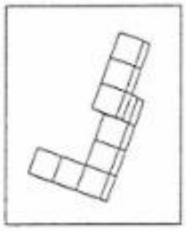


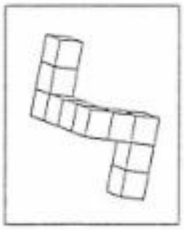


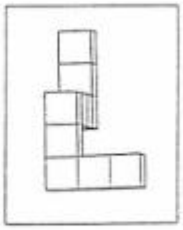












Correct choice for 1: second and third, for 2: first and fourth
3: first and third

Actual test proceeds with the following instructions:

Directions: Select the two images from the four options on the right that accurately represent a rotation of the numbered figure on the left. There are two and only two correct answers. You will have three and a half minutes to complete as many of the 12 items as you can. Your score will be based on both accuracy and speed.