CHARACTERIZING THE GROWTH IN SPATIAL THINKING ABILITIES IN METEOROLOGY STUDENTS ACROSS THE CURRICULUM

by

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ABSTRACT

LAUREN ELISE AUGUSTA DECKER. Characterizing the Growth in Spatial Thinking Abilities in Meteorology Students Across the Curriculum
(Under the direction of Dr. Casey Davenport)

Spatial thinking skills are essential to student success in disciplines such as geology, atmospheric science, and geography. In particular, previous work on spatial thinking in the atmospheric sciences has demonstrated that skills such as mental animation, disembedding, and perspective taking have been shown to be important for interpreting, understanding, and predicting the four-dimensional atmosphere. However, when students develop and build on such skills as they progress through the meteorology curriculum is unknown. In this study, the Spatial Thinking Abilities Test (STAT) is used to quantify the extent of spatial thinking abilities in undergraduate students enrolled in courses required for the meteorology major at a large public university in the southeastern United States. Using a subset of 12 multiple choice questions, STAT is administered twice a semester in each course as a pre-test and post-test. Starting in Spring 2022 and continuing through Fall 2022 and Spring 2023, data was collected from students across 10 required courses. There were several key findings from the three semesters of data collection. First, STEM majors outperformed non-STEM majors for all administrations of the STAT. The second key finding is similar to the first: Meteorology majors scored higher on average than non-Meteorology majors for both the pre- and post-test in the Fall 2022 semester, and the Spring 2023 pre-test. Third, on average Males outperformed Females, which was true for all three pre-test administrations and the Fall 2022 post-test. Additionally, by looking at the normalized learning gain for each group of students, it provided insight on improvements on specific spatial thinking skills. In the Spring 2022 semester, STEM majors showed more improvement compared to non-STEM majors. Non-METR (STEM) majors showed the most

improvement in spatial thinking skills compared to Meteorology majors and non-Meteorology majors. Lastly, females showed larger improvement in spatial thinking skills compared to males in the same semester, however, males showed more improvement than females in Fall 2022.

Finally, the Pathways Students provided important information that can help characterize the growth of spatial thinking skills in meteorology students. Group 1 (including students who took Global Environmental Change, Fundamentals of Meteorology and Atmospheric Thermodynamics) showed little to no improvements in overall spatial thinking abilities. Group 2 (includes students enrolled in Atmospheric Thermodynamics, Physical and Synoptic Meteorology, and Atmospheric Dynamics I and Climate Dynamics) showed the most improvement in spatial thinking abilities between the three groups. And Group 3 (made up from students enrolled in Atmospheric Dynamics I and Climate Dynamics and Advanced Dynamics II and Advanced Synoptic) also had a positive normalized learning gain which showed improvements in overall spatial thinking abilities. This data helps provide crucial steppingstones to developing and including pedagogical interventions to support students spatial thinking skills and success in meteorology.

ACKNOWLEDGMENTS

I would like to acknowledge and give my warmest thanks to my advisor Dr. Casey Davenport who helped make this work possible. Her support, guidance and overall insights throughout this research project have made this an inspiring experience for me, and I look forward to continuing our work in the future. I would also like to thank the professors in the meteorology department at The University of North Carolina at Charlotte for helping me with data collection for my study, this wouldn't have been possible without your help.

I would also like to give special thanks to my fiancé, Parker Burns, and my parents, David and Kelly Decker, for their continuous support and understanding when undertaking my research and writing. I am forever grateful for their unconditional love and support throughout this entire process and every day.

Finally, I would like to thank God for giving me the passion and courage to complete this research project.

DEDICATION

This thesis is dedicated to my fiancé, Parker Burns, to my parents, David and Kelly Decker and to my future students.

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1. Introduction and Motivation

Spatial thinking skills, which refer to the ability to find meaning in the shape, size, orientation, location, direction or trajectory, of objects, processes or phenomena, or the relative positions in space of multiple objects, processes or phenomena (National Research Council 2006), are used to perform a variety of tasks using skills such as spatial visualization, mental rotation, penetrative thinking, navigation, and disembedding, among others (Ormand et al. 2017). Importantly, spatial thinking abilities have been demonstrated to be highly correlated with success in science, technology, engineering, and mathematics (STEM) fields, including the geosciences (e.g., Lee and Bednarz 2012; Hegarty 2014; Yoon and Min 2016; Ormand et al. 2017; McNeal and Petcovic 2020; Kreager et al. 2022). These skills are largely taught implicitly to students in a domain-specific context (e.g., reading weather maps), though it has been demonstrated that educational interventions and targeted training on spatial reasoning improve spatial thinking abilities, which further enhances student success (e.g., Titus and Horsman 2009; Lee and Bednarz 2012; Uttal et al. 2012; Uttal et al. 2013). Notably, no such interventions have been created in the context of meteorology.

The application of spatial thinking skills is well-understood in fields such as geology (e.g., Petcovic et al. 2016; Petcovic et al. 2020; Bateman et al. 2022) and geography (e.g., Lee and Bednarz 2012; Metoyer et al. 2015), but exploration in the field of meteorology has been somewhat limited. Meteorology is an inherently spatial discipline; atmospheric data is often represented on maps of various horizontal and spatial scales that require incisive analysis to understand physical processes and to support the generation of weather forecasts. For example, in the undergraduate meteorology curriculum, students receive substantial, focused instruction in identifying and analyzing the spatial patterns of variables such as temperature, pressure, or wind. Students must also combine information from multiple maps to create mental models of processes and be able to manipulate these models over time and space; such unique skills are necessary for success in the program and beyond in postgraduate careers (e.g., McNeal et al. 2018; McNeal et al. 2019a). Yet, students nevertheless struggle to visualize and understand atmospheric motion from studying weather maps and identify key spatial patterns in data (McNeal et al. 2019b).

In spite of the importance of thinking spatially in meteorology, we do not currently understand the progression in spatial reasoning abilities as undergraduate meteorology students advance through the curriculum. Is there a smooth progression each year as a result of continued, routine practice with manipulating meteorological data? Do some courses improve spatial thinking skills more than others? Are there courses that inadvertently weaken spatial thinking skills? Is prior elective coursework in related fields such as geography, or other student characteristics such as additional majors or minors correlated to spatial thinking skills? Such knowledge would be valuable to not only provide a foundation of how and where spatial thinking skills are applied in meteorology but would also help determine where targeted pedagogical activities and improvements could be made to the curriculum, thus enhancing student outcomes and success for all meteorology programs. Thus, the purpose of this study is to document the evolution in meteorology students' spatial thinking abilities as they progress through the undergraduate meteorology curriculum. This will be achieved through administration of a spatial thinking abilities test to all students enrolled in required courses in an undergraduate meteorology program.

2. Background

a. Spatial Thinking Skills and STEM

Spatial thinking is a psychological construct that describes the cognitive ability to find meaning in the shape, size, orientation, or relative position of one or more objects, processes, or phenomena (National Research Council 2006). These skills have been explored in cognition science (e.g., Vandenburg and Kuse 1978; Lord 1985; Shear et al. 2001; Uttal et al. 2012; Uttal et al 2013), as well as throughout many STEM disciplines, including chemistry (e.g., Talley 1973; Wu and Shah 2004), physics (e.g., Pallrand and Seever 1984; Kozhevnikov et al. 2007), calculus (e.g., Newcombe 2010; Sorby et al. 2013), geology (e.g., Titus and Horsman 2009; Ormand et al. 2014; Petcovic et al. 2020), geography (e.g., Lee and Bednarz 2012; Ishikawa 2013; Kim and Bednarz 2013; Bednarz and Lee 2019), and atmospheric science (e.g., McNeal et al. 2018; McNeal et al. 2019a, McNeal et al. 2019b; McNeal and Petcovic 2020). Spatial thinking skills are vital for all STEM fields and substantially influence the development of conceptual understanding necessary to learn STEM concepts and succeed in these fields (e.g., Lord 1985; Titus and Horsman 2009; Uttal et al. 2013; Hegarty 2014, Ormand et al. 2017; Sorby et al. 2018; McNeal et al. 2019a; McNeal et al. 2020). Not only is spatial thinking vital for success in a STEM major, but these skills also support the next generation of STEM professionals (Lord 1985; Kim and Bednarz 2013; Metoyer et al. 2015; Bednarz and Lee 2019).

b. Spatial Thinking Skills by Discipline

The application of spatial reasoning varies by discipline. For example, the extensive use of maps in geography (e.g., Ishikawa 2013; Kim and Bednarz 2013; Bednarz and Lee 2019) and geology (e.g., Titus and Horsman 2009; Petcovic et al 2020; Bateman et al. 2022) necessitates the use of spatial reasoning. In the geosciences, skills such as mental rotation, disembedding, 3-D spatial visualization, and others, have been shown to be important (e.g., Rapp et al. 2004; Manduca and Kastens 2012; Ormand et al. 2014). A more complete description of spatial reasoning skills used in varying disciplines is provided next.

(1) Spatial Thinking Skills in Geology

Titus and Horsman (2009) tested undergraduate students' spatial skills (defined by the authors as a "complex process that involves both visual abilities and the formation of mental images") to see if there was improvement after they enrolled in introductory geology courses and higher-level geology courses. These skills were measured by a pre- and post-course survey that characterized their range of spatial reasoning abilities, focusing on performance of tasks related to (1) spatial relations, defined as "the ability to mentally rotate an object about its center", (2) spatial manipulations, defined as "the ability to mentally manipulate an image into another arrangement", and (3) visual penetrative ability, defined as, "the ability to mentally imagine what is inside of a solid object" (Fig. 2.1; Titus and Horsman 2009). The authors' assessment determined that each of these skills were important for geology; for example, geology majors performed markedly higher on the spatial reasoning test compared to non-majors, indicating that the regular disciplinary use of these skills aids in their growth. Additionally, upper-level geology majors performed better on the spatial reasoning test compared to the introductory geology students, consistent with the fact that geology majors spend more time on developing and applying spatial reasoning skills to domain-specific tasks such as putting data on paper, envisioning how rock formations change through time, and slicing through rock formations (Titus and Horsman 2009).

Ormand et al. (2014) measured the spatial thinking abilities of undergraduate students enrolled in introductory and advanced geology courses at three different colleges (a community college, liberal arts college, and a public research university) in the Midwest over a two-year time frame. This study assessed several geology courses, including introductory geology, mineralogy, sedimentology and stratigraphy, hydrogeology, structural geology, and tectonics courses. Students that were enrolled in these classes took several tests to measure their spatial reasoning skills, including the Purdue Visualization of Rotations (Guay 1976), the ETS Hidden Figures Test (Ekstrom et al. 1976), the Planes of Reference test (Titus and Horsman 2009), and the Geologic Block Cross-sectioning Test (Ormand et al. 2014; Fig. 2.2). Every participant in the study took the Purdue Visualization of Rotations Test to gain a baseline for comparison, followed by one or more of the other spatial reasoning tests (Fig. 2.3). Administering multiple spatial reasoning tests was done to fully assess three individual spatial skills: mental rotation (defined as "visualizing the effect of rotating an object"), penetrative thinking (defined as "visualizing spatial relations inside an object"), and disembedding (defined as "isolating and attending to one aspect of a complex display or scene"). The psychometric tests were administered to any student willing to participate that is enrolled in the courses listed previously, geology major or non-geology major, taken during the first and last weeks of classes in a semester. Along with scores from the tests, student course grades and cumulative GPAs were also collected.

All students showed an overall modest improvement (e.g., the average class gains in PVRT scores ranged from 3.5% to 13.3%) in their spatial skill test score between the beginning and end of the semester, regardless of whether they were introductory or upper-level students. However, students in introductory courses had a larger gain compared to upper-level students. Those who performed well on the spatial thinking tests tend to show proficiency with multiple spatial thinking skills. However, because students took a variety of tests, they found that there were also many individual students who demonstrated strong spatial skills in one category (e.g., disembedding), but performed poorly in another (e.g., rotation). This could be from the test-retest effect, where students show improvements, but they could be from the students taking multiple tests that are testing the same aspect of spatial reasoning (Ormand et al. 2014).

Disembedding, spatial visualization and mental rotation have been labelled important subsections of spatial thinking in geology. Students in both the Titus and Horsman (2009) and Ormand et al. (2014) studies demonstrated small improvements over the course of a semester, with upperclassmen having more advanced spatial skills than introductory students, consistent with more time and practice with spatial tasks. Additionally, this suggests a linear progression of spatial reasoning skills; such an evolution will be explored further in the current study.

(2) Spatial Thinking Skills in Geography

Spatial reasoning is central to the field of geography; the ability to understand space is a central organizing concept of the discipline. Broadly, spatial thinking abilities fall into 3 main categories in geography: spatial orientation (the ability to comprehend the arrangement of elements within a visual pattern), spatial visualization (mental ability to manipulate, rotate, invert, or twist an image), and spatial relations (recognizing spatial distributions and spatial patterns; Golledge and Stimson 1997; Lee and Bednarz 2009; Metoyer et al. 2015; Fig. 2.4). Importantly, geographers use spatial thinking skills when creating maps to organize, collect, interpret, and analyze geographic information (Metoyer et al. 2015). They also rely on map readers to be able to distinguish between important factors such as patterns, different line weights, grey tones to convey the geographical information that they gathered (Bednarz and Lee 2019).

Unlike other STEM disciplines, geography curricula provide more purposeful and directed opportunities for students to learn "in space" (Metoyer et al. 2015), and thus inherently spend more time than other geoscience disciplines with focused time working on spatial reasoning.

Additionally, required courses such as Geographic Information System (GIS) positively impact students' scores on spatial abilities tests (e.g., Lee and Bednarz 2012; Kim and Bednarz 2013; Low et al. 2014; Metoyer et al. 2015). This relationship was first demonstrated by Lee and Bednarz (2009), where students completed a spatial reasoning pre- and post-test before and after a GIS course; as a direct result of the course and instruction in skills such as spatial orientation, spatial visualization, and spatial relations, students improved their spatial thinking skills on average about 2.5 points between the pre- and post-test. Importantly, GIS allows its users to adopt a new perspective on 2-D and 3-D representations and permits manipulation of spatial features (Lee and Bednarz 2009). Teaching students to use GIS is key for the development of spatial reasoning skills; indeed, even students who complete just one GIS course still demonstrated significant improvements in spatial reasoning (Metoyer et al. 2015). By making the connections and correlations between spatial thinking skills and GIS provides an insight into effective ways that informal and formal training can be shaped (Bednarz and Lee 2012).

(3) Spatial Thinking Skills in Meteorology

Within the geosciences, substantial work has been conducted to understand spatial reasoning skills specific to disciplines such as geology and geography, which provides useful context for understanding of the role of spatial thinking in meteorology tasks (McNeal et al. 2018). Like the field of geology, meteorology requires students to apply spatial reasoning to properly interpret data on maps (e.g., topographic maps in geology vs. isobaric maps in meteorology) and 3-D spatial visualization to read 2-D maps and transform them to 3-D. Even with these similarities, the spatial skills necessary for success can still diverge. Notably, geologists' study solid Earth features, whereas meteorologists largely focus on fluid phenomena that are constantly changing over time and space (McNeal et al. 2018). Thus, it is important to understand how spatial thinking is unique in the atmospheric sciences; to date, only a few studies have examined spatial thinking in a meteorological context.

To begin to identify the spatial thinking skills specific to the discipline of meteorology, McNeal et al. (2018) administered a survey to 93 professional meteorologists and students studying meteorology, where they were asked to identify which spatial thinking skills, they perceive they use when observing a series of meteorological charts, maps, and images from a significant weather event. The participants were able to identify the highest-ranking spatial thinking skills that meteorologists use to analyze weather maps: mental animation, disembedding, and perspective taking. Mental animation, defined as "developing a plausible scenario of a sequence of events based on static information" (McNeal and Petcovic 2020), was identified as one of the highest-ranking spatial thinking skills in meteorology, in line with the reality that the atmosphere is a continuously changing fluid. For example, meteorologists use mental animation to fill in the gaps between fixed snapshots of data (e.g., four-panel model plots) to aid in forecasting (McNeal et al. 2018).

The spatial thinking skill of disembedding (defined as "observing a complex scene, observing and recognizing patterns, and isolating the important aspects from distracting, nonessential ones"; McNeal and Petcovic 2020) viewed as key for meteorologists due to heavy reliance on geographic maps of meteorological data, which can at times have an overwhelming amount of data displayed (e.g., Fig. 2.5). While weather maps such as Fig. 2.5 can appear to be chaotic and difficult to read, meteorologists are able to rapidly identify key information and discern relevant patterns using disembedding (e.g., creating a mental image like Fig. 2.6). This skill is unique from mental animation, which relies on dynamic relationships (McNeal et al. 2018). Importantly, disembedding does factor into how students' approach and complete meteorology tasks. In a separate study, McNeal et al. (2019b) asked three meteorology students to participate in a "think-aloud" session where they were doing meteorology tasks and providing verbal data. The three meteorology students were similar in age, but had different expertise in disembedding (low, medium, high). After evaluating the participants, and their verbal cues, found that individuals will rely on past experience, knowledge, and cognitive skills to solve meteorology tasks (McNeal et al. 2019b). Noting that knowledge is the primary indicator of success in meteorology, but also it is hard to know what to look for if the participant has not been taught that yet in their career, because it is impossible for a student to discern patterns they do not know to look for (McNeal et al. 2019a; McNeal et al. 2019b).

The final key spatial thinking skill in meteorology identified by McNeal et al. (2018) was perspective taking, defined as "envisioning how something would appear from different vantage points" (McNeal and Petcovic 2020). This skill was viewed as important for meteorologists due to the regular use of remote sensing data such as radar and satellite; particularly for short-term forecasting, the ability to examine and interpret such images is vital for accurate forecasts (McNeal et al. 2018).

While it is evident that there are some unique spatial thinking skills applied in the field of meteorology (mental animation, disembedding, and perspective taking) and that these skills are essential to successfully performing meteorological tasks, unlike some other disciplines (e.g., geology, geography), there is no clear understanding of when these skills are gained. Determining how students' progress in their spatial reasoning abilities is a central component of this study, which will provide an important foundation for improving the meteorology curriculum.

c. Sex Differences

It is widely known that there is a gender gap in terms of representation in males versus females in STEM courses and fields (Wang and Degol 2017). While there are many reasons for the presence of this gap, one potentially contributing factor, subject to some debate, is the apparent difference in spatial skills when comparing males and females in STEM (e.g., Linn and Petersen 1985; Hsi et al. 1997; Casey et al. 2001; Liben 2015; Reilly et al. 2017; Gold et al. 2018; Bartlett and Camba 2023). Indeed, the difference in spatial reasoning abilities in men versus women has been found to be one of the "most robust and consistently found phenomenon in all of cognitive science" (Reilly et al. 2017). The explanation for this discrepancy is not fully clear; biological differences have been suggested (e.g., Bock and Kolakowski 1973; Yen 1975; Levy 1976; Nyborg 1983; Howard et al. 1992), as well as varying educational and sociocultural experiences (e.g., Gold et al. 2018), or a combination of both (e.g., Linn and Petersen 1985; Reilly et al. 2017).

Notably, certain spatial thinking skills have larger gender gaps than others, though this is not true for other skills. The most common spatial skill to show a gender gap is mental rotation (Linn and Petersen 1985; Hsi et al. 1997; Casey et al. 2001; Titus and Horsman 2009; Liben 2015; Reilly et al. 2017; Gold et al. 2018; Bartlett and Camba 2023); indeed, it is the "cognitive ability with the largest documented sex difference in favor of men" (Hegarty 2018). Linn and Petersen (1985) found that males outperform females at any age where they are old enough to be tested and hypothesize that the difference in performance is from a separation in rate of rotation, efficiency in applying strategies, or using analytic strategies (Linn and Petersen 1985). In contrast, spatial skills such as disembedding and penetrative thinking tend to show no statistically significant differences in male versus female performance (Linn and Petersen 1985; Gold et al. 2018).

Interestingly, sex differences in spatial abilities are not necessarily constant over time. Titus and Horsman (2009) found that sex differences in performance went away in upper-level geology courses in all types of spatial thinking skills, with the exception of mental rotation, where male participants outperformed female participants. The exact reason for these specific skills to show either a gender gap or not remains unknown.

d. Instruments

In the studies described above, most of the instruments used to measure spatial thinking skills were created with an emphasis on two categories of spatial thinking: spatial visualization and spatial orientation (Bednarz and Lee 2019). Common tests to quantify spatial reasoning abilities include the Vandenburg and Kuse Test of Mental Rotation (Vandenburg and Kuse 1978), the Spatial Thinking Abilities Test (Lee and Bednarz 2012), and the Education Testing Services Hidden Figures Test (Ekstrom et al. 1976). Each test has a slightly different emphasis, described below.

The Vandenburg and Kuse Test of Mental Rotation, used in studies such as Ormand et al. (2017), McNeal et al. (2019a), and McNeal and Petcovic (2020), consists of 20 questions using pencil and paper. Each question has an object that the participant is asked to mentally rotate and pick out of four answers which is the correct option where there are two correct answers and two distractors (Fig. 2.7; Vandenburg and Kuse 1978). This test provides crucial information in students' ability to perform rotations of objects mentally and can be used on larger sample sizes. McNeal and Petcovic (2020) found no effect of spatial visualization skill measured by the Vandenburg and Kuse Test of Mental Rotation in relation to meteorology tasks and that the test specifically measures solid body motion and not fluid motion.

The Education Testing Services Hidden Figures Test, used in studies such as Ormand et al. (2014), Gold et al. (2018), McNeal et al. (2019b), and McNeal and Petcovic (2020), focuses on the skill of disembedding by measuring the ability to keep a given visual or configuration in mind, and then dissembed it from other defined material (Fig. 2.8; Ekstrom et al. 1976). There are sixteen items on the assessment taken on a computer with each item being worth a point with there being no penalty for incorrect answers. The participants taking the assessment are asked to look at a diagram with horizontal, vertical, and diagonal lines and identify which one of the five answers (geometric figures) is hidden within the diagram. The questions vary from less difficult to more difficult and has been described as a “verbal” test (Bejar and Yocom 1986). Performance on this test has been shown to be correlated with students’ persistence in sciences (Ormand et al. 2014). The main drawback to using this test is its verbal nature, along with the need for specific computer software, making it difficult to administer to a large group of students. Additionally, McNeal and Petcovic (2020) argued that the Hidden Figures Test works well for solid Earth disembedding applications, but there would need to be modifications that better capture the skills that fluid Earth scientists use.

The Spatial Thinking Abilities Test by Bednarz and Lee (2012) takes geography knowledge and combines it with spatial thinking skills. This test consists of 16 multiple choice questions and performance tasks and was designed to evaluate individual’s growth in their spatial thinking abilities (Fig. 2.9; Lee and Bednarz 2012). The STAT measures: (1) comprehending orientation and direction; (2) comparing map information to graphic information; (3) choosing the best location based on multiple spatial factors; (4) imagining a slope profile based on a topographic map; (5) correlating spatially distributed phenomena; (6) mentally visualizing 3-D images based on 2-D information; (7) overlay and dissolving maps; (8) comprehending geographic features represented as a point, line, or polygon. The STAT puts into consideration practicality, comprehensibility, cognitive processes (maximizing spatial processes and minimizing verbal processes), psychometric rational, mode of representation, and practical restraints into a compact multiple-choice exam (Lee and Bednarz 2012). The Spatial Thinking Abilities Test has been rigorously evaluated and validated and used in numerous studies (e.g., Ishikawa 2013; Jo et al. 2016; Collins 2018; Duarte 2022) and found to be a reliable holistic measure of spatial thinking skills, meaning that the result from taking the STAT is capable of producing consistent results from one test to the next (Lee and Bednarz 2019). Overall, the holistic assessment of spatial thinking and its ease of administration makes it a popular choice for studies testing large groups of students. In the context of the current study, questions that include meteorological data on STAT are of particular interest given the lack of other meteorological spatial reasoning resources (McNeal and Petcovic 2020).

e. Summary

Spatial thinking abilities have been proven to be a major factor in succeeding in STEM disciplines (e.g., Pallrand et al. 1984; Wu and Shah 2004; Kozhenvnikov et al. 2007; Hegarty 2014), including the geosciences. In geology, key spatial thinking skills include disembedding, spatial visualization, and mental rotation (e.g., Titus and Horsman 2009; Petcovic et al. 2020), while in geography, important skills include spatial orientation, spatial visualization, and spatial relations (e.g., Lee and Bednarz 2012; Ishikawa 2013; Kim and Bednarz 2013; Bednarz and Lee 2019). In meteorology, a limited set of studies have demonstrated that students and professionals tend to use mental animation, disembedding, and perspective taking skills (e.g., McNeal et al. 2018; McNeal et al. 2019a, McNeal et al. 2019b; McNeal and Petcovic 2020). While such explorations are useful in identifying key skills and overlaps with other sciences, several questions remain. For example, what does the growth of spatial thinking skills look like as students' progress through the curriculum? Are there courses that support the development of these skills more than others? Are there courses that inadvertently weaken or confuse spatial thinking skills? Are students who take supplemental courses in geography or GIS more readily able to grasp spatial concepts in meteorology? By understanding the answers to such questions, it would be possible to identify where improvements could be made to the meteorology curriculum and enhance student success. This study will contribute to this goal by quantifying spatial thinking skills as students' progress in required meteorology courses. The details of this approach will be discussed in the next chapter.

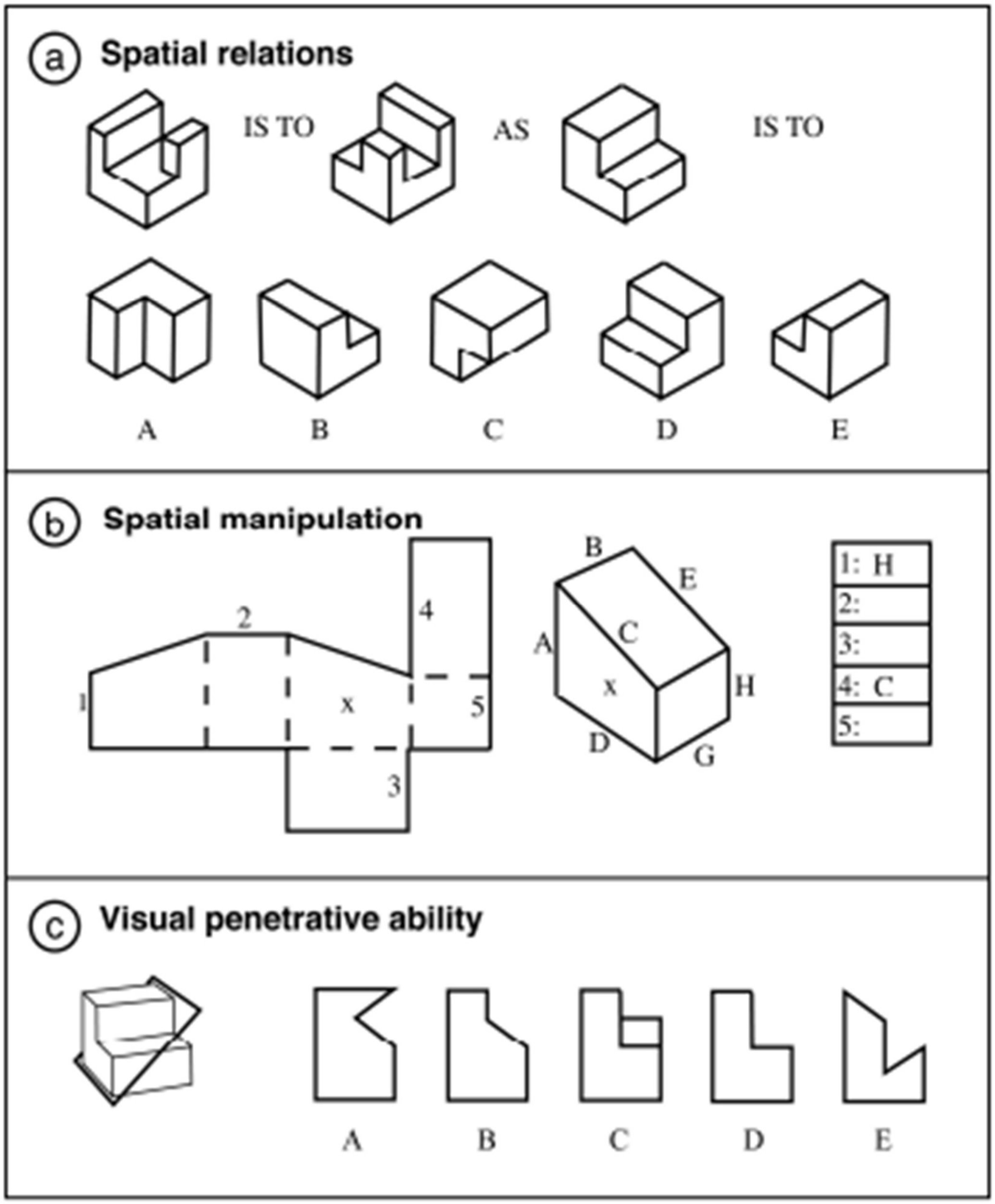


Figure 2.1: *Examples of a question from each section of the spatial thinking assessment administered in Titus and Horsman (2009).*

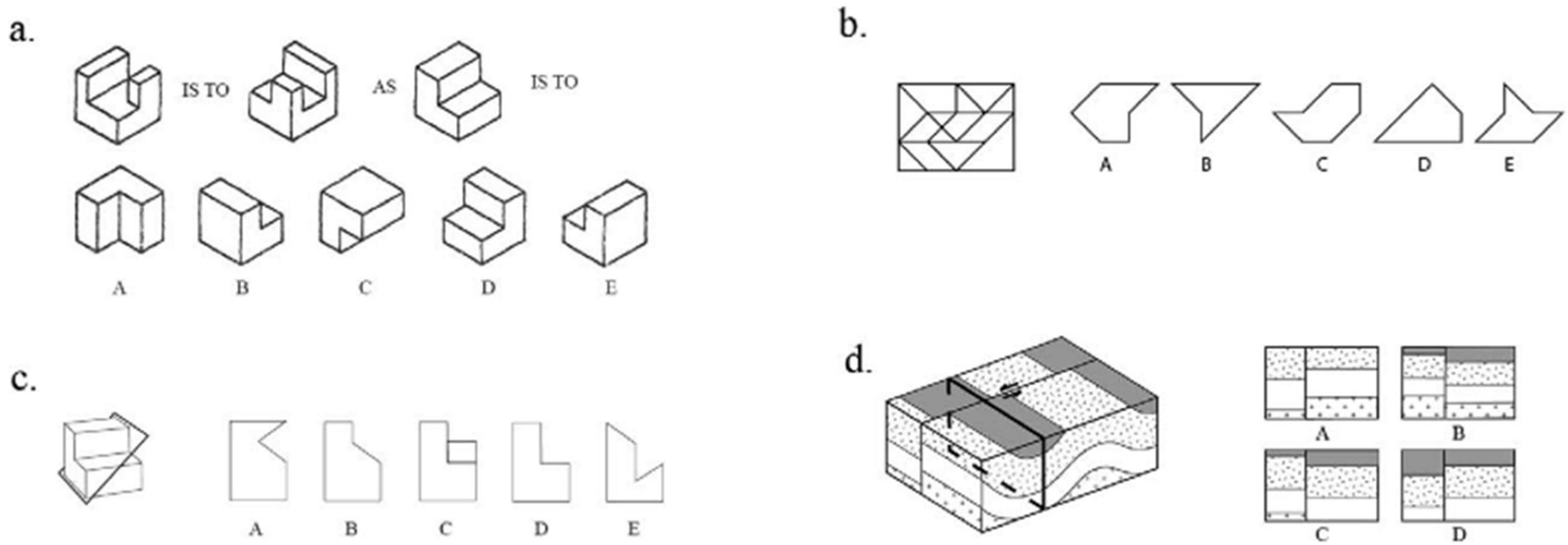


__Figure 2.2:__ Examples of spatial thinking test questions for the four different tests used in Ormand et al. (2014).

Term	Courses	Liberal Arts College	Comprehensive University	Research University
Winter, 2009	Introductory Geology, Hydrogeology, Mineralogy, and Structural Geology	Purdue Visualization of Rotations		
Winter and Spring, 2010	Introductory Geology	Purdue Visualization of Rotations, ETS Hidden Figures		Purdue Visualization of Rotations, ETS Hidden Figures
	Sedimentology & Stratigraphy		Purdue Visualization of Rotations, ETS Hidden Figures	
	Structural Geology			Purdue Visualization of Rotations, ETS Hidden Figures, Planes of Reference, Block diagrams
	Tectonics	Purdue Visualization of Rotations, ETS Hidden Figures, Planes of Reference, Block diagrams		

Figure 2.3: *Information regarding participants in the Ormand et al. (2014) study and the psychometric tests each set of completed.*

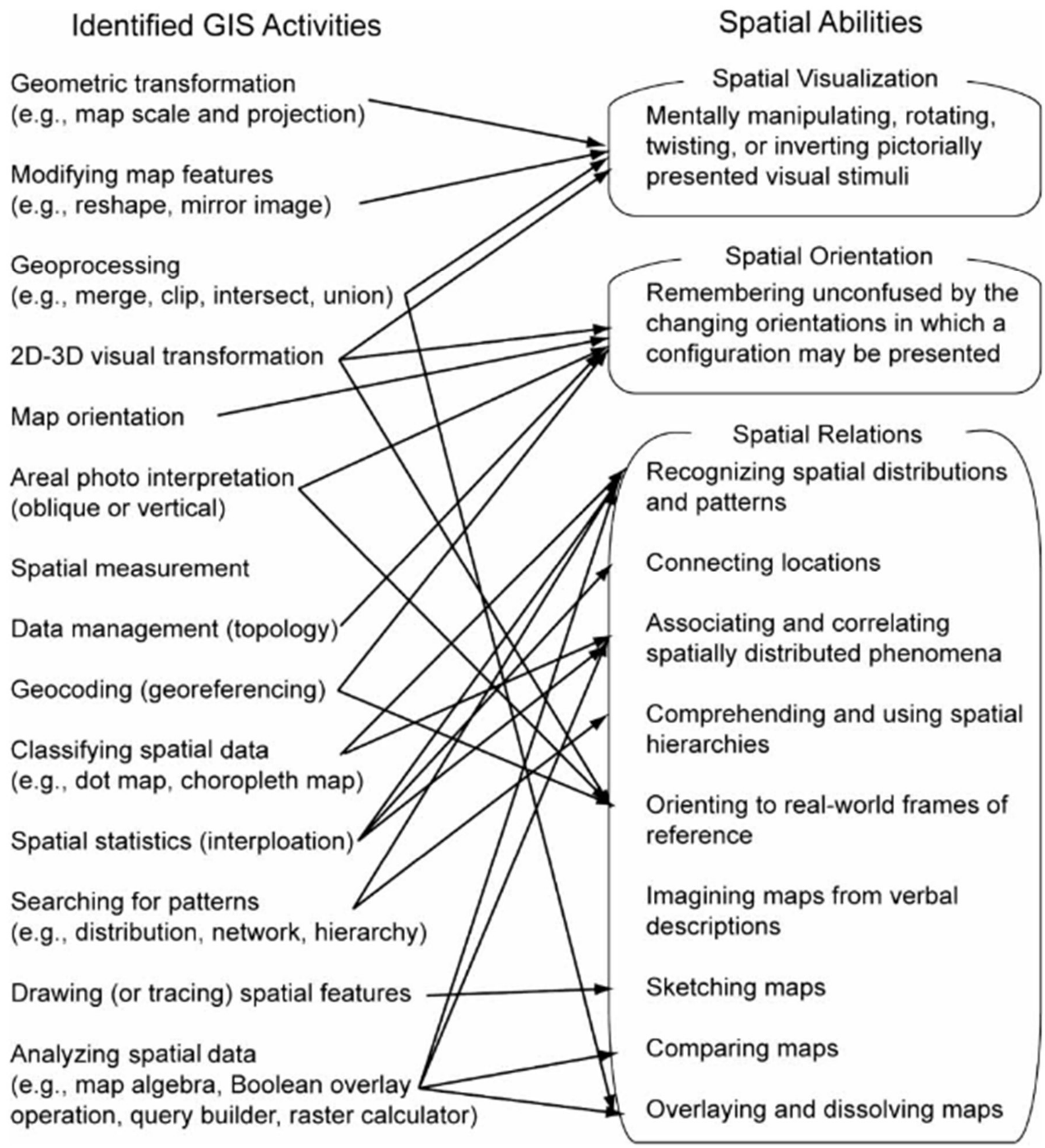


Figure 2.4: *Schematic of the relationship between the Geography Information System (GIS) and the three subgroups of spatial thinking abilities: spatial visualization, spatial orientation and spatial relations (Lee and Bednarz 2009).*

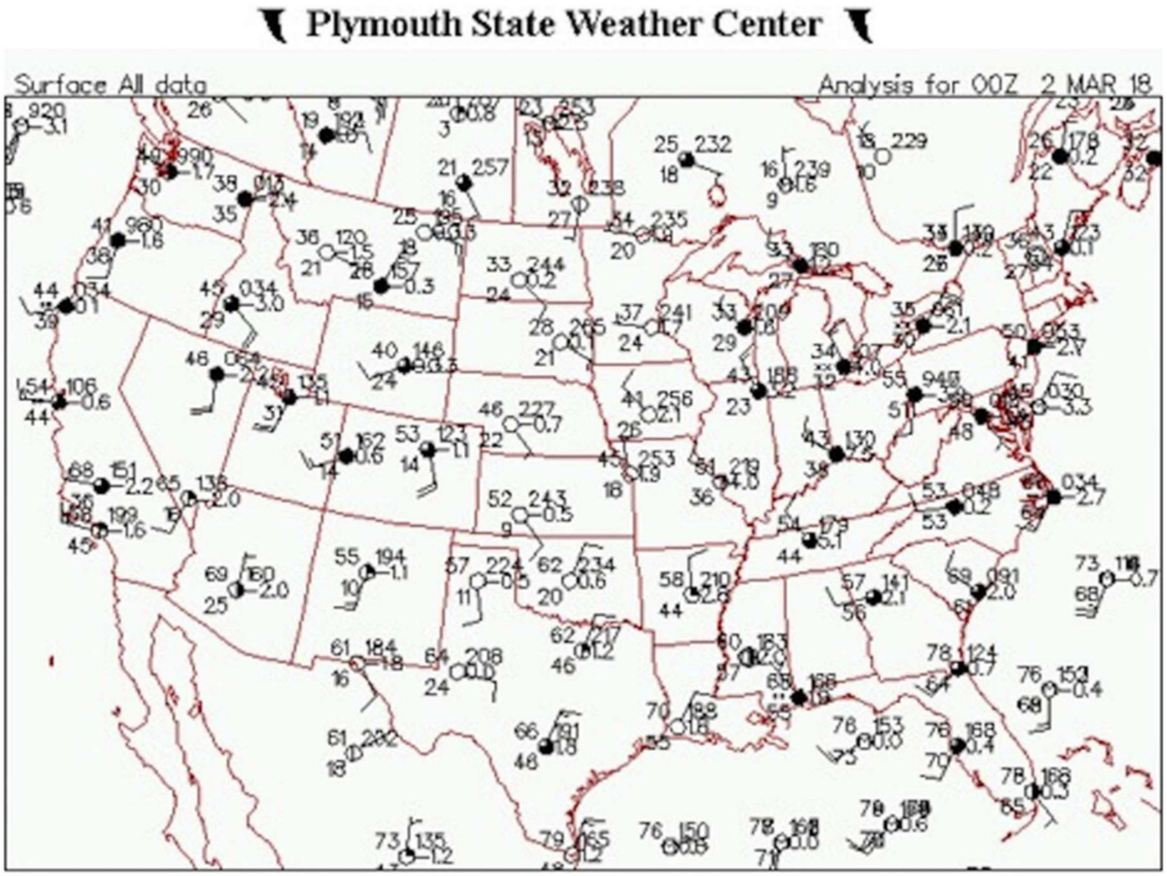


Figure 2.5*: Sample surface weather map demonstrating complexity in meteorological data requiring the use of disembedding (from McNeal et al. 2019a).*

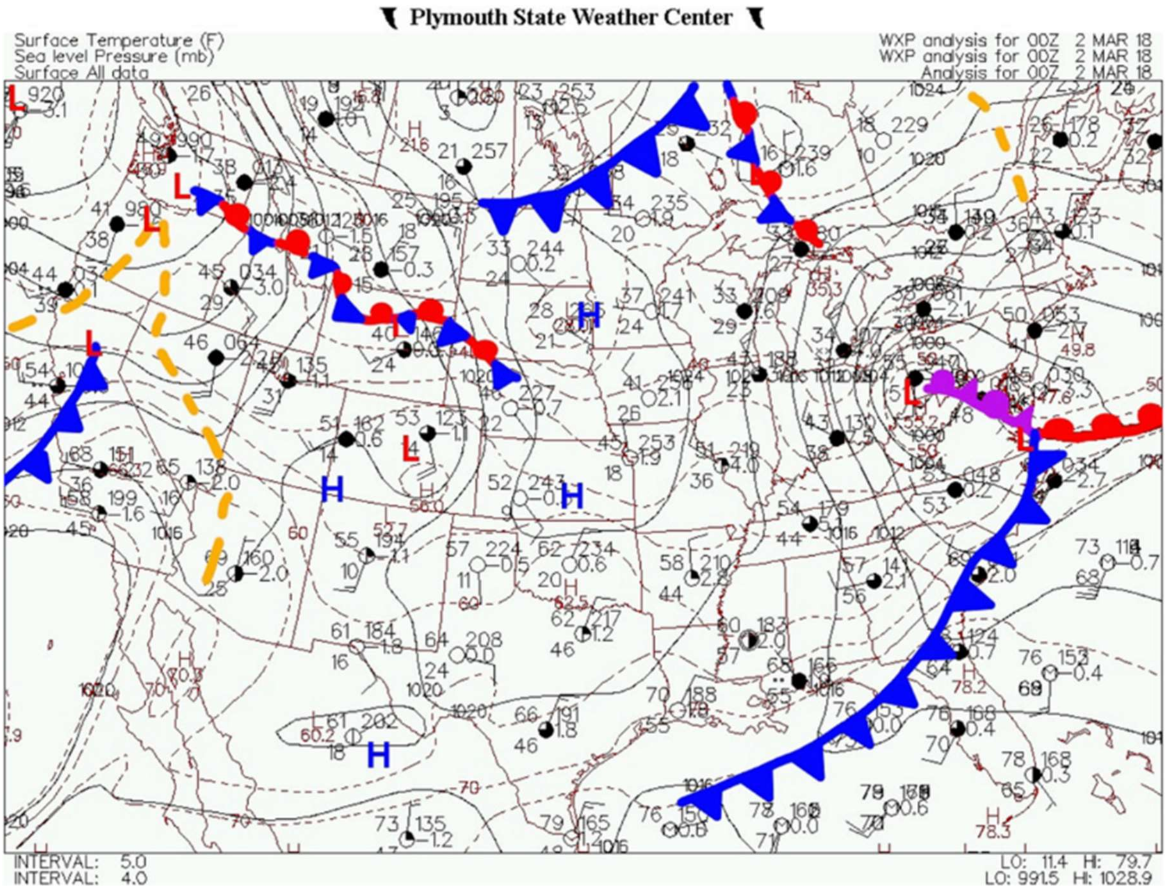


Figure 2.6: *As in Fig. 2.5, with annotations and patterns discerned via disembedding (from McNeal et al. 2019a).*

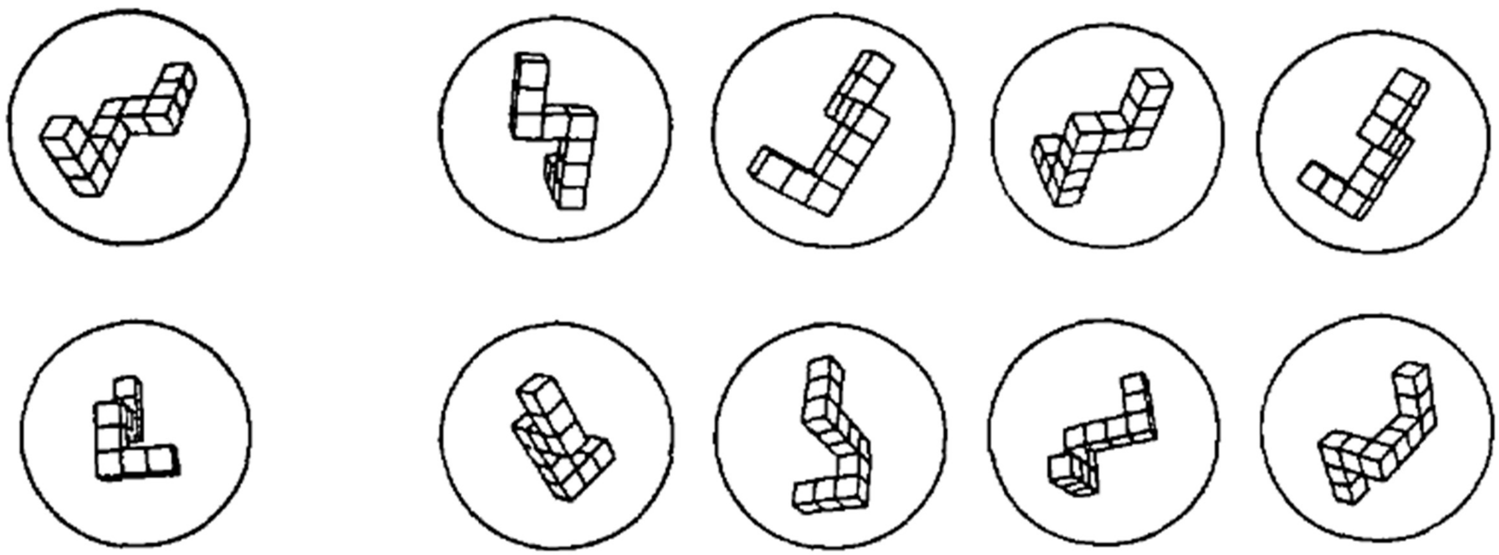


Figure 2.7: Sample question from the Vandenburg and Kuse Mental Rotations Test (Vandenburg and Kuse 1978).

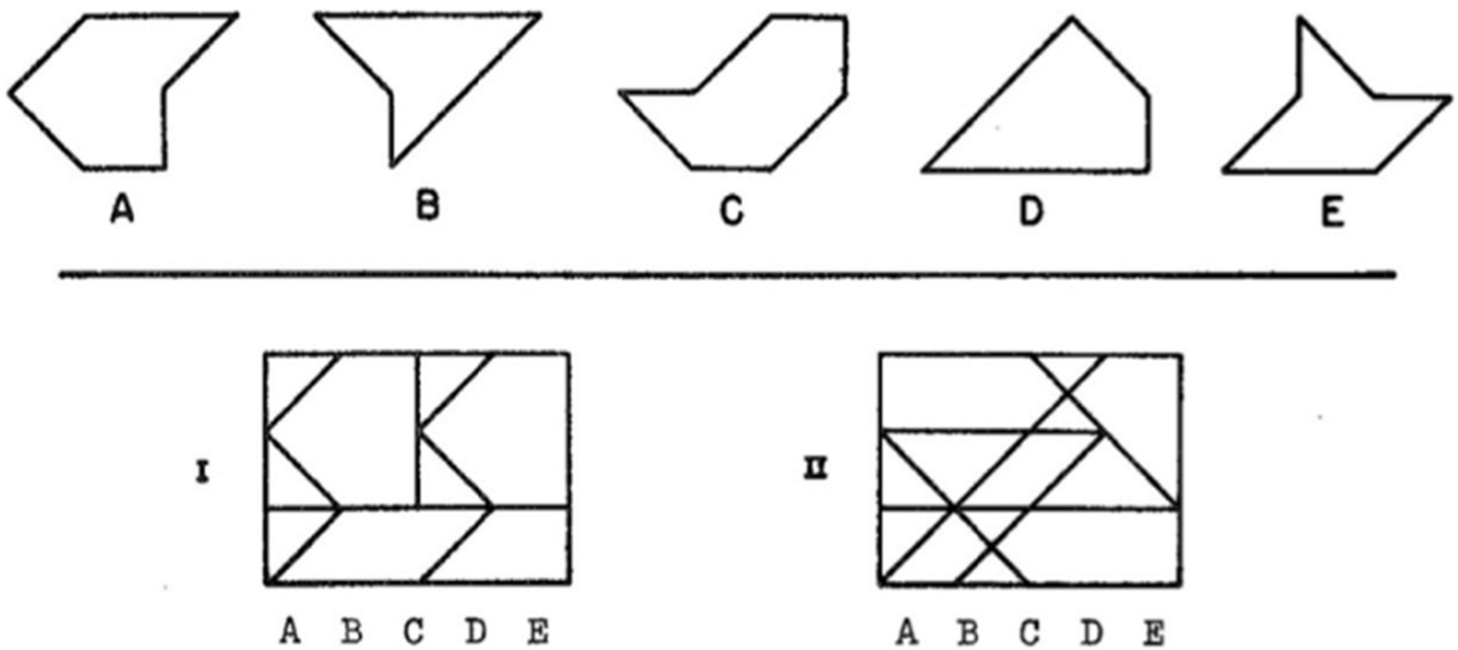
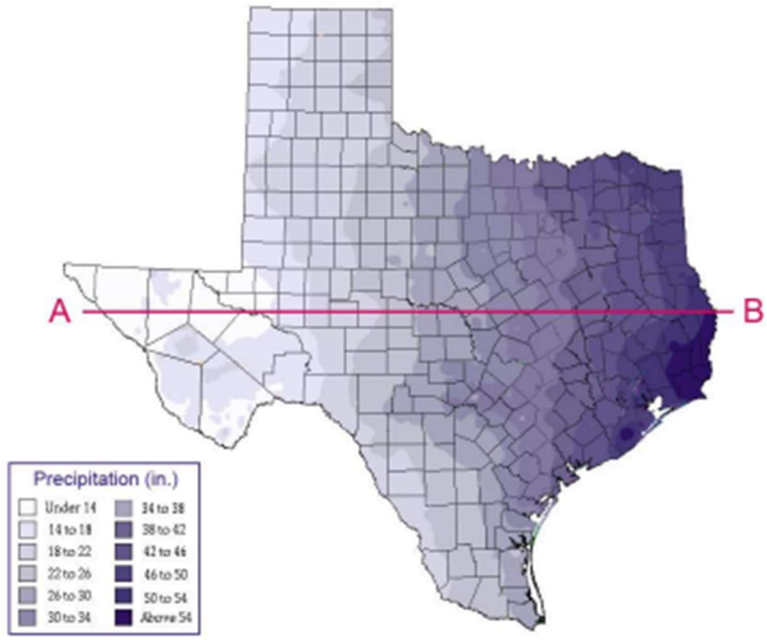


Figure 2.8: *Sample question from the Hidden Figures Test (Ekstrom et al. 1976)*



3. If you draw a graph showing change of Texas annual precipitation between A and B, the graph will be _______ .

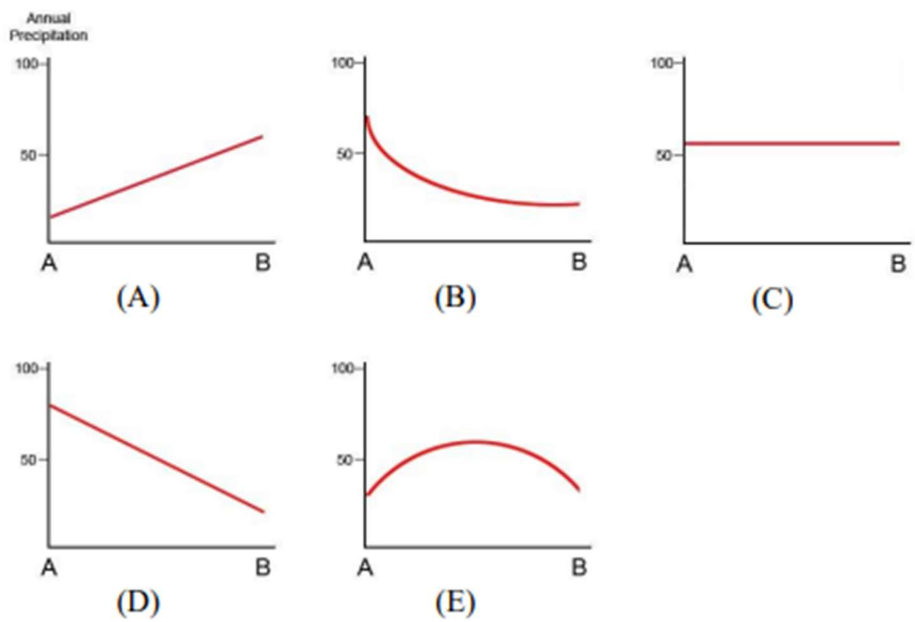


Figure 2.9: *Sample question from the Spatial Thinking Abilities Test (Lee and Bednarz 2012).*

3. Data and Methods

a. Instrument Justification

The Spatial Thinking Abilities Test (STAT; Lee and Bednarz 2012) is used in this study as a holistic measure of spatial thinking skills. While originally designed to evaluate the effect of GIS learning on spatial thinking abilities, this instrument holds promise as suitable to understanding spatial thinking as applied to the discipline of meteorology as a result of including questions testing the ability to correlate spatially distributed phenomena, a skill likely used by meteorologists when analyzing surface and upper-air maps (McNeal and Petcovic 2020). The STAT exam is of interest as a result of having been validated as being able to evaluate a variety of spatial skills (Lee and Bednarz 2012). Though overall STAT scores are useful as a holistic measure of spatial reasoning abilities, each question does measure different specific spatial skills, which may be useful to assess subsets of spatial abilities in meteorology students.

Logistical considerations were also a factor in selecting the STAT exam. Unlike other popular spatial reasoning tests that require pencil-and-paper responses (e.g., Vandenburg and Kuse 1978), STAT is a multiple-choice exam, which is easily administered and graded. Additionally, the exam is flexible, meaning that the test has been shown to be valid for a variety of combinations of questions (Bednarz and Lee 2019). For this study, we chose to use 12 of the 16 questions (Table 3.1); the 4 excluded questions were removed as a result of evaluating knowledge of specific vocabulary not encountered in the field of meteorology. Also, beginning in Fall 2022 for the post-test, questions were randomized in an attempt to keep students from remembering the order of questions and remembering their answers.

b. Participants

The STAT exam was administered to 10 courses required for the undergraduate meteorology degree at the University of North Carolina at Charlotte, including: (1) Introduction to Meteorology; (2) Global Environmental Change; (3) Fundamentals of Meteorology; (4) Atmospheric Thermodynamics; (5) Synoptic Meteorology; (6) Physical Meteorology; (7) Atmospheric Dynamics I; (8) Climate Dynamics; (9) Advanced Atmospheric Dynamics II; and (10) Advanced Synoptic Meteorology. A few required courses were excluded from this study as the content does not explicitly incorporate or rely on spatial reasoning and thus would be less likely contribute to the development of a students' spatial thinking abilities. Some of the classes included students that were not meteorology majors (e.g., Introduction to Meteorology); however, participants were not required to be a meteorology major.

c. Participant Recruitment and Data Collection

Following Institutional Review Board approval (#IRB-22-0390), the data collection process begun during the Spring 2022 semester. Each class was recruited via in-person or virtual visits to encourage participation. A recruiting script was read, where students were provided the context for the study, requirements for participation, length of involvement, as well as with a discussion of the incentive for participation (extra credit; 10 points for completing both the pre- and post-test). In the event of students being enrolled in multiple classes at the same time, students were permitted to take the STAT test twice (to earn extra credit in each of their classes); when this occurred, only their first attempt of the STAT was included in the analysis (this was not explicitly told to students to encourage their efforts when completing the test).

Students were directed to their course learning management system to provide consent and take the STAT exam within the next 48 hours (before the start of the second day of class). The exam had a 20-minute time limit imposed to complete the 12-question multiple-choice test.

Following the deadline, course instructors downloaded the responses to a spreadsheet and uploaded the data to a secure Dropbox location for the researchers. A similar process occurred at the end of the semester; in the last week of classes, students were reminded to participate and take the STAT exam again by the last day of class. Additionally, at the end of the semester, course instructors provided final course grades along with responses to the STAT exam.

d. Data Analysis

To quantify the progression in spatial thinking skills throughout the curriculum, assessments of STAT scores for all participants were conducted, as well as among various subsets of participants. To ensure our results were reliable and could be interpreted appropriately, a series of steps were taken to remove potentially problematic data points. First, if a student took the test in 5 minutes or less, these responses were removed, as it was more likely that guessing was occurring, or students were not providing thoughtful responses. For example, Wise (2017) defines two types of multiple-choice test behaviors: rapid guessing behavior and solution behavior. Rapid guessing behavior occurs when the examinee is skimming for keywords, but not actively considering the items in the question, whereas solution behavior indicates that the examinee is reading each question with care and actively trying to find the correct answer. Altogether, this indicates that, to a point, longer time spent responding to a question suggests a more thoughtful response. Exactly how long a student should take to respond to a multiple-choice question depends on the question itself, but prior work measuring response time effort (RTE) found that students who were demonstrating rapid guessing behaviors had a mean response under 5 seconds per question, while the mean response time for examinees showing solution behaviors was around one minute (Wise and Kong 2005; Wise 2017). In the context of the present study, the 5 minute or less threshold was thus used to remove responses that were likely using rapid guessing; this allows, on average, for students to take at least 30 seconds per question to complete the STAT exam, and up to 1.5 minutes per question given the overall 20-minute time limit.

An attention check question was also added to the test to determine if the students were paying attention and reading through the questions carefully or not. The question was added for the Fall 2022 post-test administration and was included in each subsequent administration. If students did not answer the attention check question correctly, they were removed from the dataset. For the Fall 2022 post-test there was only 1 student who did not answer the attention check question correctly, and for the Spring 2023 pre-test there were 3 students. In addition to time to finish data and the attention check question, students were also removed from the dataset if they did not give consent to be in the study, did not answer all 12 of the questions on the STAT, or did not answer demographic questions.

To fully characterize the progression in spatial thinking abilities as quantified by the STAT exam, we identified a subset of students who were enrolled in sequential required courses (e.g., Introduction to Meteorology followed by Global Environmental Change, or Synoptic Meteorology to Dynamic Meteorology). This assessment will allow us to pinpoint whether there is a common course or point within the curriculum where spatial thinking skills are rapidly gained. This may also be useful in determining where inventions may be needed to support student success.

Summary statistics (i.e., mean, median, mode, standard deviation) were first calculated as an overview of performance on STAT. The time it took students to finish the STAT administration was also considered to determine which students were quickly clicking through the questions. Time to finish was also used to determine the average time per question, along with average time to complete. Correlations were done to determine if there is a connection between the time it took students to finish the STAT and their STAT score. In addition to comparing the distribution of pre- vs. post-test scores within subgroups, we will also be comparing pre-test and post-test distributions to other subgroups. Identifying differences in gains (or losses) in STAT scores based on student gender, major, and class year; such demographic characteristics have been shown to be associated with higher or lower spatial thinking abilities (e.g., Vandenburg and Kuse 1978; Lord 1985; Uttal et al. 2012; Uttal et al. 2013; Ormand et al. 2014; McNeal and Petcovic 2020). While academic standing (i.e., freshman, sophomore, junior, senior, or 5th year or up) has not explicitly been tied to spatial skills, we wanted to determine if the growth in spatial thinking skills is linear as students' progress through the curriculum, and whether this progression varied among subsets of students. The questions on the STAT have also been grouped together based on the spatial skill they test, to determine if one group of students performs better on specific tasks (Table 3.2). Lastly, to determine whether spatial thinking skills are predictive of course success, the pre- and post-tests STAT scores were correlated with final course grades. Correlations between the pre- and post-tests will be calculated to see how similar each data set is to each other.

Question Number	Spatial Thinking Components that are Measured
Questions #1-2	Comprehends orientation and direction
Question #3	Discerning spatial patterns and graphing spatial transitions
Question #4	Comprehending overlay and dissolve and inferring a spatial aura
Question #5	Recognizing spatial form (such as cross-sections to 3-D block diagrams or images), being able to transform perceptions, representation, and images from one dimension to another and the reverse and graphic spatial transition
Questions #6-7	Comprehending spatial association (positive or negative), making a spatial comparison, and assessing a spatial association along with graphing a spatial transition
Question #8	Being able to transform perceptions, representations, and images from one dimension to another and the reverse
Questions #9-12	Overlay and dissolve

Table 3.1: *Descriptions of the spatial thinking components for the 12 STAT questions used in this study (taken from Lee and Bednarz 2012).*

Question Number	**Spatial Thinking Skill Group**
Questions #1-2	Spatial Orientation
Questions #3, 4, 6, 7	Spatial Relations
Questions #5, 8	Perspective Taking
Questions #9-12	Spatial Manipulation and Disembedding

Table 3. 2: *The groups that question from the Spatial Thinking Abilities Test were put into based on which spatial skill they test.*

4. Results

Results from the STAT pre- and post-tests from Spring 2022 semester and Fall 2022 semester will be shown, as well as pre-test results from the Spring 2023 semester. Note that all data has been filtered to remove incomplete responses, tests completed in less than 5 min, duplicates (i.e., if a student is enrolled in 2 required courses at the same time), and incorrect responses to the attention check question (see more details in Chapter 3). Emphasis will be placed on summary statistics and performance, with additional details on how various subsets such as gender, major, and grade level performed.

a. All Participants

In the Spring 2022 semester a total of 191 students took the pre-test, while a total of 156 took the post-test. Notably, performance was similar overall for both administrations, indicating minimal changes in spatial thinking skills (e.g., pre-test average was 7.3 while the post-test average was 7.5 and Fall 2022 post-test average was 7.5; Table 4.1). The distribution of STAT scores shows a few key results. First, there is a large range of scores on both the pre- and post-test, from none correct to all correct (i.e., low spatial reasoning to high spatial reasoning). Second, there is substantial overlap in the distributions of pre- and post-test scores, consistent with the broadly similar summary statistics (Table 4.1; Fig. 4.1). However, it should also be noted that a larger number of students received higher STAT scores (i.e., 10 – 11) on the post-test, which is another suggestion of some positive impact of instruction.

For the Fall 2022 semester, there were a total of 244 students who took the pre-test and a total of 241 took the post-test. Similar to the Spring 2022 semester, performance was similar for both the pre- and the post-test, once again, indicating minimal changes in students' spatial abilities (e.g., pre-test average was 7.2 while the post-test average was 7.5 and Fall 2022 post-test average was 7.5). The frequency distribution of pre-test STAT scores shows that there is a large range of scores, from none correct to all correct (i.e., low spatial reasoning to high spatial reasoning; Fig. 4.2). There is a large overlap between scores from the pre- and post-tests which is in line with what the statistics for this group show (Table 4.1). There is an increase in the number of students scoring higher on the post-test (i.e., 10-12), indicating some positive impact of instruction and improvement in spatial thinking skills.

b. Major

Meteorology courses, particularly at the lower levels, intersect with multiple majors (e.g., Earth and Environmental Sciences, Geography, and Geology); additionally, METR 1102 represents one popular option to fulfill a general education science course requirement for all undergraduate degrees. Given prior research demonstrating that exposure to spatial concepts is important for developing spatial reasoning skills (e.g., Lee and Bednarz 2012) and that some majors are inherently more spatial than others, it is worthwhile to explore differences in STAT performance based on major. For each major described below, comparisons were made between those in the major and those outside the major (e.g., meteorology vs. non-meteorology). Students that were included in the STEM subgroup included majors such as computer science, meteorology, earth and environmental science, and mathematics, among others. Students that were included in the non-STEM category included majors such as business, communications, English, finance, marketing, and undecided.

(1) STEM Majors vs. Non-STEM Majors

During Spring 2022, a total of 104 (87) STEM majors (non-STEM majors) completed the STAT pre-test, while 87 (70) completed the post-test. Compared to non-STEM majors, STEM majors scored around a point higher on average on both the pre-test and post-test, indicating that students enrolled in a STEM major have stronger spatial thinking skills than non-STEM majors (Table 4.2). On the other hand, non-majors stayed the same, suggesting a lack of improvement or decrease in spatial thinking abilities, suggesting that their spatial thinking skills did not improve or change from instruction (Table 4.2). Even so, there was a frequency increase of students who scored higher STAT scores for STEM majors (i.e., 10-12) on the post-test, this is another suggestion of positive impact of instruction, whereas for non-majors there was an increase in number of students scoring a 10, suggesting a small amount of improvement (Figs. 4.4-4.5).

In Fall 2022 a total of 151 (91) STEM majors (non-STEM majors) completed the pre-test and averaged 7.7 (6.2), while 151 (90) took the post-test and averaged 8 (6.7). Similar to Spring 2022, STEM majors scored on average around a point higher than non-STEM majors on both the pre- and post-test (Table 4.3). Some improvements are indicated within STEM majors between the increase in average score, but also with an increase in percentage of students scoring better scores on the STAT on the post-test (i.e., 9-12; Fig. 4.6). For non-STEM students, they also showed an increase in percentage of students scoring higher on the post-test than pre-test, which indicates that their spatial reasoning skills improved, however their average STAT score had a minimal increase (Table 4.3 and Fig. 4.6).

Lastly, for Spring 2023 141 (164) STEM majors (non-STEM majors) completed the pre-test and averaged 7.5 (6.5). Once again, similar to Spring and Fall 2022 semesters, STEM majors outperformed non-STEM majors by an entire point on average on the STAT pre-test (Table 4.4; Figs. 4.8 - 4.9). Overall, the results of this study are consistent with previous work in that STEM majors have stronger spatial thinking abilities (e.g., Titus and Horsman 2009).

(2) METR Majors vs. Non-METR Majors

In Spring 2022, a total of 33 (158) Meteorology majors (non-meteorology majors) completed the pre-test and averaged 7.7 (7.3), followed by 28 (129) students that completed the post-test and averaged 8 (7.5). Overall, a larger number of meteorology majors received higher STAT scores (i.e., 10-12) on the post-test compared to the pre-test, indicating improvement in spatial reasoning abilities (Fig. 4.10). Similar results were found for non-METR majors as well (Fig. 4.11). When comparing these subgroups to each other, meteorology majors received only slightly higher STAT scores on average (Table 4.5).

For the Fall 2022 semester, there were a total of 42 (198) meteorology majors (non-meteorology majors) that took the STAT pre-test and averaged 8.1 (7.5), while 47 (194) took the post-test and averaged 8.7 (7.8). In contrast to Spring 2022, meteorology majors scored almost an entire point higher on average for the post-test than non-majors (Table 4.6), indicating an enhanced benefit of instruction. Additionally, meteorology majors had an increase in the percentage of students scoring a perfect 12 on the STAT on the post-test (Fig. 4.13). Similarly, non-majors also showed an increase in the percentage of students who scored high scores on the STAT, but not as large of an increase at Meteorology majors had (i.e., 10-12; Fig. 4.14). The Spring 2023 pre-test results also showed a nearly identical positive performance bias for meteorology majors (Table 4.6 and Fig. 4.16).

Given that non-meteorology majors encompass other STEM majors, which have been shown to have strong spatial reasoning (e.g., Lord 1985; Uttal et al. 2003; Sorby et al. 2018; McNeal et al. 2020), we wished to compare performance on the STAT among meteorology, STEM non-meteorology, and non-STEM/non-meteorology major groups. For Spring 2022 there were 33 (71) meteorology (STEM non-meteorology) majors who took the pre-test and averaged 7.7 (7.6), while there were 28 (59) that completed the post-test and averaged 8.04 (8.05).

Performance between the two groups was similar overall, supporting prior work indicating that any STEM background is correlated with strong spatial thinking skills (Titus and Horsman 2009; Metoyer 2015; Sorby et al. 2018). Additionally, similar improvements occurred on average between the pre- and post-test (Table 4.5; Fig. 4.10 and Fig. 4.12). Fall 2022, however, showed some different results based on the 42 (106) meteorology majors (STEM non-meteorology) that completed the pre-test and averaged 8.1 (7.5), and the 47 (105) that took the post-test and averaged 8.7 (7.8). There was an increase in percentage of students receiving higher scores (i.e., 10 – 12) on the STAT for both groups suggesting positive impact of instruction, but STEM non-meteorology showed a higher percentage of students scoring better on the post-test (Fig. 4.15). Even so, while both groups showed improvement in their overall mean STAT score between pre- and post-tests, meteorology majors scored on average almost an entire point higher than STEM non-meteorology on the post-test (Table 4.6). Similar results were also found in the Spring 2023 pre-test, suggesting that spatial abilities could be stronger in meteorology majors compared to other STEM majors, though additional data would need to be collected to confirm this finding (Table 4.7; Fig. 4.16 and Fig. 4.18).

c. Sex Differences

To determine the impact of gender on STAT performance (e.g., as demonstrated in Newcombe 2010; Hegarty 2014; Sorby et al. 2018), students were grouped based on their self-identified gender. Note that because of small sample sizes in some options, only results for male and female subsets will be shown.

In Spring 2022, a total of 80 (92) females (males) completed the pre-test and averaged 7.1 (7.5), while 94 (73) females (males) took the post-test and averaged 7.6 (7.5). Females showed improvement in their STAT score over the semester, while males received similar or slightly worse STAT scores between the pre- and post-test (Table 4.8), which is also evident in the distribution of scores, indicating substantial overlap (Figs. 4.19-4.20). However, a larger number of females received higher STAT scores (i.e., 10 – 11) on the post-test, and males also showed an increase in higher STAT scores, just a smaller percentage of students compared to females (i.e., 10-12; Figs. 4.19 - 4.20).

The data from Fall 2022 tells a different story, however. A total of 99 (130) females (males) took the pre-test and averaged 6.8 (7.4), while 107 (122) completed the post-test and averaged 7.4 (8). Males scored around one point better on average than females on both the pre- and post-test, indicating stronger spatial thinking abilities compared to females and in line with previous research (e.g., Hegarty 2014). Though females did increase their mean STAT score on the post-test, the increase was much smaller compared to the male improvement in performance. The frequency distribution for females shows a large overlap in pre-test and post-test scores which is consistent with their summary statistics (Table 4.9; Fig. 4.21). The frequency distribution for females shows that the small increase in mean STAT score comes from a slight increase in percentage of students scoring higher STAT scores (i.e., 11-12), while males had a larger increase in students scoring higher STAT scores (i.e., 9-12; Figs. 4.21 - 4.22). This shows that while some females benefited from instruction, males tend to benefit more and showed more improvement than females. Results from the Spring 2023 pre-test were also similar, supporting the claim that males perform better than females when it comes to spatial reasoning skills. The reason as to why is still unclear (Linn and Petersen 1985; Howard et al. 1992; Liben 2015; Gold et al. 2018); such an exploration is left for future work.

d. Grade Level

Grade level was included to determine if spatial thinking is different with each grade level in an attempt to characterize the growth of spatial abilities. It is expected that seniors would have stronger spatial thinking skills than freshmen due to the nature of seniors using spatial thinking skills more often and gaining experience through their schooling (e.g., Titus and Horsman 2009; Ormand et al. 2014). Therefore, the students were put in subgroups based on grade level to aim to understand the progression of spatial thinking abilities. Note that Introduction to Meteorology (METR 1102) has a large subset of students spanning across all grade levels, which provides a control for the extent of experience with meteorological content and presumably use of spatial thinking skills.

(1) Freshmen

In the Spring 2022 semester a total of 19 (15) freshmen took the pre-test (post-test) and averaged 7.7 (6.7). The performance between the two administrations showed a few key factors. First, the mean score for the pre-test was an entire point higher than the post-test, suggesting that freshmen spatial reasoning skills may have weakened throughout the semester. Second, the maximum score for the pre-test was 12 while it was 10 for the post-test (Table 4.11). Notably, this is a very small sample size which could affect the statistics that were calculated. For the Fall 2022 semester the sample size increased slightly with 32 (33) freshmen taking the pre-test (post-test) where the students averaged 6.7 (6.8). While the overall mean STAT score increased between the pre- and post-test, the change was small, suggesting only minor shifts in spatial reasoning abilities (Table 4.12). Even so, more students received higher scores (i.e., 10 – 11) on the post-test (Fig. 4.25), showing some improvement due to instruction. Notably, the Spring 2023 semester had a large increase in participation with 109 students completing the pre-test, with a similar average

STAT score to Fall 2022 (Table 4.13), indicating that the previous datasets, while smaller, may still be fairly representative.

(2) Sophomores

There were 58 (42) sophomores that completed the pre-test (post-test) during the Spring 2022 semester and had an average STAT score of 7.2 (7.9). As shown in Table 4.11, the average STAT score improved slightly between the two administrations of the test; while not a large increase, the range of scores for the post-test was smaller than the pre-test range, which indicates that the students strengthened their spatial reasoning skills. Additionally, the frequency distribution of STAT scores shows a large increase in the number of students scoring 10 on the post-test (Fig. 4.26). Notably, in comparison to the freshmen, sophomores also scored an entire point higher on the post-test, supporting the claim that students' spatial abilities should increase as they continue through their schooling.

In Fall 2022, 83 students completed both the pre- and post-test, improving their score in between, though with a large overlap in distributions (Table 4.12; Fig. 4.30). There was an increase in students scoring higher STAT scores (i.e., 10-11), indicating that there was some positive impact of instruction. Comparing sophomores to freshmen, there are minimal differences in pre-test scores indicating that the students are starting with similar spatial abilities.

Lastly, the Spring 2023 semester had 94 sophomores take the pre-test administration and had an average STAT score similar to students from the Spring 2022 semester. Notably, sophomores from the Spring 2023 semester scored higher on average than freshmen did, further supporting the claim that as students are further along in their academic career, their spatial skills improve with time and practice.

(3) Juniors

For the Spring 2022 semester there were 51 (47) juniors who took the pre-test (post-test) and averaged 7.14 (7.19). While there was a minimal change in the average STAT score between the pre- and the post-test, the frequency distribution shows an increase in the number of students scoring high scores on the STAT for the post-test (i.e., 10-12; Table 4.11; Fig. 4.27). However, the increase in higher scores is balanced out by an increase in the range from the pre-test to the post-test, indicating that while some students did perform better on the post-test, most of the students did not see many changes or improvements in their spatial thinking abilities.

For the Fall 2022 semester there were 60 (61) juniors that took the pre-test (post-test) who averaged 7.2 (7.8). Changes in average STAT performance were minimal, however, the slight increase in STAT score can be seen from the increase in students scoring higher on the post-test (i.e., 9-12; Table 4.12 and Fig. 4.31). The range does increase for the post-test, but the increase comes with students scoring a 12, when the highest score on the pre-test was 11. This suggests again that there was positive impact of instruction even though the average STAT score showed minimal changes.

Spring 2023 had the lowest scoring mean on the pre-test out of the three semesters with 48 students completing the test (Table 4.13). There are minimal differences between the freshmen average STAT score and juniors' pre-test average STAT score, showing that many students may start out at a similar level of spatial reasoning skills, but this could potentially be an outlier and not represent the data accurately. However, like Spring and Fall 2022, sophomores outperformed juniors in Spring 2023.

(4) Seniors

In Spring 2022 there were 56 (47) seniors who took the pre-test (post-test) averaging 7.4 (7.9). The mean STAT score between the pre- and post-tests shows an improvement in spatial thinking abilities, along with an increase in the number of students scoring higher STAT scores (i.e., 10-12; Table 4.11; Fig. 4.28). In spite of similar mean and median scores, the mode did increase by 1 point on the post-test, though the standard deviation and range was also higher, suggesting that instruction was beneficial for some, but not all students.

In Fall 2022, there were 64 (58) students that completed the pre-test (post-test) and averaged 7.7 (8.2) on the STAT. The average for both the pre- and post-test was higher compared to seniors who completed the test in Spring 2022. The increase in mean STAT score between the first administration to the next indicates that the students were strengthening their spatial thinking abilities. In addition to the small increase in mean, there was also an increase in the number of students who scored a perfect score on the STAT along with an increase in higher scores (i.e., 8-10; Table 4.12 and Fig. 4.32). Results from the Spring 2023 pre-test were similar to the Fall 2022 pre-test results, but more data will need to be collected to fully characterize the Spring 2023 semester. But the average score for seniors was higher than the freshmen, sophomores and juniors that took the test.

Sophomores did on average score higher on the STAT for the post-test, suggesting that sophomores either are in classes that better strengthen their spatial reasoning skills or, that they have had more experience using spatial skills and are more confident in them. Comparing juniors to freshmen, the juniors outperformed the freshmen on the post-test in Spring 2022, however, not by much. Interestingly, the sophomores on average had better STAT scores than juniors for both the pre- and post-tests, which suggests that maybe it is not simply what year the student is in and that a student's spatial abilities are more correlated with the class they are taking. Juniors scored higher on average on the pre-test and an entire point on average for the post-test compared to freshmen, supporting the claim that as students' progress through their schooling their spatial abilities get stronger. However, the mean STAT score for sophomores was similar to juniors on the pre-test, and sophomores scored higher on the post-test compared to juniors, showing that it could potentially be related to specific classes that students take and not just what year they are. Comparing the seniors to freshmen, seniors scored an entire point higher on the post-test, suggesting that the progression of spatial thinking abilities could be linear. There are few differences in performance between sophomores and seniors, however, seniors outperformed juniors on both the pre- and the post-tests again suggesting linear progression of spatial thinking skills.

e. Grade Levels within METR 1102

This section discusses and analyzes the differences in spatial thinking skills of the students enrolled in Introduction to Meteorology (METR 1102). The class has a large number of students enrolled and we wanted to analyze and compare how each grade levels spatial skills were to see if there was a pattern between the different grades.

(1) Freshmen METR 1102

There was a total of 14 (13) freshmen enrolled in METR 1102 that took the pre-test (post-test) administration of the STAT in Spring 2022 and averaged 7.6 (6.5). Noting the small sample size, the average STAT score decreased between the pre- and post-tests by an entire point, indicating that students did not find the instruction to be beneficial to strengthening their spatial thinking abilities (Table 4.14). The decrease in STAT score is also evident on the frequency distribution of scores. There is a decrease in students scoring higher scores (i.e., 11-12; Fig. 4.37). Excluding the pre-test, sophomores outperformed freshmen by over a point suggesting linear progression of spatial thinking skills. To further support the claim that spatial skills progress linearly, juniors and seniors enrolled in METR 1102 also showed better performance on the STAT post-tests compared to freshmen.

For the Fall 2022 semester there were 32 (33) students enrolled in METR 1102 that completed the pre-test (post-test) and had an average score of 6.7 (6.8). Comparatively, there were minimal differences between the pre- and post-test suggesting a lack of improvement for the semester (Table 4.15). The distribution of scores indicates some improvement in spatial skills as there was an increase in students scoring 10 and 11 on the STAT (Figure 4.41). Sophomores and Juniors had similar scores for both the pre- and post-tests while seniors performed better. Suggesting that spatial thinking skills are linear. The Spring 2023 semester had similar results as Fall 2022 and sophomores and seniors scored higher on the pre-test suggesting a linear progression in spatial skills.

(2) Sophomores METR 1102

There were 42 (32) students enrolled in METR 1102 as sophomores that took the pre-test (post-test) and averaged 7.1 (8.1) on the STAT. Overall performance indicates that there was an improvement in spatial thinking skills throughout the semester as the average STAT score improved an entire point. Additionally, the range between the two tests decreased by two which is another indication of improvement in spatial thinking abilities (Table 4.14). A third indicator of improvements is shown in the distribution of STAT scores where there was a large increase in students scoring 10, and an increase in students scoring 12 (Figure 4.38). The sophomores in METR 1102 outperformed the freshmen by an entire point, and slightly performed better than juniors and seniors on the post-test, but not on the pre-test.

For Fall 2022 there were 65 (68) students that took the pre-test (post-test) and averaged 6.6 (6.9). There were few indications of weaking or improvements in spatial thinking skills as there was a minimal increase in the average STAT score between the two tests along with the range and the median not changing much (Table 4.15). The distribution of scores shows an increase in higher scores (i.e., 10-11), which does indicate improvements (Figure 4.42). Comparing to other grades, there were minimal differences in mean STAT scores. Which indicates that overall, this class may not aid in students' spatial abilities.

The average for sophomores in the Spring 2023 semester is similar to the performance on the pre-test in Spring 2022. Sophomores and seniors performed similarly on the pre-test while juniors and freshmen were outperformed by the sophomores.

(3) Juniors METR 1102

There was a small number of students who completed the pre-test for Spring 2022 at 23 students and averaged 6.4, whereas there were 37 students that completed the post-test and averaged 6.6. Juniors showed little to no improvement in their average STAT score (Table 4.14). The distribution of scores, however, does show some improvement because it shows an increase in students scoring 10 and 11 on the STAT (Figure 4.39). Juniors had similar performance to freshmen on the post-test, but not the pre-test, while sophomores outperformed juniors on both the pre- and post-test. Seniors had a better mean score for the pre- and post-test. Indicating that overall, there may not be a linear progression in spatial thinking skills as students' progress in their undergraduate degree.

Fall 2022 included 33 (35) students who took the pre-test (post-test) with averages on the STAT being 6.6 (6.8). The average performance on the STAT showed minimal improvements in spatial thinking skills. The average STAT score changed slightly, while the median, mode and range all stayed the same between the two administrations (Table 4.15). Comparatively, freshmen, sophomores, and juniors all have similar statistics between the tests, while seniors outperformed the different subgroups. This indicates that the progression of spatial thinking skills could be linear but tends to not be.

In Spring 2023 there were 31 students that completed the STAT. This group had the lowest average STAT score out of all the subgroups in METR 1102. Suggesting that the improvement and progression of spatial thinking abilities is not linked to grade level.

(4) Seniors METR 1102

For Spring 2022 there were 44 (37) seniors enrolled in METR 1102 that completed the pre-test (post-test) who averaged a 7.3 (7.8) on the STAT. The average STAT score did not vary much between the pre- and post-tests, similar to the rest of the descriptive statistics (Table 4.14). There was an increase in the number of students scoring 10 and 11 on the STAT, however, no students scored a perfect score on the post-test (Figure 4.40). Freshmen and sophomores outperformed seniors on the pre-test, while only sophomores scored higher than seniors on the post-test. This suggests that spatial thinking skills might not be linear or correlate with a student's grade level.

There were 31 (32) seniors enrolled in METR 1102 in Fall 2022 that completed the pre-test (post-test) where their mean STAT score was 6.9 (7.3). The average STAT score increased almost half a point between the two administrations of the test. Additionally, the range decreased for the post-test and the mode increased (Table 4.15). All are indications of improvement in spatial thinking skills throughout the semester. Seniors outperformed freshmen, sophomores, and juniors indicating that spatial skills might be linear and get stronger as students are in school longer.

In Spring 2023, there were 42 seniors who took the STAT pre-test. Comparatively, seniors had a stronger performance on the STAT than freshmen and juniors. And performed similarly to sophomores overall. This suggests that there's a possibility that students start out in similar places with their spatial thinking skills but diverge when taking the post-test.

f. Grouped Spatial Skills

The STAT is a holistic measure of spatial thinking abilities, but also contains questions related to specific spatial skills (Lee and Bednarz 2009; Lee and Bednarz 2012; Bednarz and Lee 2019). We have created four different categories that all 12 questions fall into: spatial orientation, spatial relations, perspective taking, and spatial manipulation / disembedding (Table 3.2). The categories were determined from Lee and Bednarz (2012) explanations of what each question on the STAT tested. We grouped them using like terms to how they described each question. Student performance was then examined in each category, focusing on scores of all students as well as the various demographic subgroups.

Questions 1 and 2 on the STAT were identified as questions that test students' spatial orientation. The order of the questions varied for each semester, but this analysis accounts for the different order of questions. Overall performance for the Spring 2022 semester showed that a majority of students answered both questions correctly on the pre- and post-tests (e.g., 77% answered both questions correctly on the pre-test and 78% on the post-test). There was an average normalized learning gain of 1.8%, indicating that all students slightly improved this skill (Fig. 4.49 and Fig. 4.50). Meteorology majors had the largest average normalized learning gain of 13%, indicating that they improved the most in spatial orientation in the Spring 2022 semester (Fig. 4.64 and Fig. 4.65). Fall 2022 showed similar patterns with 76% of students answering both questions correctly on the pre-test and 78% on the post-test with a normalized learning gain of 1.5% for questions 1 and 2 (Fig. 4.51 and Fig. 4.52). For this semester the Seniors enrolled in

METR 1102 had the largest learning gain of 20%, showing improvement in their spatial orientation skills (Fig. 4.123 and Fig. 4.124).

Questions 3, 4, 6, and 7 were put into the Spatial Relations category. Performance was slightly worse for these questions compared to the Spatial Orientation questions. Sixty-eight percent of students in the Spring 2022 semester answered all four questions correctly for the post-test while 66% of students answered them correctly on the post-test, where the normalized learning gain was -3.1% for the four questions (Fig. 4.49 and Fig. 4.50). Seniors enrolled in METR 1102 had the largest improvement in scores with a 9.3% increase (Fig. 4.115 and Fig. 4.116), followed by Females who had an 8.9% increase on average (Fig. 4.79 and Fig. 4.80). This indicates that these students had instruction from their courses that helped them strengthen their spatial relations abilities. Fall 2022 had similar percentages of students answering all four questions correctly (e.g., 63.9% on the pre-test and 66.7% on the post-test), however, this semester there was an increase in the normalized learning gains of 5% (Fig. 4.51 and Fig. 4.52). Overall, showing improvement for all students in their abilities pertaining to spatial relations. Juniors showed the most improvement overall with an increase in learning gain of 21.7% for the four questions (Fig. 4.101 and Fig. 4.102). Showing that the classes the juniors were enrolled in were having large positive impacts on students' spatial relation abilities.

Questions 5 and 8 were identified as the Perspective Taking questions on the STAT. Performance on these questions decrease from the questions in the spatial orientation and spatial relations categories where 55.9% of students in the Spring 2022 semester answered both questions correctly on the pre-test and 52% on the post-test. Where the normalized learning gain was -7%, indicating that the students did not improve their perspective taking skills through the classes they were enrolled in (Fig. 4.49 and Fig. 4.50). Non-METR (STEM) majors improved their perspective taking skills the most and had a learning gain of 12.5% for both questions combined (Fig. 4.68 and Fig. 4.69). So, while all students did not show improvement, some students saw positive impacts of instruction. For Fall 2022, 53.7% of students answered both questions correctly for the pre-test and 55.8% on the post-test, with a normalized learning gain of 3.8% (Fig. 4.51 and Fig. 4.52). Meteorology majors had the largest increase in learning gains with a 16.5% increase in students answering these questions correctly between the pre- and post-tests, showing that meteorology majors had a large impact of instruction in the courses they were enrolled in (Fig. 4.70 and Fig. 4.71).

Spatial manipulation and disembedding were the questions that had the lowest percentage of students answering questions 9, 10, 11, and 12. In Spring 2022, 48.8% of students answered all four questions correctly for the pre-test and 51.7% on the post-test with a normalized learning gain of 7.8% (Fig. 4.49 and Fig. 4.50). However, while these questions had the lowest percentage of students answering these correctly, this group shows that almost every single subgroup of students showed a large positive learning gain between the pre- and post-tests. Where sophomores enrolled in METR 1102 had the largest overall average gain at 52.3% between the pre- and the post-test (Fig. 4.111 and Fig. 4.112). Twelve out of 15 subgroups had a normalized learning gain above 10%. The groups that had less than 10% improvement were Freshmen, Juniors, and Freshmen (METR 1102). These large improvements in the number of students answering these questions correctly show that the courses that they were enrolled in had a large positive impact on students' spatial manipulation and disembedding skills.

Fall 2022 showed more improvement between the pre- and post-test compared to Spring 2022 semester. 46.3% of students answered all four questions correctly on the pre-test and 55.1% on the post-test with an averaged normalized learning gain of 20.3% for all four questions (Fig.

4.51 and Fig. 4.52). Like Spring 2022 semester, 12 out of 15 subgroups had learning gains of above 10%. The subgroups that did not meet this criteria were Females, Juniors (METR 1102), Seniors (METR 1102). Again, Sophomores enrolled in METR 1102 had the highest average learning gain of 28.4% for all four questions (Fig. 4.119 and Fig. 4.120). The large impact of instruction across both the Spring and Fall 2022 semesters indicates that the required meteorology classes aid in the development and improvement of students' spatial manipulation and disembedding skills.

g. Pathways Students

To characterize the progression of spatial thinking abilities as students advance through the meteorology curriculum, cohorts of students were examined as they completed sequential coursework. Based on current data collection, Pathways Students are followed between the Spring 2022 and Fall 2022 pre- and post-test through the Spring 2023 pre-test.

(1) Group 1

Group 1 consists of 12 students who started in Global Environmental Change (ESCI 3101) in Spring 2022, then continued to Fundamentals of Meteorology (METR 3140) in Fall 2022, and then enrolled in Atmospheric Thermodynamics (METR 3210) in Spring 2023. The overall average STAT score was 9 for the first administration and there was a slight decrease in average score for the last administration at 8.92 (Fig. 4.129 and Fig. 4.131). The minimal changes in mean STAT score indicate that there was not much impact of instruction overall for this group of students throughout the 5 administrations of the STAT. Additionally, the average normalized learning gain between the students first attempt and last attempt was 1.11%, supporting the claim that the students who took these three classes, have not shown significant improvements in their spatial thinking abilities. Some students showed more improvements than others (i.e., normalized learning gains of 22.22% and 40%), while others showed zero improvement in their normalized learning gain because they scored a 12 for both administrations of the test. It is not fully clear why larger improvements were not present, but we suspect that the classes could require the use of spatial skills periodically throughout the semester, which would help students improve slightly, while other classes may require students to think spatially more often.

(2) Group 2

Group 2 consists of 16 students who enrolled in Atmospheric Thermodynamics (METR 3210) in Spring 2022, followed by Synoptic Meteorology (METR 3245) and Physical Meteorology (METR 3220) in Fall 2022, then Atmospheric Dynamics I (METR 3250) and Climate Dynamics (METR 4205) in Spring 2023. The pre-test average for this group was 8.19, while the post-test average was 8.94, showing a slight increase in overall spatial thinking abilities (Fig. 4.131 and Fig. 4.132). An additional piece of evidence that shows that this group did improve their spatial thinking skills is the average normalized learning gain which was 19.20%, though there was a large range, as one student exhibited a 200% increase, while others had 0% change due to consistently high (i.e., a 12) scores on both the pre- and post-test. The overall positive learning gains from this group suggest that these classes the students are taking support the strengthening of their spatial skills over time.

(3) Group 3

The last cohort followed through the administrations of STAT first enrolled in either Atmospheric Meteorology I (METR 3250) or Climate Dynamics (METR 4205) in Spring 2022. These students were only followed through four administrations of the STAT as there are no required classes in the meteorology curriculum in the last semester of their senior year (Spring 2023). There were 9 students included in this group and they averaged an 8.67 on the pre-test and a 9.22 on the post-test, indicating a positive impact of instruction throughout the two semesters (Fig. 4.133 and Fig. 4.134). Additionally, there was a positive averaged normalized learning gain of 5.47% for the group, with supports the claim that the classes these students were enrolled in supported and aided in the learning of spatial thinking skills. Some students had learning gains of 83.33% while others were negative, or at 0% from scoring the same score for their first and last administration of the test. Overall, there is support that students are improving their spatial thinking skills through the classes that they are enrolled in, suggesting that the curriculum for the classes for these semesters supports growth in spatial abilities.

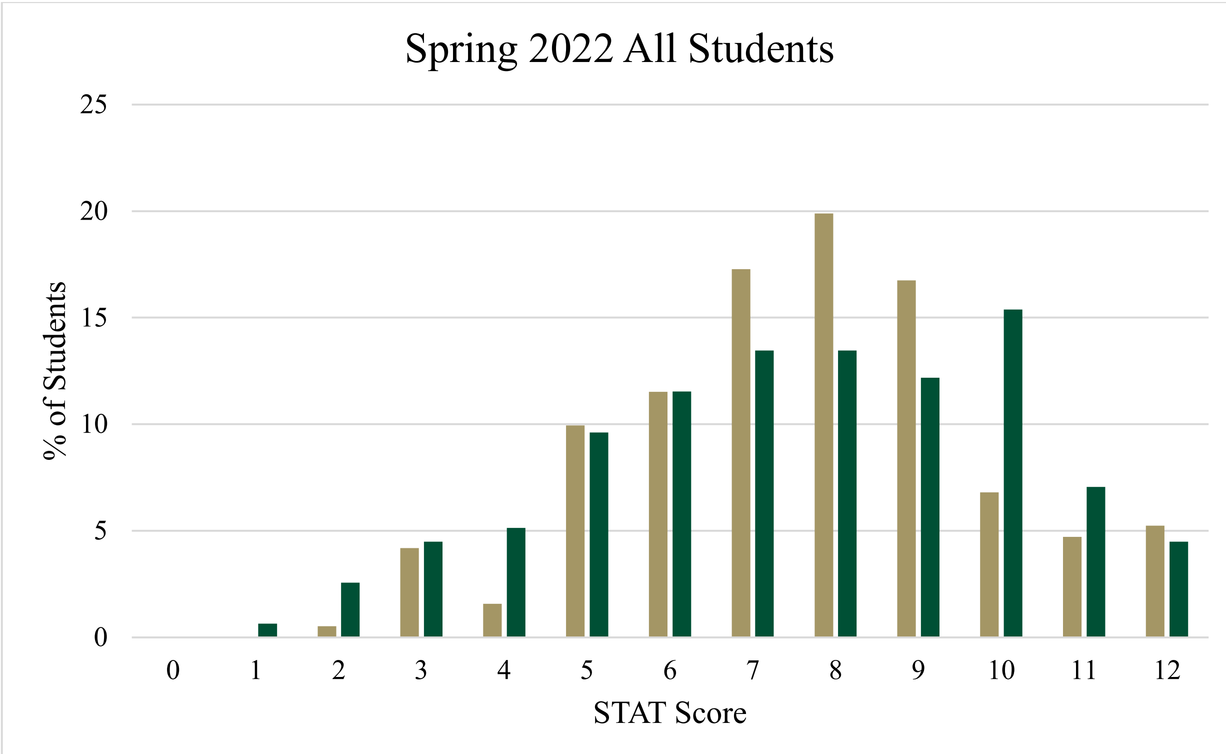


Figure 4. 1: *Frequency distribution for All Students in the Spring 2022 semester. The graph shows the pre-test results in gold, and the post-test results in green.*

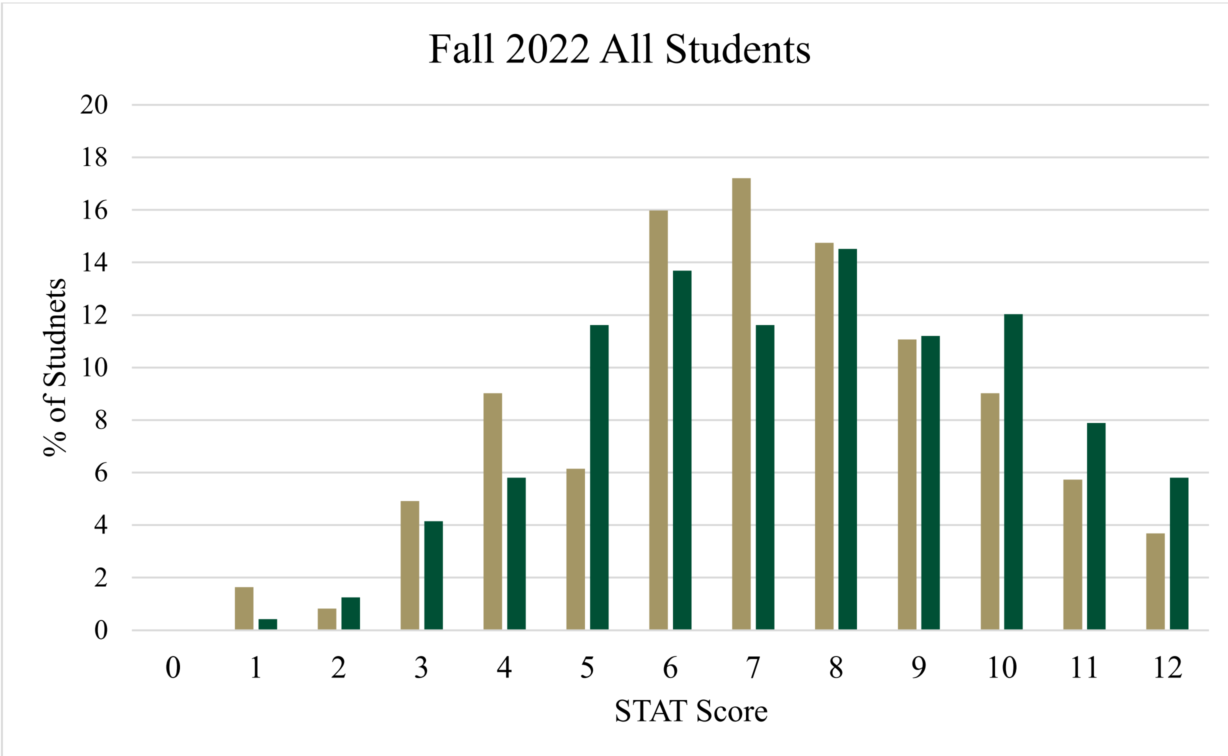


Figure 4. 2: *Frequency distribution for All Students in the Fall 2022 semester. The graph shows the pre-test results in gold, and the post-test results in green.*

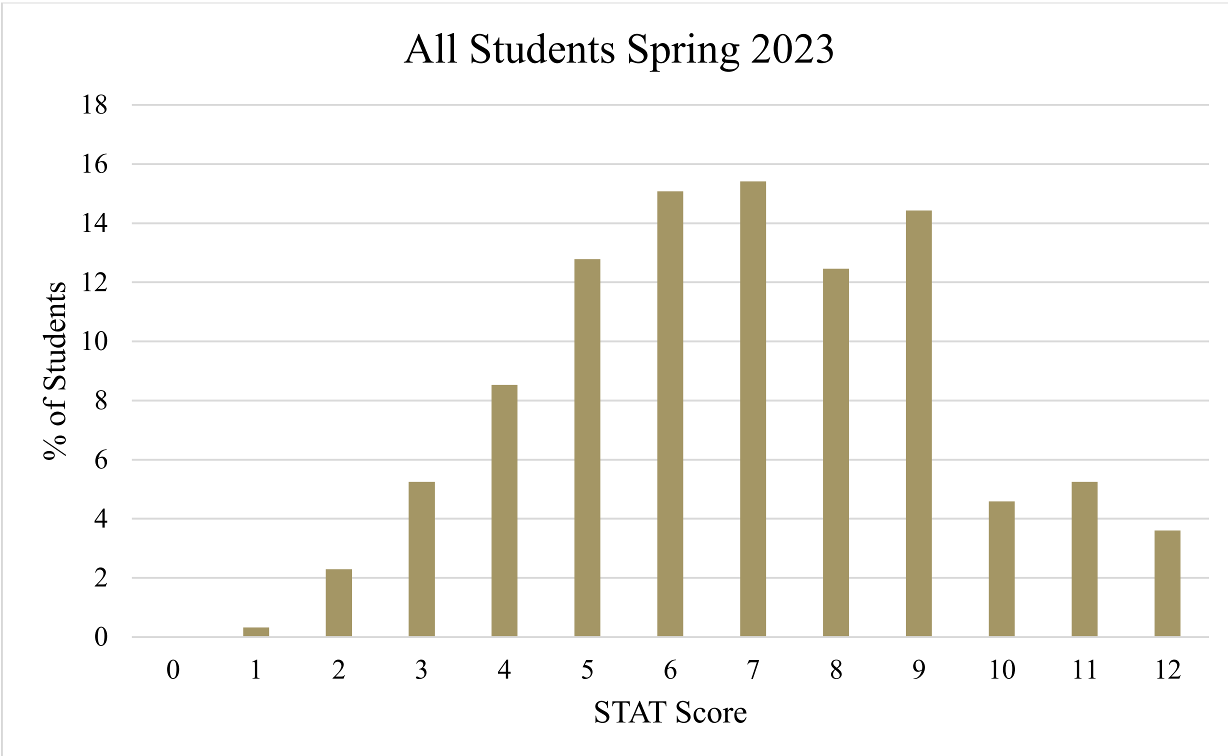


Figure 4. 3: *Frequency distribution for All Students pre-test results in the Spring 2023 semester.*

All Students					
	Spring 2022		***Fall 2022***		***Spring 2023***
Statistics	**Pre-Test** (n = 191)	**Post-Test** (n = 156)	**Pre-Test** (n = 244)	**Post-Test** (n = 241)	**Pre-Test** (n = 305)
Mean	7.32	7.54	7.16	7.54	6.93
Median	7	8	7	8	7
Mode	8	10	7	8	7
Range	11	11	11	11	11
Skewness	-0.198	-0.305	-0.137	-0.099	0.080
Standard Deviation	2.33	2.56	2.46	2.54	2.41

Table 4. 1: *Summary statistics on STAT performance for All Students in the Spring 2022, Fall 2022, and Spring 2023 semesters.*

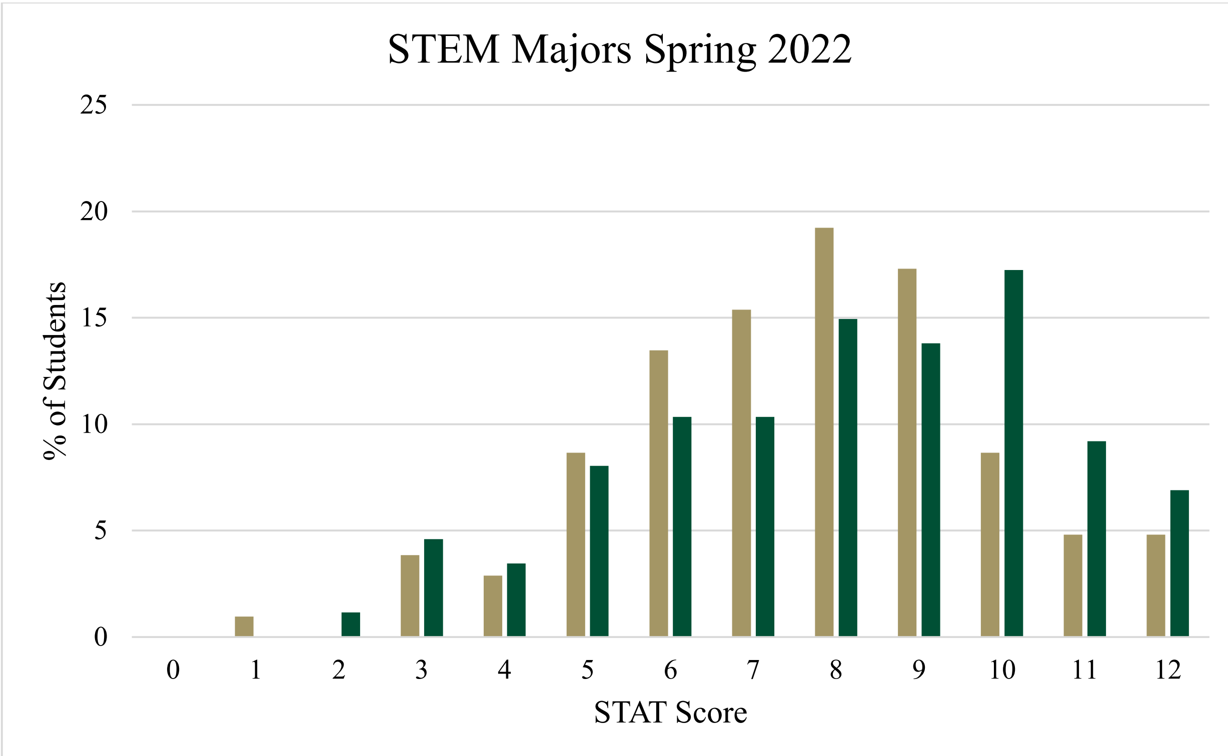


Figure 4. 4: *Frequency distribution for STEM Majors in the Spring 2022 semester. The graph shows the pre-test results in gold, and the post-test results in green.*

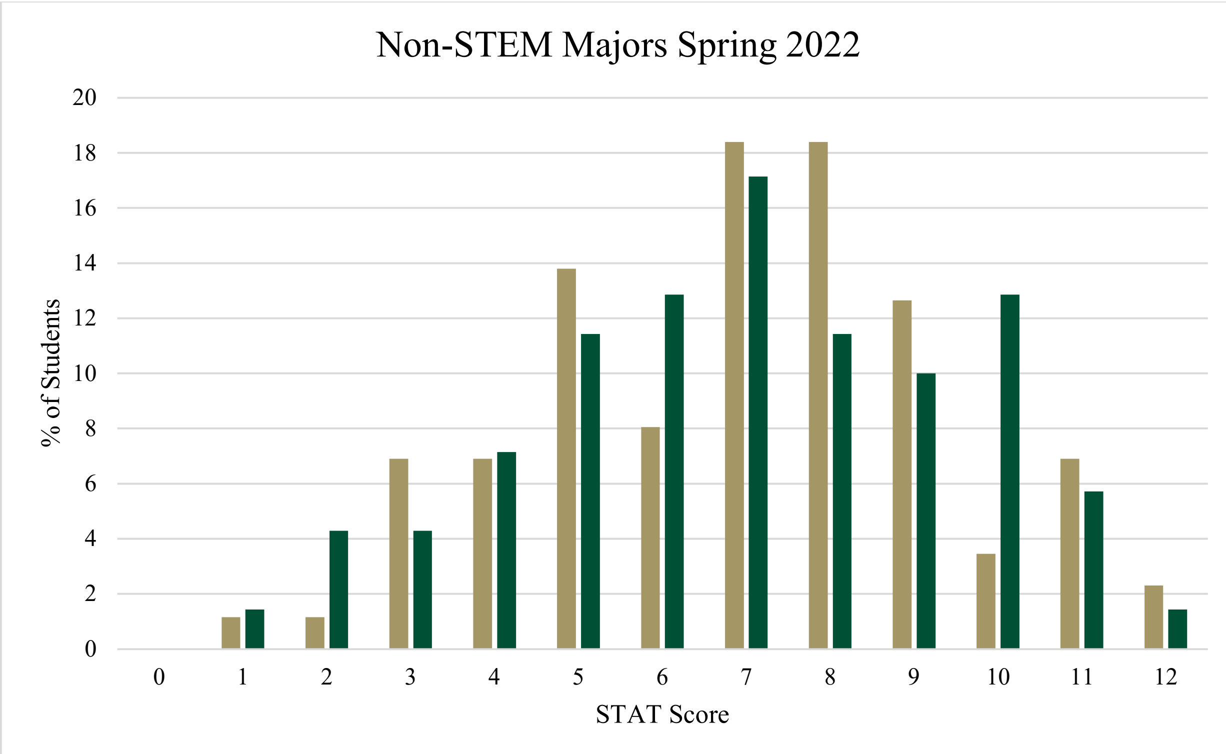


Figure 4. 5: *Frequency distribution for Non-STEM Majors in the Spring 2022 semester. The graph shows the pre-test results in gold, and the post-test results in green.*

STEM vs. Non-STEM Majors Spring 2022				
	STEM Majors		***Non-STEM Majors***	
Statistics	**Pre-Test** (n = 104)	**Post-Test** (n = 87)	**Pre-Test** (n = 87)	**Post-Test** (n = 70)
Mean	7.63	8.05	6.97	6.95
Median	8	8	7	7
Mode	8	10	8	7
Range	11	10	11	11
Skewness	-0.246	-0.402	-0.102	-0.219
Standard Deviation	2.23	2.49	2.41	2.56

Table 4. 2: *Summary statistics on STAT performance for STEM Majors and Non-STEM Majors in the Spring 2022 semester.*

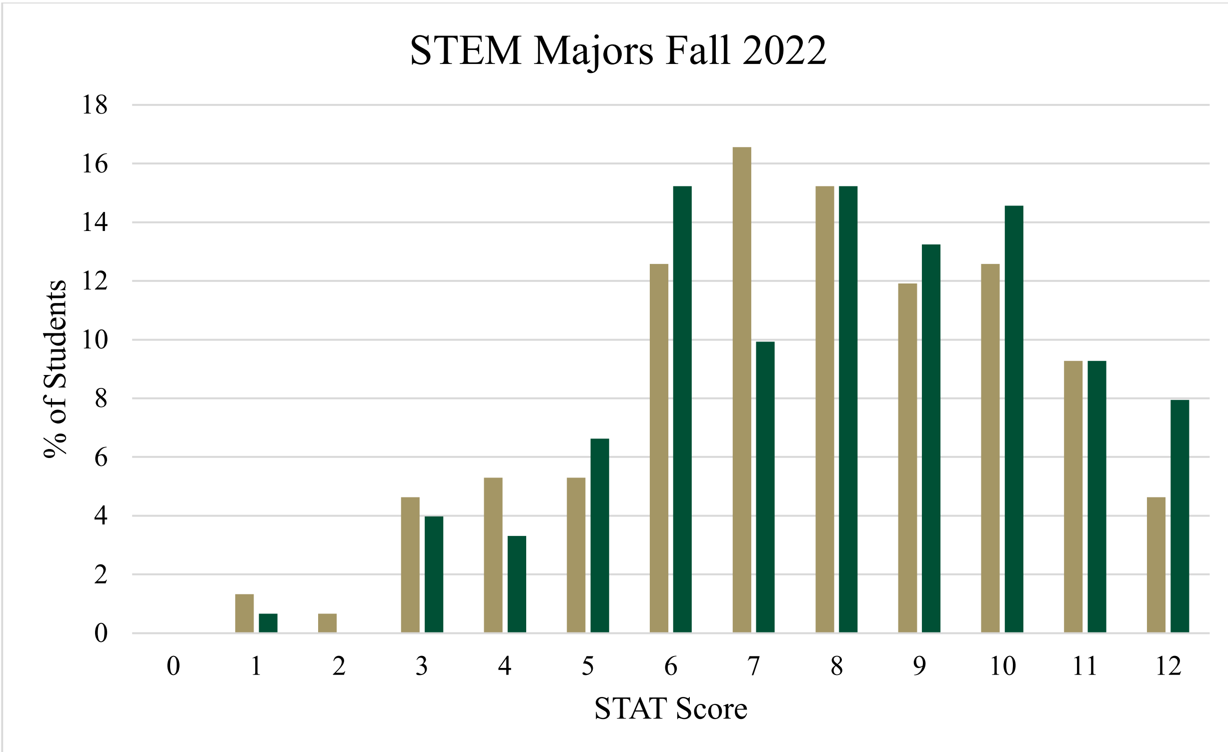


Figure 4. 6: *Frequency distribution of STEM Majors in the Fall 2022 semester. The graph shows the pre-test results in gold, and the post-test results in green.*

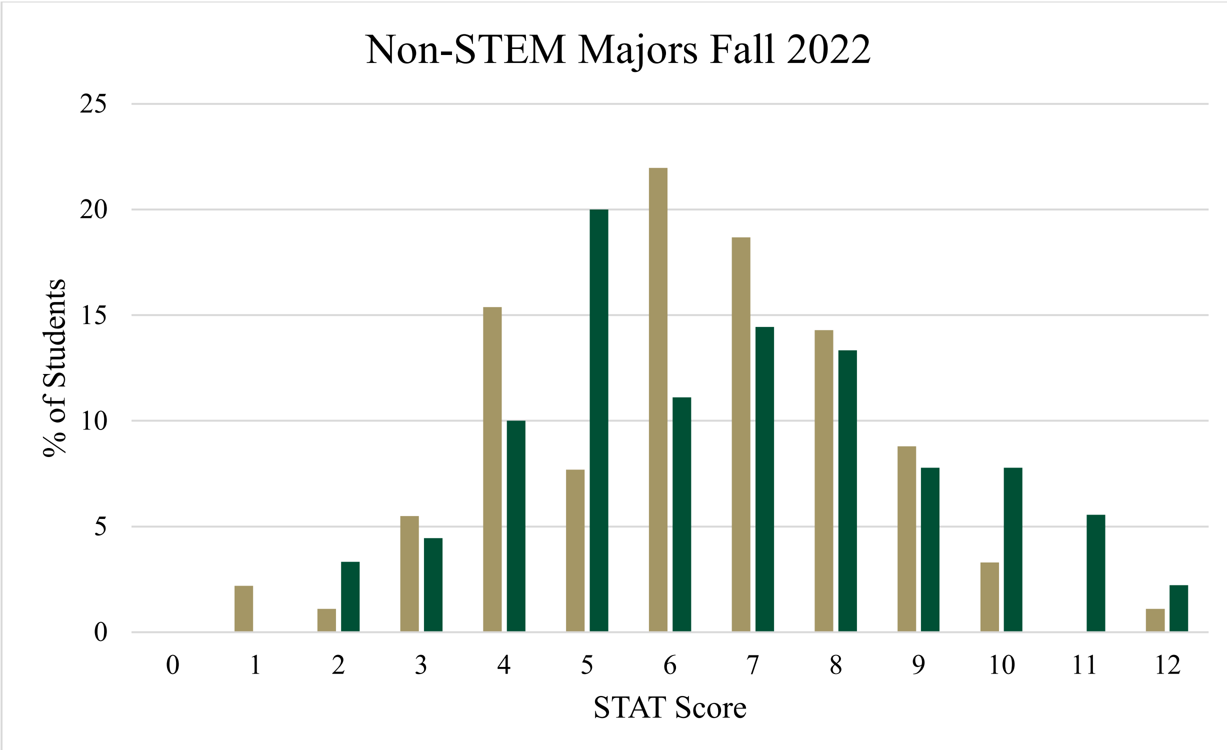


Figure 4. 7: *Frequency distribution of Non-STEM Majors in the Fall 2022 semester. The graph shows the pre-test results in gold, and the post-test results in green.*

STEM vs. Non-STEM Majors Fall 2022				
	STEM Majors		***Non-STEM Majors***	
Statistics	**Pre-Test** (n = 151)	**Post-Test** (n = 151)	**Pre-Test** (n = 91)	**Post-Test** (n = 90)
Mean	7.68	8.03	6.23	6.7
Median	8	8	6	7
Mode	7	6	6	5
Range	11	11	11	10
Skewness	-0.351	-0.297	-0.120	0.220
Standard Deviation	2.48	2.45	2.10	2.43

Table 4. 3: *Summary statistics on STAT performance for STEM Majors and Non-STEM Majors in the Fall 2022 semester.*

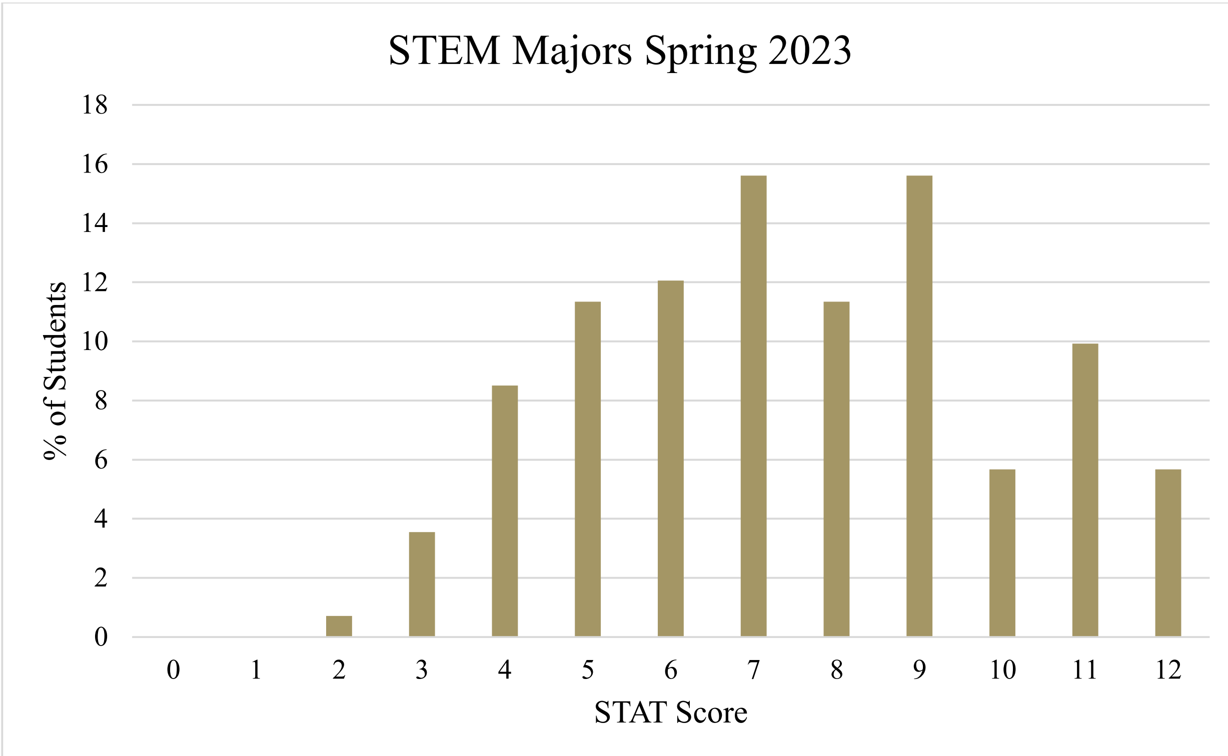


Figure 4. 8: *Frequency distribution for STEM Majors pre-test results in the Spring 2023 semester.*

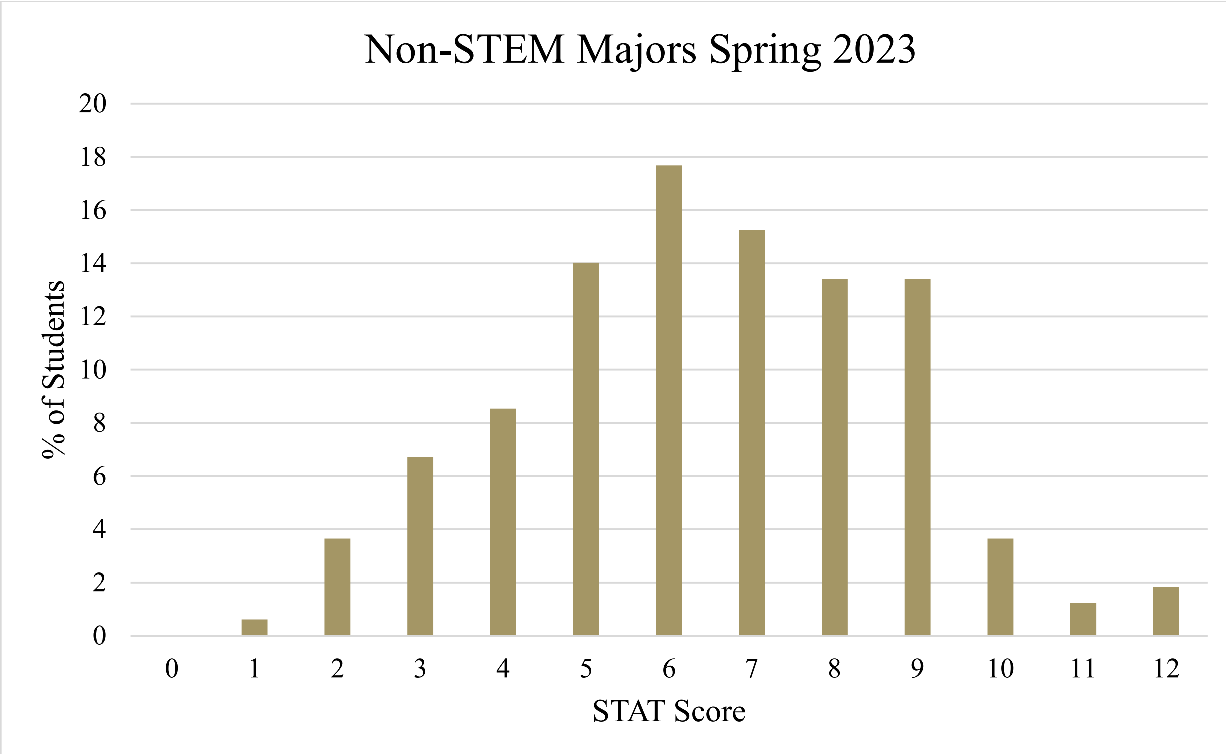


Figure 4. 9: *Frequency distribution for Non-STEM Majors pre-test results in the Spring 2023 semester.*

STEM vs. Non-STEM Spring 2023		
	STEM Majors	***Non-STEM Majors***
Statistics	**Pre-Test** (n = 141)	**Pre-Test** (n = 164)
Mean	7.50	6.45
Median	7	6
Mode	7	6
Range	10	11
Skewness	0.044	-0.002
Standard Deviation	2.48	2.26

Table 4. 4: *Summary statistics on STAT performance for STEM Majors and Non-STEM Majors in the Spring 2023 semester.*

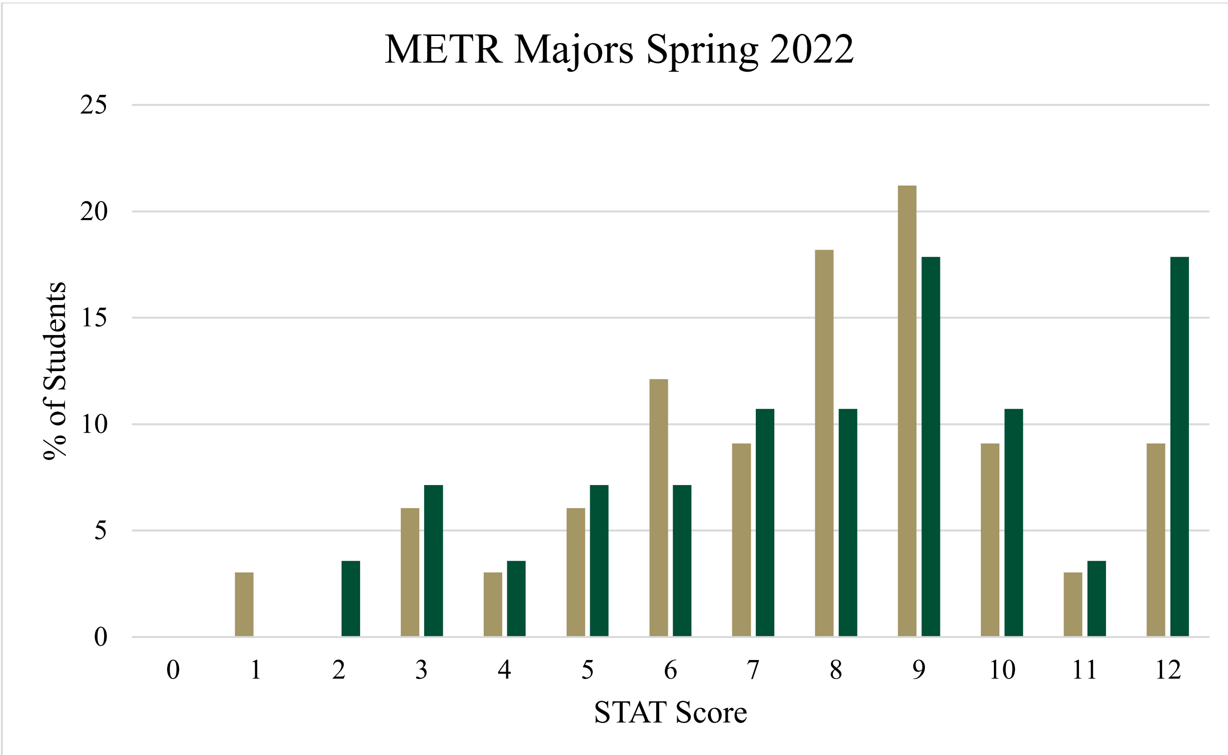


Figure 4. 10: *Frequency distribution for Meteorology Majors in the Spring 2022 semester. The graph shows the pre-test results in gold, and the post-test results in green.*

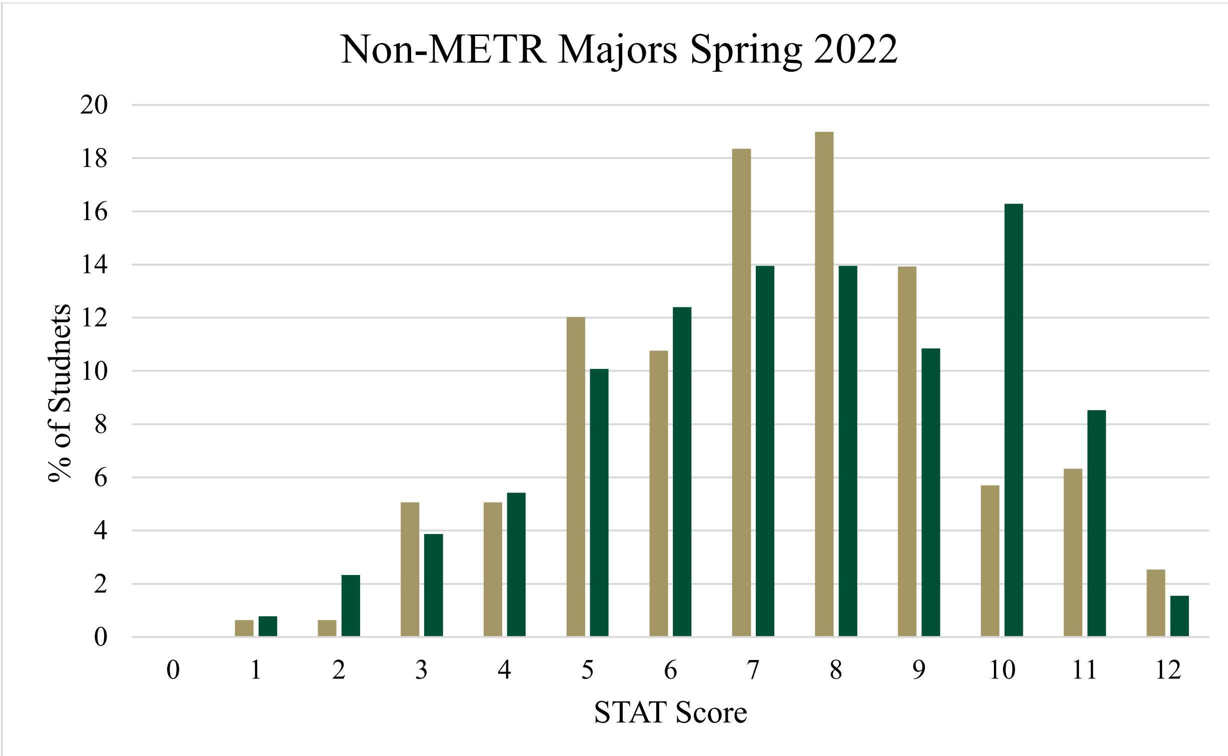


Figure 4. 11: *Frequency distribution for Non-Meteorology Majors in the Spring 2022 semester. The graph shows the pre-test results in gold, and the post-test results in green.*

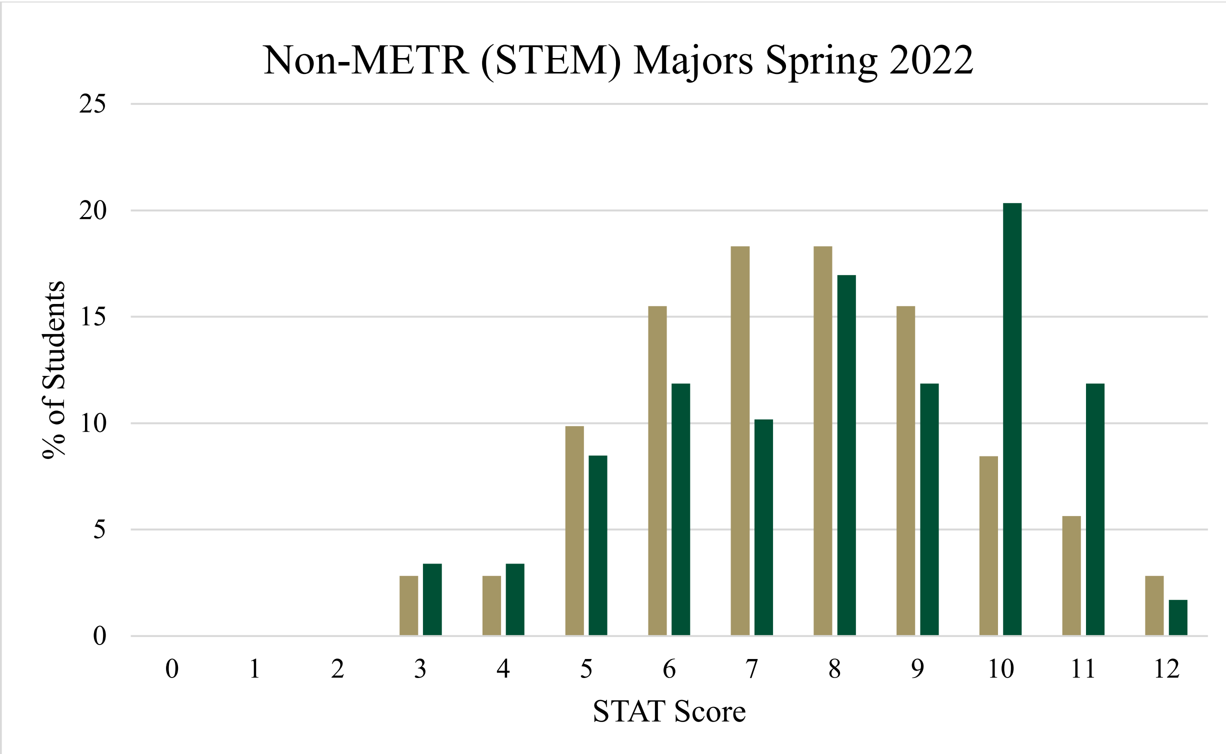


Figure 4. 12: *Frequency distribution for Non-Meteorology (STEM) Majors in the Spring 2022 semester. The graph shows the pre-test results in gold, and the post-test results in green.*

Meteorology vs. Non-Meteorology vs. Non-Meteorology (STEM) Spring 2022						
	METR Majors		***Non-METR Majors***		***Non-METR (STEM) Majors***	
Statistics	**Pre-Test** (n = 33)	**Post-Test** (n = 28)	**Pre-Test** (n = 158)	**Post-Test** (n = 129)	**Pre-Test** (n = 71)	**Post-Test** (n = 59)
Mean	7.70	8.04	7.25	7.46	7.56	8.05
Median	8	8.5	7	8	8	8
Mode	9	9	8	10	7	10
Range	11	10	11	11	9	9
Skewness	-0.519	-0.387	-0.137	-0.343	0.025	-0.411
Standard Deviation	2.65	2.96	2.26	2.47	2.04	2.25

Table 4. 5: *Summary statistics on STAT performance for METR Majors, Non-METR Majors, and Non-METR (STEM) Majors in the Spring 2022 semester.*

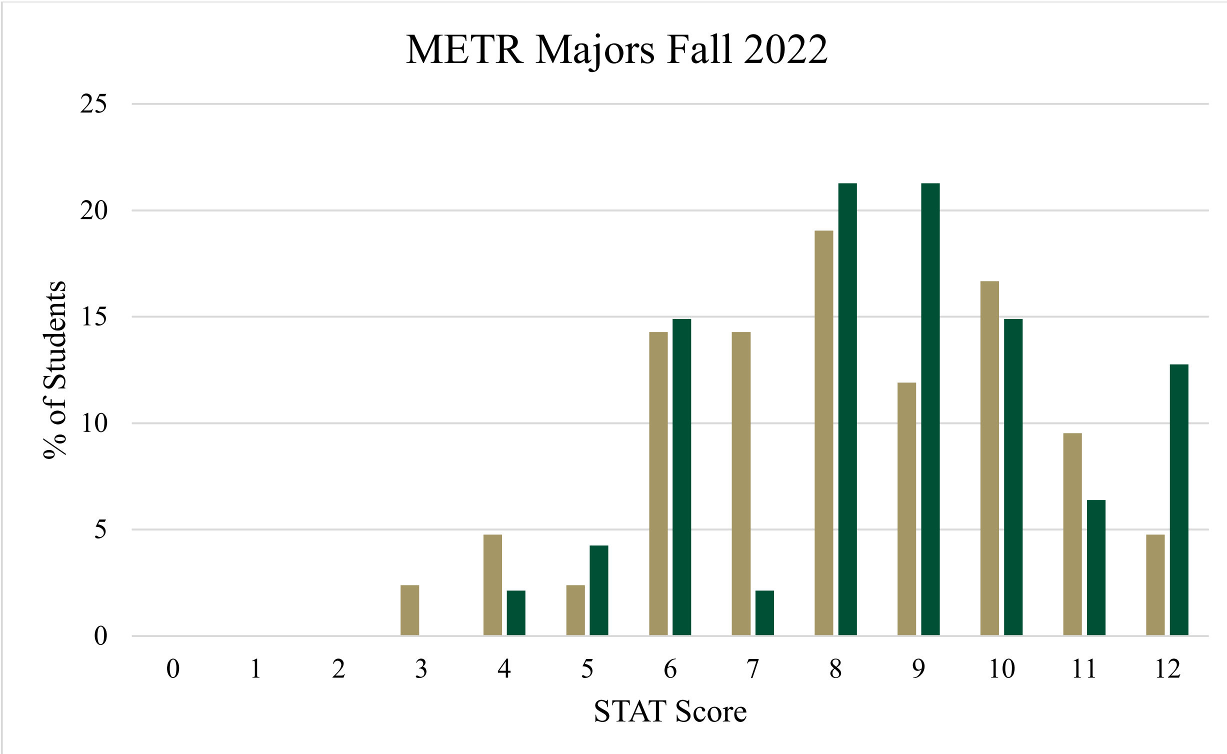


Figure 4. 13: *Frequency distribution for Meteorology Majors in the Fall 2022 semester. The graph shows the pre-test results in gold, and the post-test results in green.*

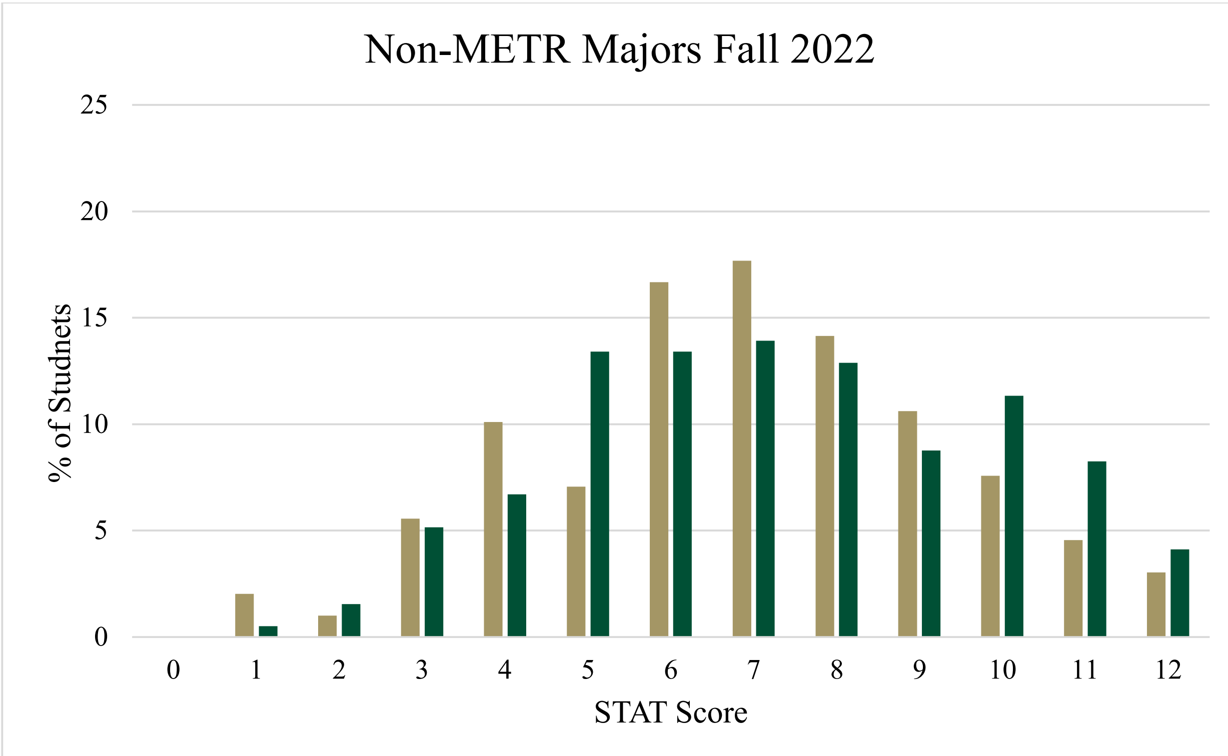


Figure 4. 14: *Frequency distribution for Non-Meteorology Majors in the Fall 2022 semester. The graph shows the pre-test results in gold, and the post-test results in green.*

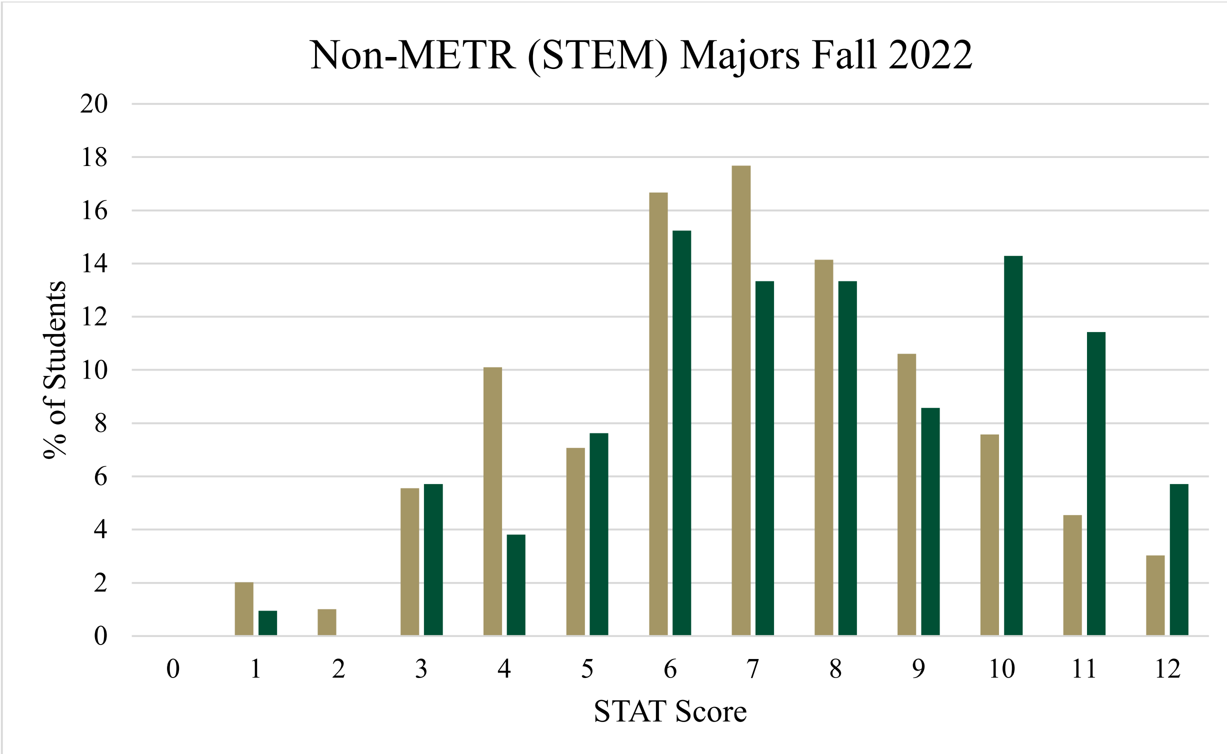


Figure 4. 15: *Frequency distribution for Non-Meteorology Majors in the Fall 2022 semester. The graph shows the pre-test results in gold, and the post-test results in green.*

Meteorology vs. Non-Meteorology vs. Non-Meteorology (STEM) Fall 2022						
	METR Majors		***Non-METR Majors***		***Non-METR (STEM) Majors***	
Statistics	**Pre-Test** (n = 42)	**Post-Test** (n = 47)	**Pre-Test** (n = 198)	**Post-Test** (n = 194)	**Pre-Test** (n = 106)	**Post-Test** (n = 105)
Mean	8.12	8.68	6.91	7.26	7.47	7.77
Median	8	9	7	7	7.5	8
Mode	8	8	7	7	7	6
Range	9	8	11	11	11	11
Skewness	-0.262	-0.177	-0.089	-0.009	-0.304	-0.235
Standard Deviation	2.19	2.10	2.45	2.55	2.59	2.56

Table 4. 6: *Summary statistics on STAT performance for METR Majors, Non-METR Majors, and Non-METR (STEM) Majors in the Fall 2022 semester.*

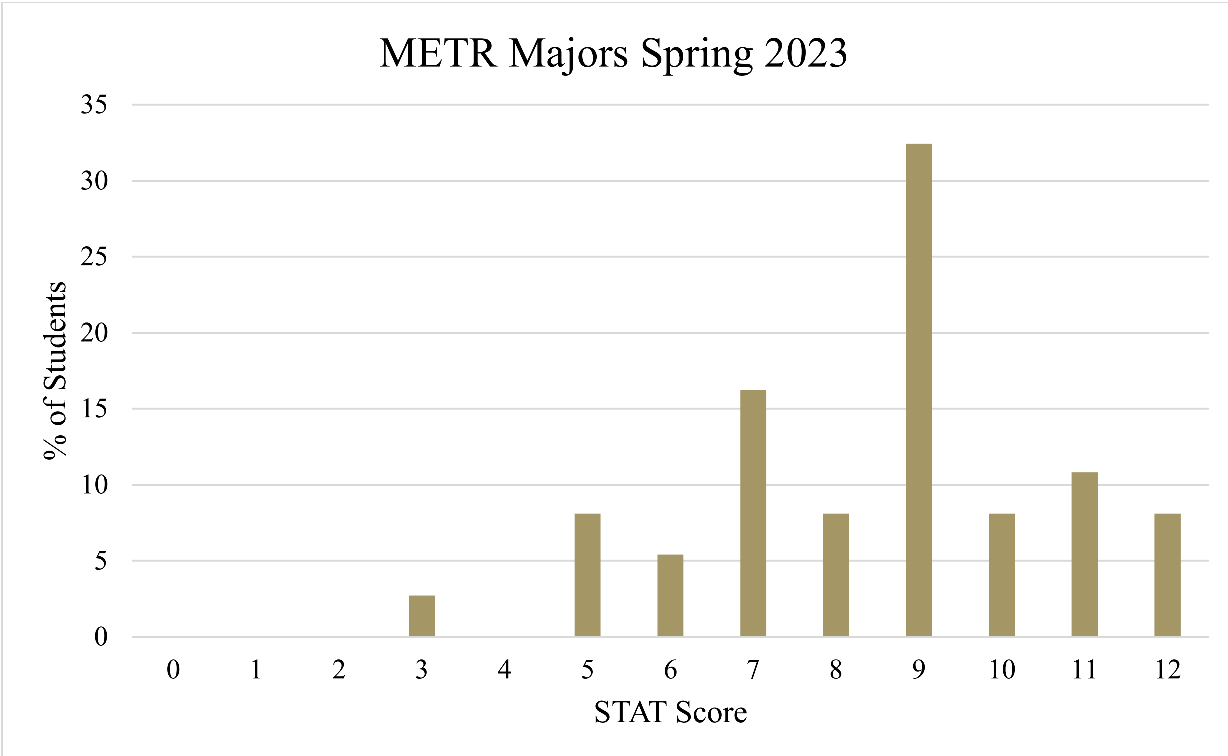


Figure 4. 16: *Frequency distribution for Meteorology Majors pre-test in the Spring 2023 semester.*

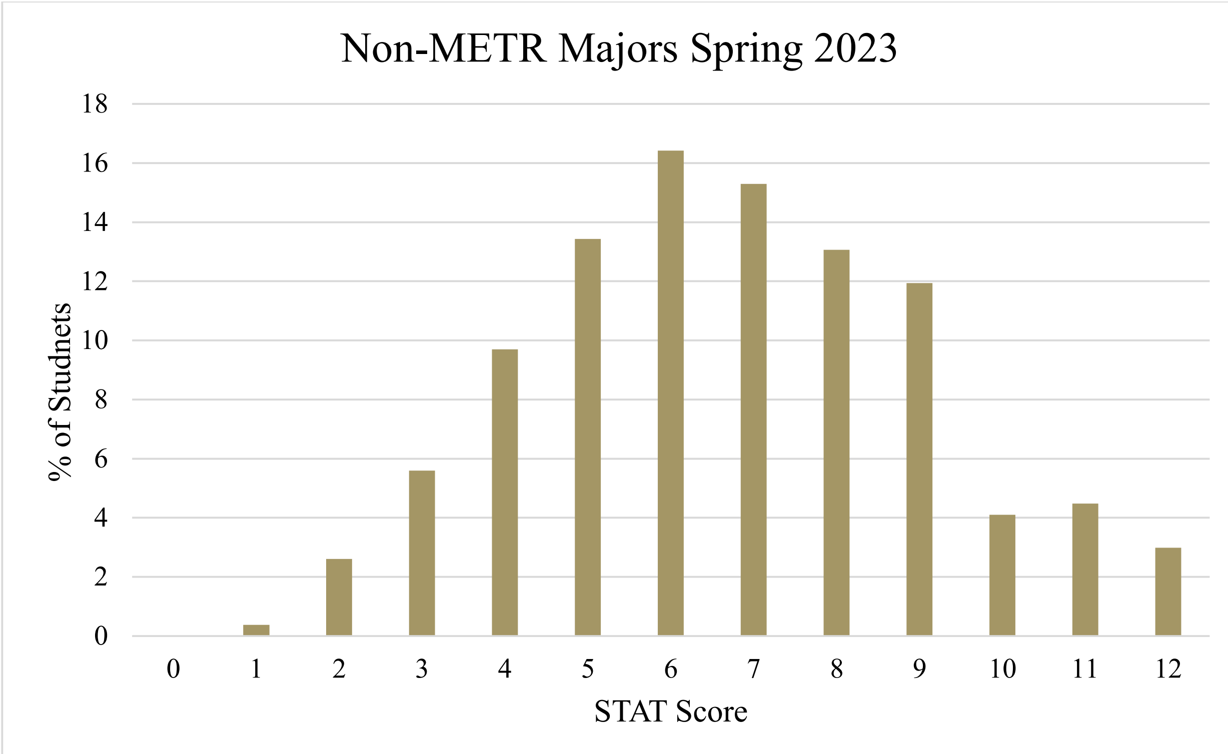


Figure 4. 17: *Frequency distribution for Non-Meteorology Majors pre-test in the Spring 2023 semester.*

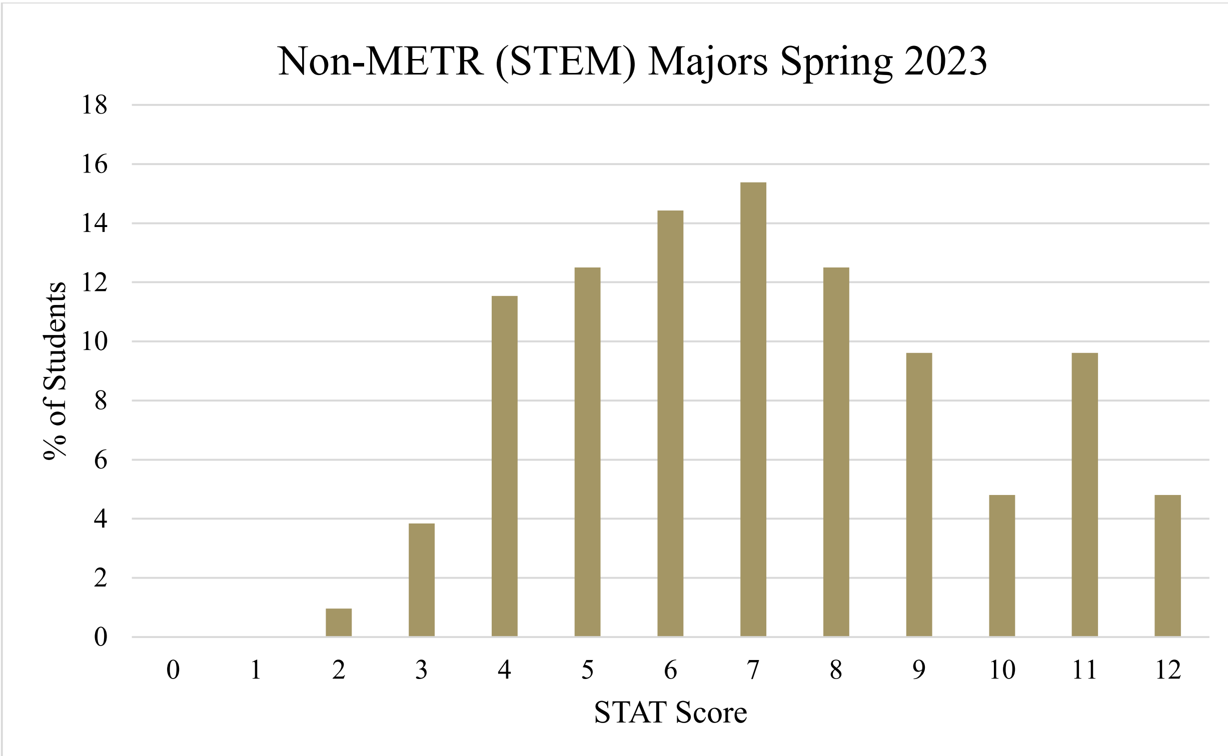


Figure 4. 18: *Frequency distribution for Non- Meteorology (STEM) Majors pre-test in the Spring 2023 semester.*

Meteorology vs. Non-Meteorology vs. Non-Meteorology (STEM) Spring 2023			
	METR Majors	***Non-METR Majors***	***Non-METR (STEM) Majors***
Statistics	**Pre-Test** (n = 37)	**Pre-Test** (n = 268)	**Pre-Test** (n = 104)
Mean	8.49	6.72	7.14
Median	9	7	7
Mode	9	6	7
Range	9	11	10
Skewness	-0.410	0.152	0.246
Standard Deviation	2.14	2.37	2.50

Table 4. 7: *Summary statistics on STAT performance for METR Majors, Non-METR Majors, and Non-METR (STEM) Majors in the Spring 2023 semester.*

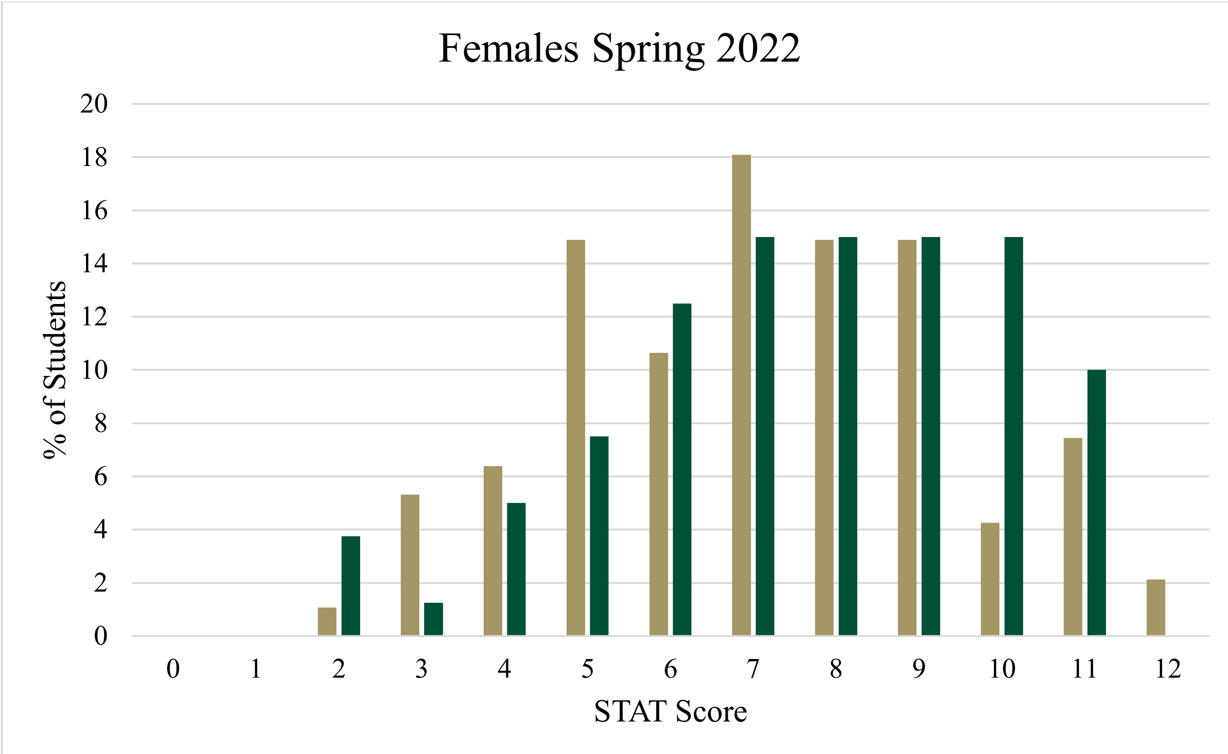


Figure 4. 19: *Frequency distribution of Females in the Spring 2022 semester. The graph shows the pre-test results in gold, and the post-test results in green.*

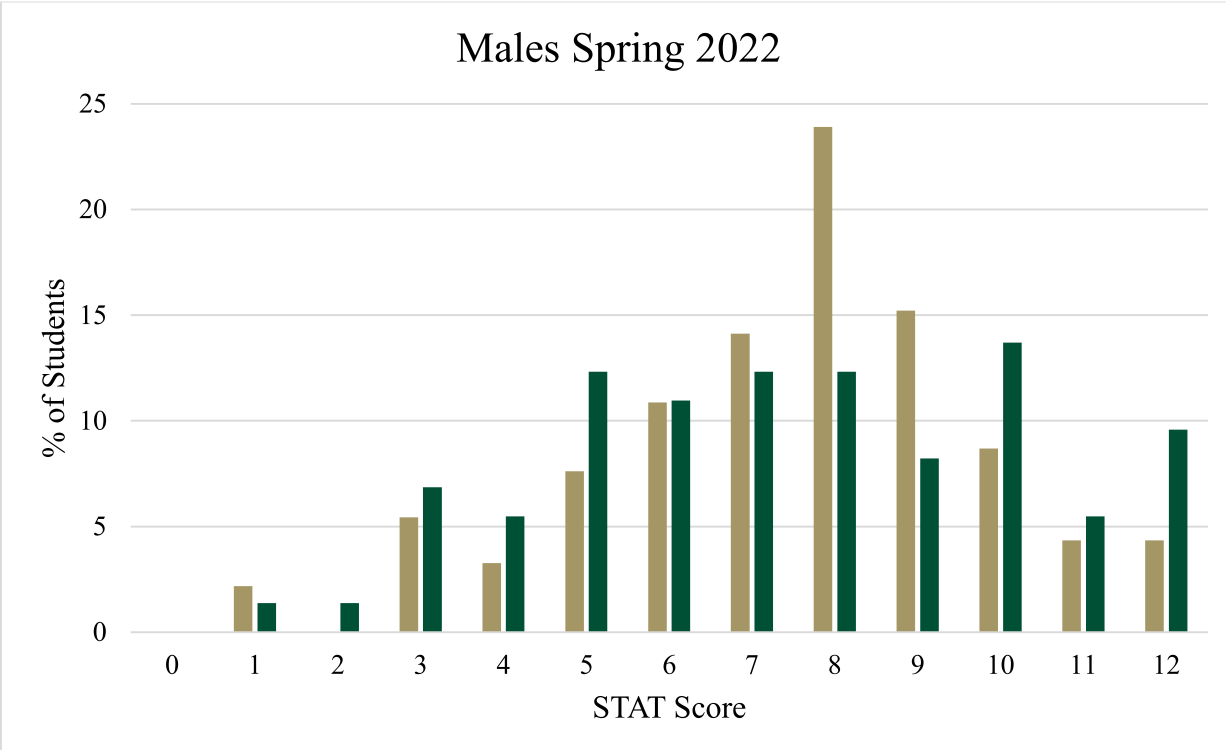


Figure 4. 20: *Frequency distribution of Males in the Spring 2022 semester. The graph shows the pre-test results in gold, and the post-test results in green.*

Females vs. Males Spring 2022				
	Females		***Males***	
Statistics	**Pre-Test** (n = 80)	**Post-Test** (n = 94)	**Pre-Test** (n = 92)	**Post-Test** (n = 73)
Mean	7.12	7.64	7.49	7.45
Median	7	8	8	7
Mode	7	9	8	10
Range	10	9	11	11
Skewness	0.027	-0.514	-0.468	-0.108
Standard Deviation	2.30	2.32	2.365	2.81

Table 4. 8: *Summary statistics on STAT performance for Females and Males in the Spring 2022 semester.*

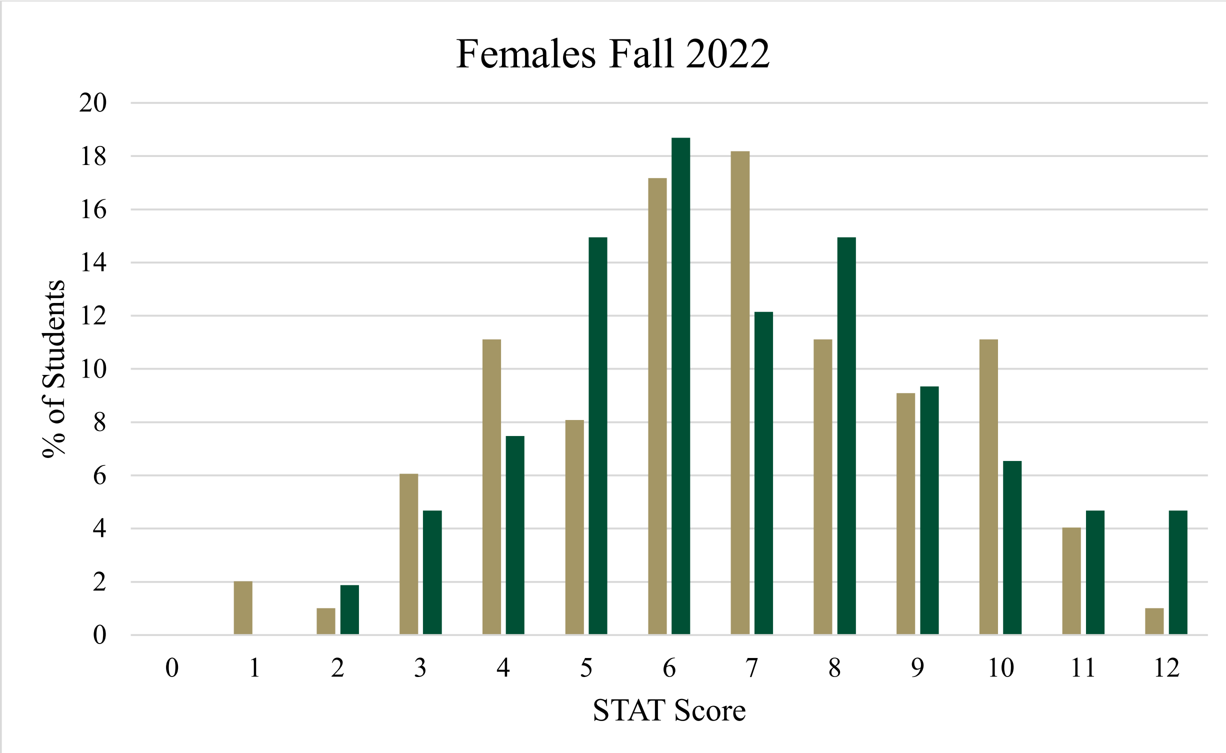


Figure 4. 21: *Frequency distribution of Females in the Fall 2022 semester. The graph shows the pre-test results in gold, and the post-test results in green.*

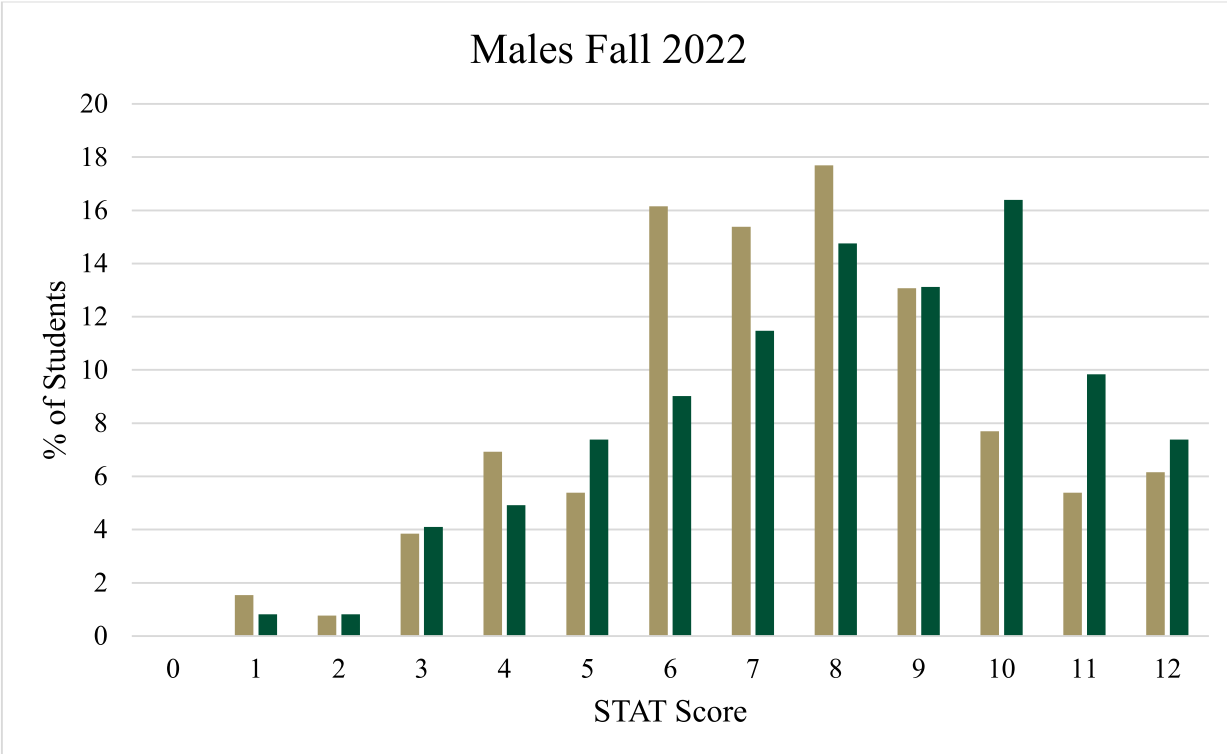


Figure 4. 22: *Frequency distribution of Males in the Fall 2022 semester. The graph shows the pre-test results in gold, and the post-test results in green.*

Females vs. Males Fall 2022				
	Females		***Males***	
Statistics	**Pre-Test** (n = 99)	**Post-Test** (n = 107)	**Pre-Test** (n = 130)	**Post-Test** (n = 122)
Mean	6.76	6.96	7.43	8.0
Median	7	7	7.5	8
Mode	7	6	8	10
Range	11	10	11	11
Skewness	-0.105	0.254	-0.178	-0.449
Standard Deviation	2.41	2.40	2.45	2.56

Table 4. 9: *Summary statistics on STAT performance for Females and Males in the Fall 2022 semester.*

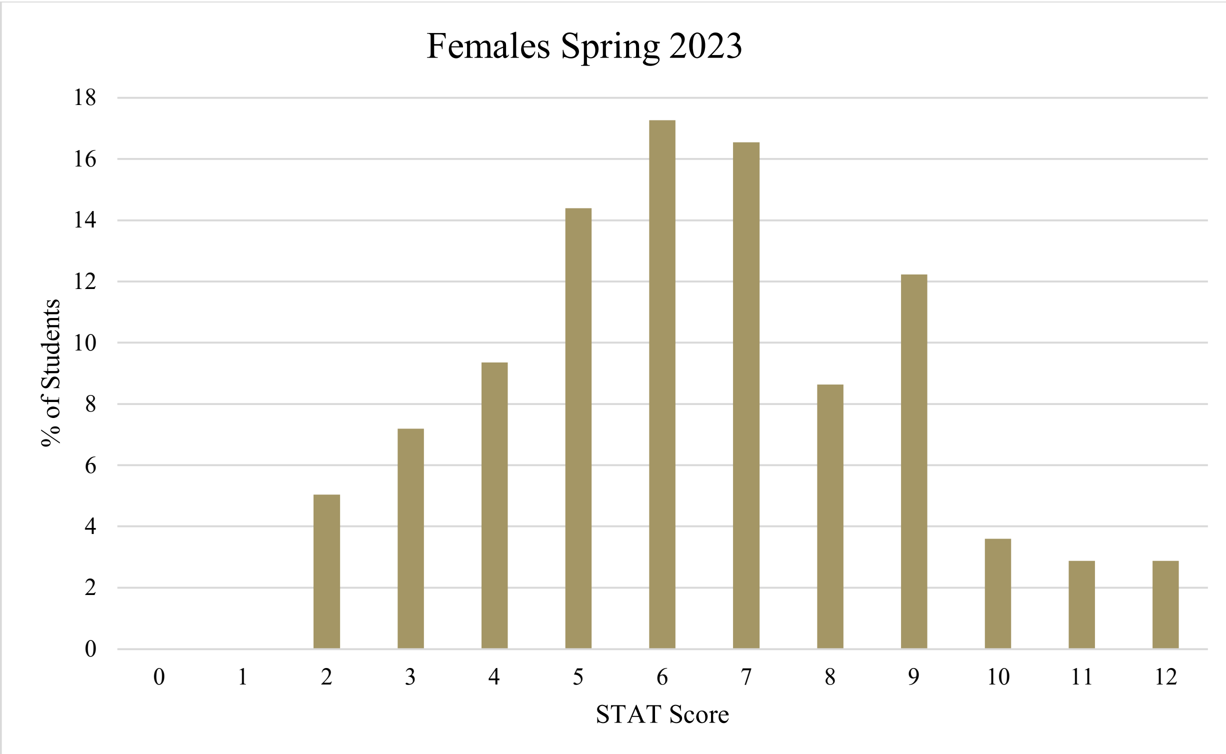


Figure 4. 23: *Frequency distribution for Females pre-test in the Spring 2023 semester.*

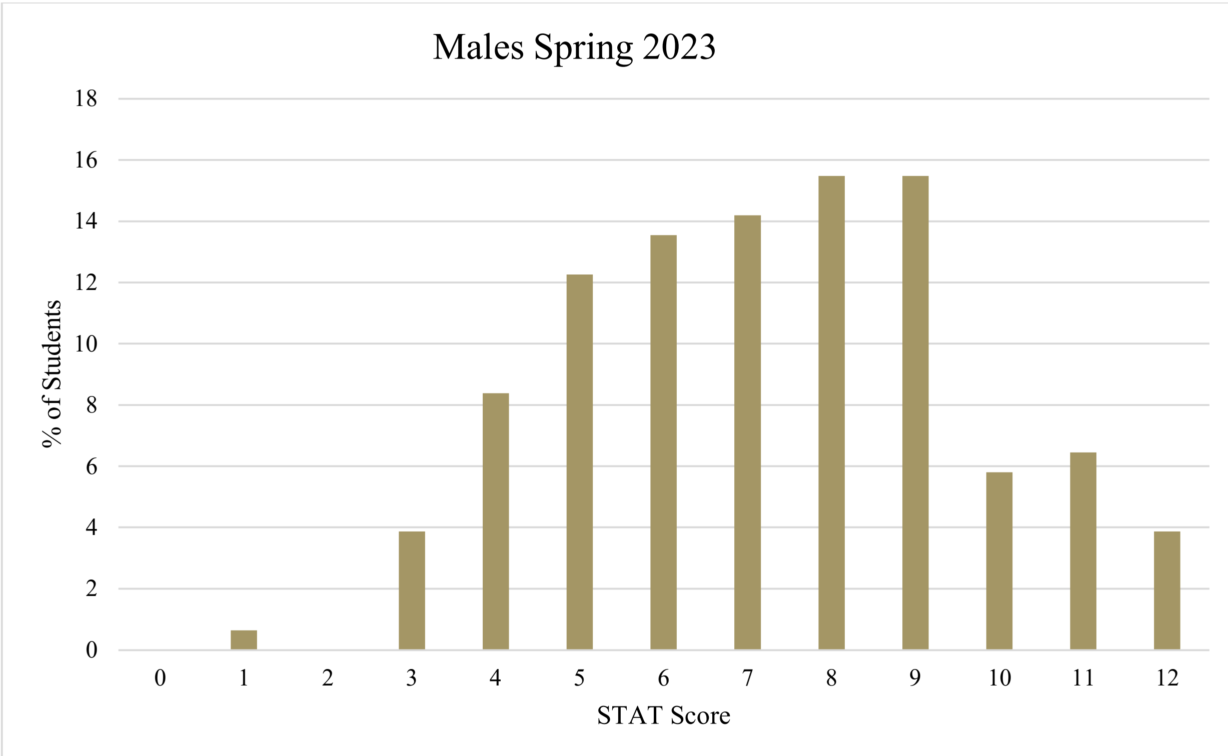


Figure 4. 24: *Frequency distribution for Males pre-test in the Spring 2023 semester.*

Females vs. Males Spring 2023		
	Females	***Males***
Statistics	**Pre-Test** (n = 139)	**Pre-Test** (n = 155)
Mean	6.42	7.26
Median	6	7
Mode	6	8
Range	10	11
Skewness	0.218	0.026
Standard Deviation	2.40	2.34

Table 4. 10: *Summary statistics on STAT performance for Females and Males in the Spring 2023 semester.*

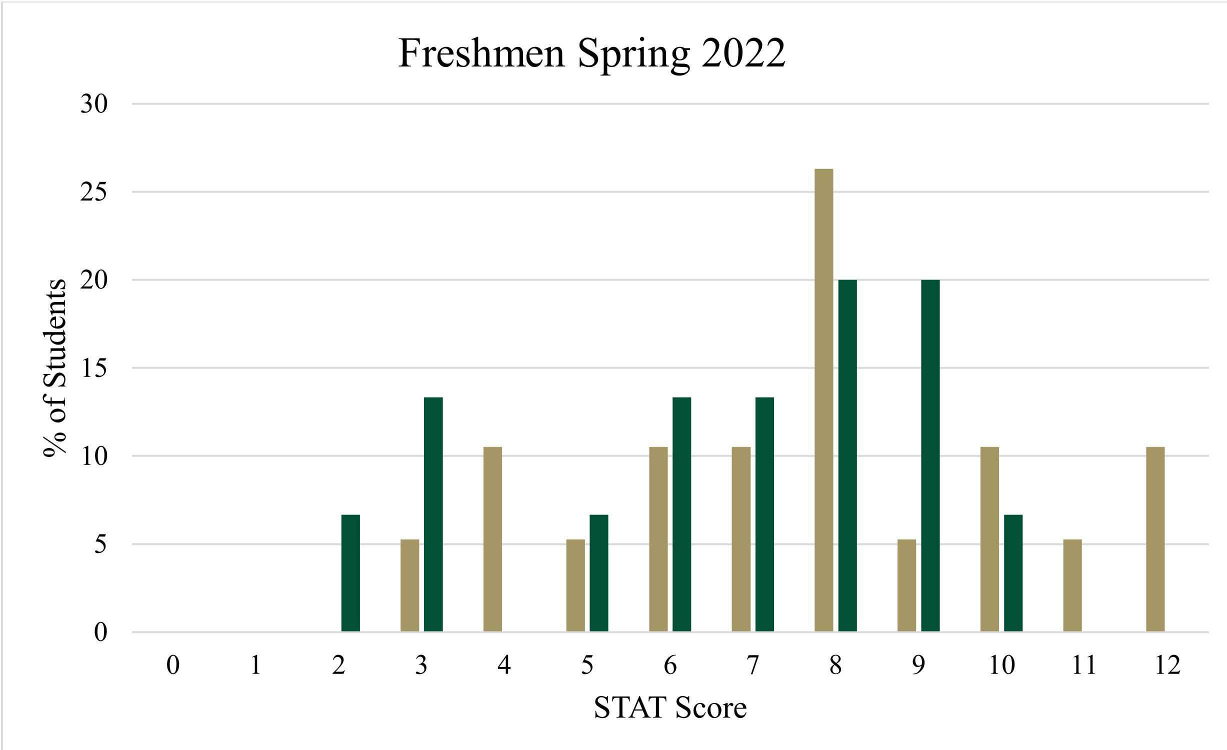


Figure 4. 25: *Frequency distribution of Freshmen in the Spring 2022 semester. The graph shows the pre-test results in gold, and the post-test results in green.*

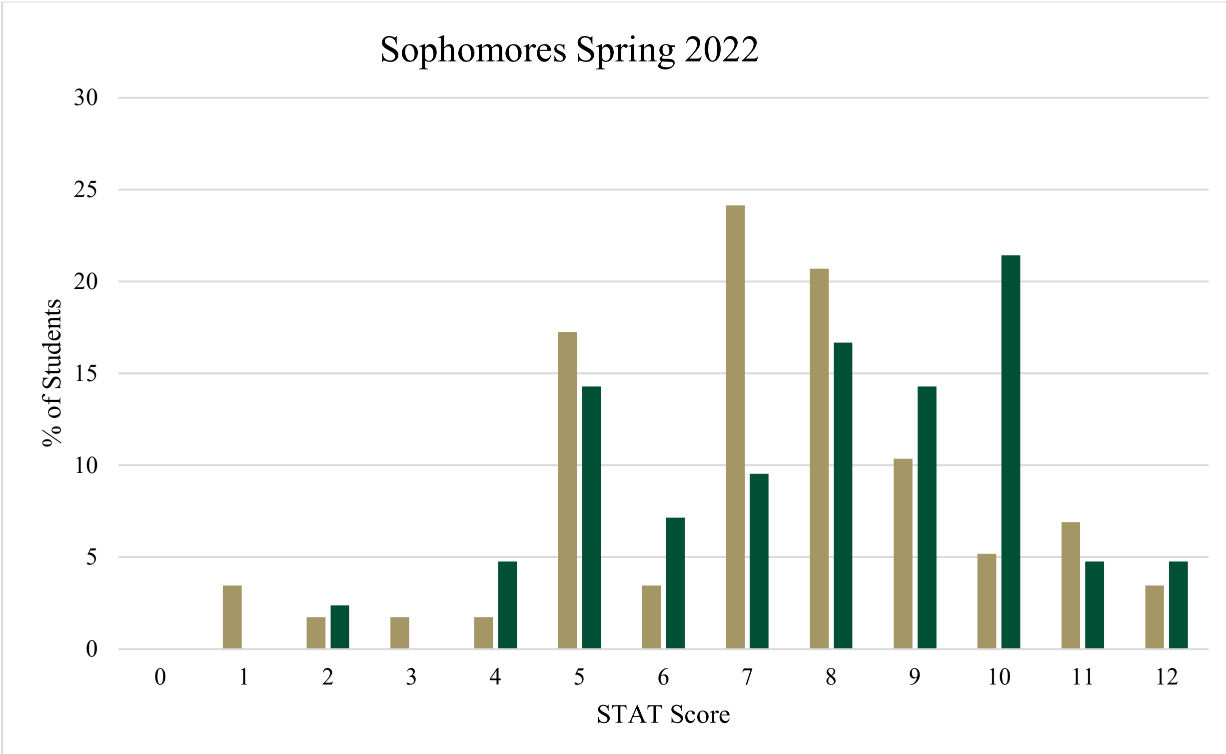


Figure 4. 26: *Frequency distribution of Sophomores in the Spring 2022 semester. The graph shows the pre-test results in gold, and the post-test results in green.*

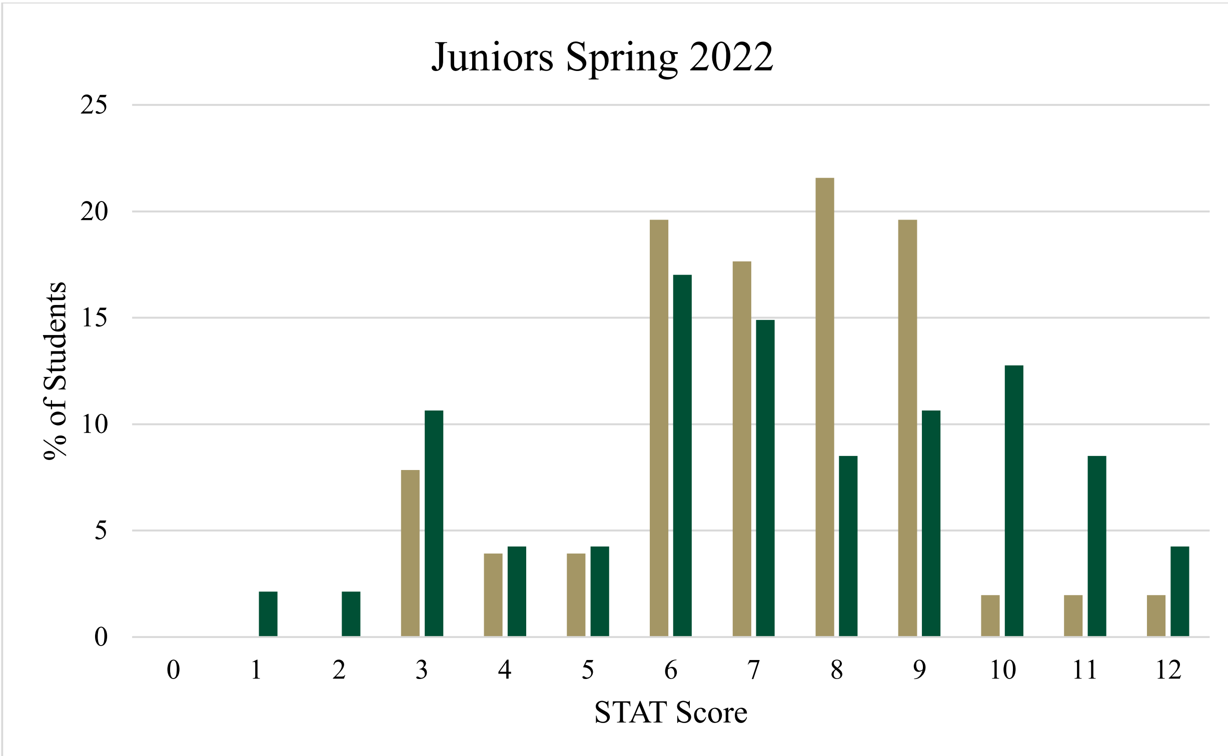


Figure 4. 27: *Frequency distribution of Juniors in the Spring 2022 semester. The graph shows the pre-test results in gold, and the post-test results in green.*

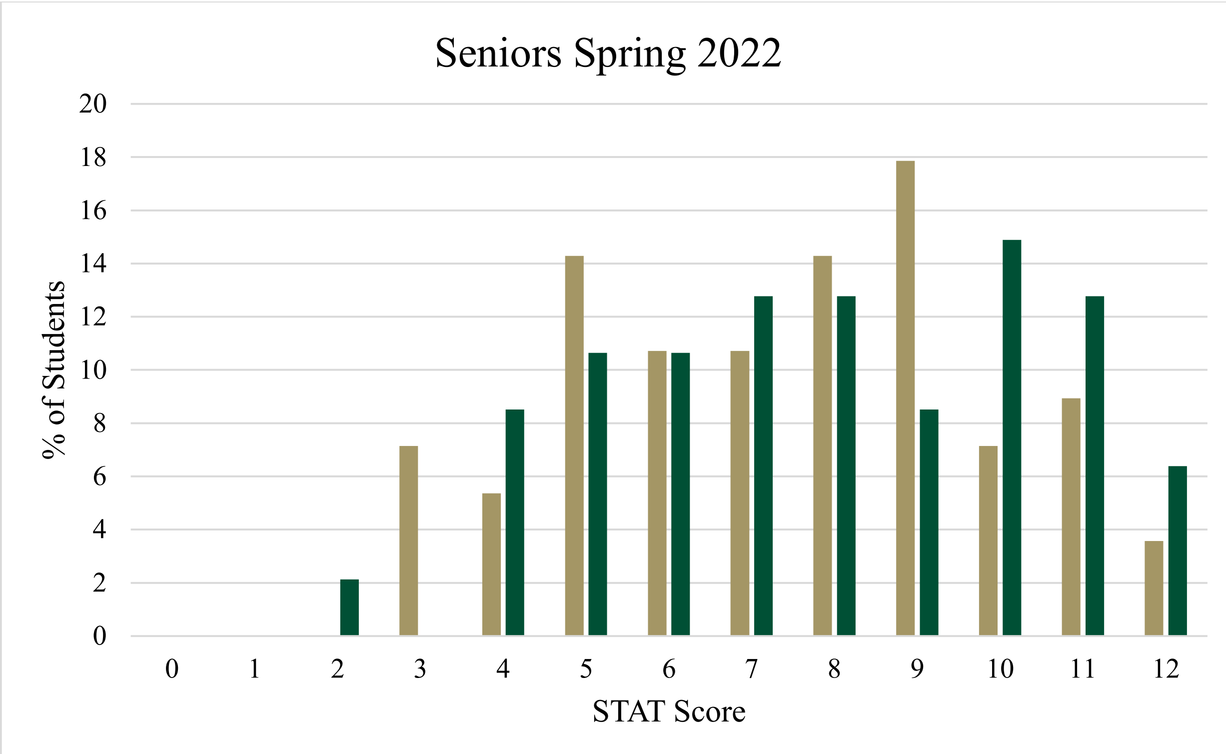


Figure 4. 28: *Frequency distribution of Seniors in the Spring 2022 semester. The graph shows the pre-test results in gold, and the post-test results in green.*

Grade Levels in the Spring 2022 Semester								
	Freshmen		***Sophomores***		***Juniors***		***Seniors***	
Statistics	**Pre-Test** (n = 19)	**Post-Test** (n = 15)	**Pre-Test** (n = 58)	**Post-Test** (n = 42)	**Pre-Test** (n = 51)	**Post-Test** (n = 47)	**Pre-Test** (n = 56)	**Post-Test** (n = 47)
Mean	7.68	6.67	7.22	7.90	7.14	7.19	7.41	7.89
Median	8	7	7	8	7	7	8	8
Mode	8	9	7	10	8	6	9	10
Range	9	8	11	10	9	11	9	10
Skewness	-0.027	-0.674	-0.391	-0.403	-0.290	-0.241	-0.071	-0.189
Standard Deviation	2.63	2.47	2.44	2.37	2.00	2.82	2.46	2.57

Table 4. 11: *Summary statistics on STAT performance for Freshmen, Sophomores, Juniors and Seniors in the Spring 2022 semester.*

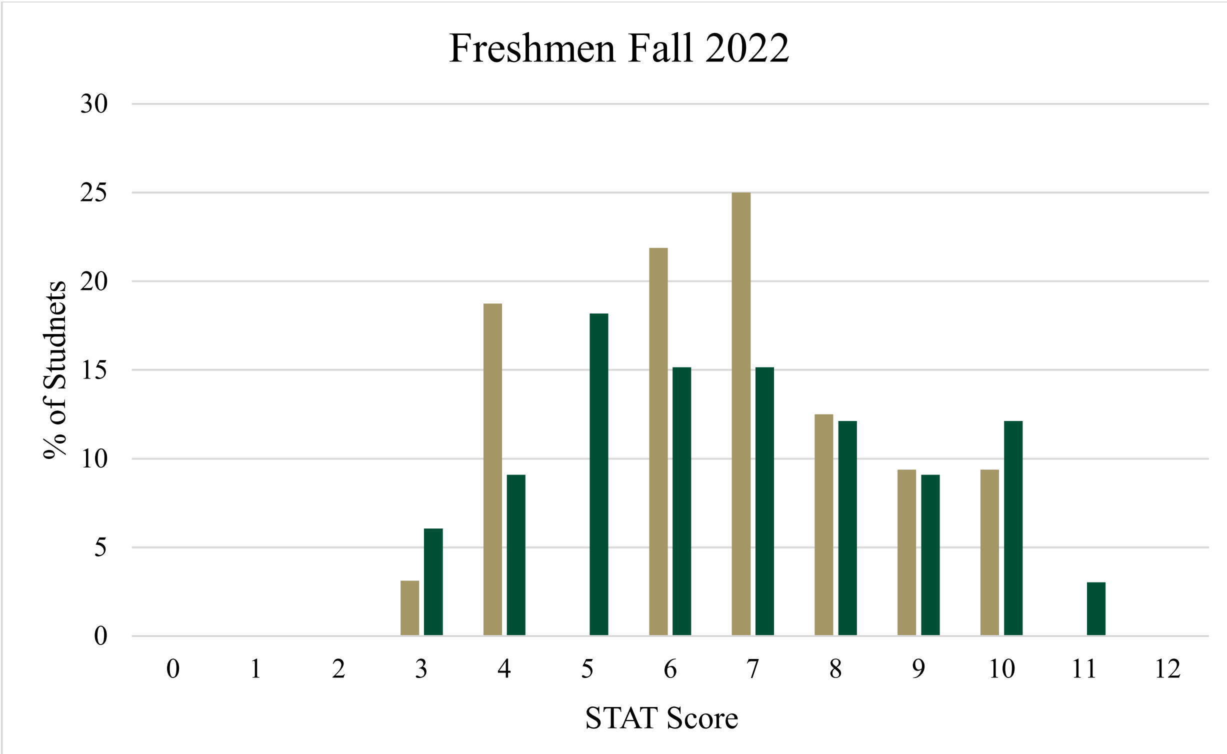


Figure 4. 29*: Frequency distribution of Freshmen in the Fall 2022 semester. The graph shows the pre-test results in gold, and the post-test results in green.*

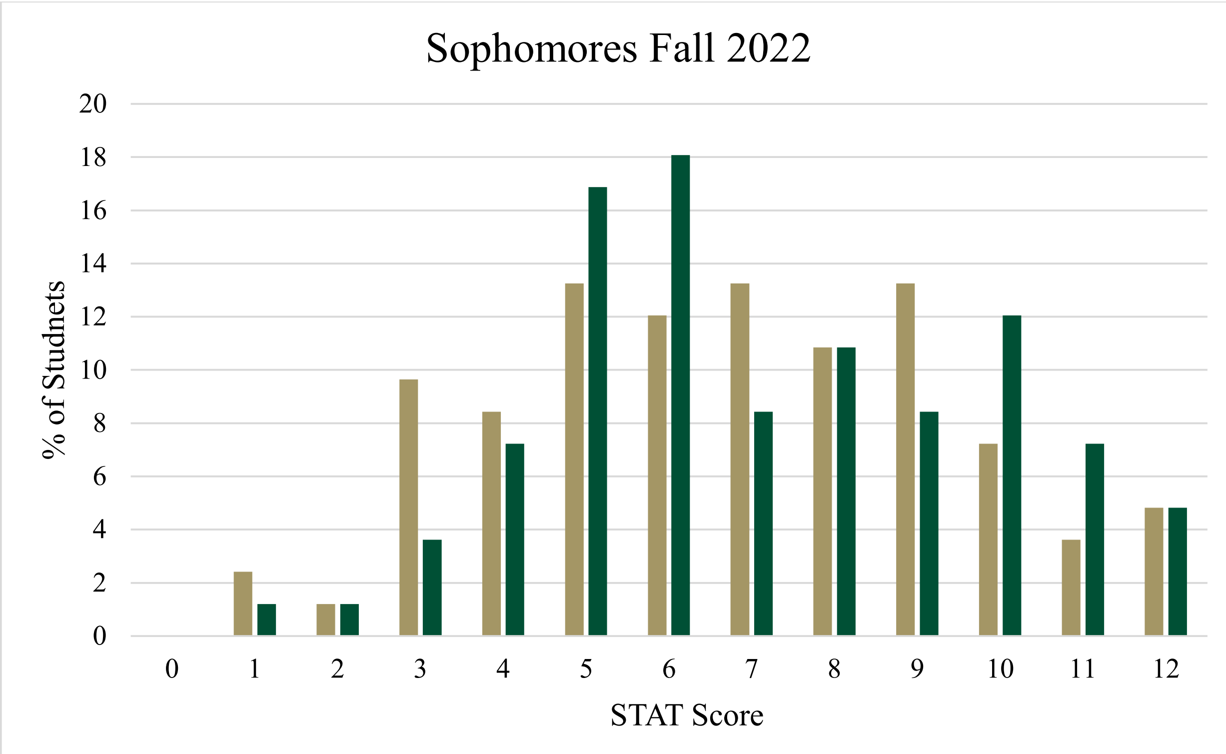


Figure 4. 30: *Frequency distribution of Sophomores in the Fall 2022 semester. The graph shows the pre-test results in gold, and the post-test results in green.*

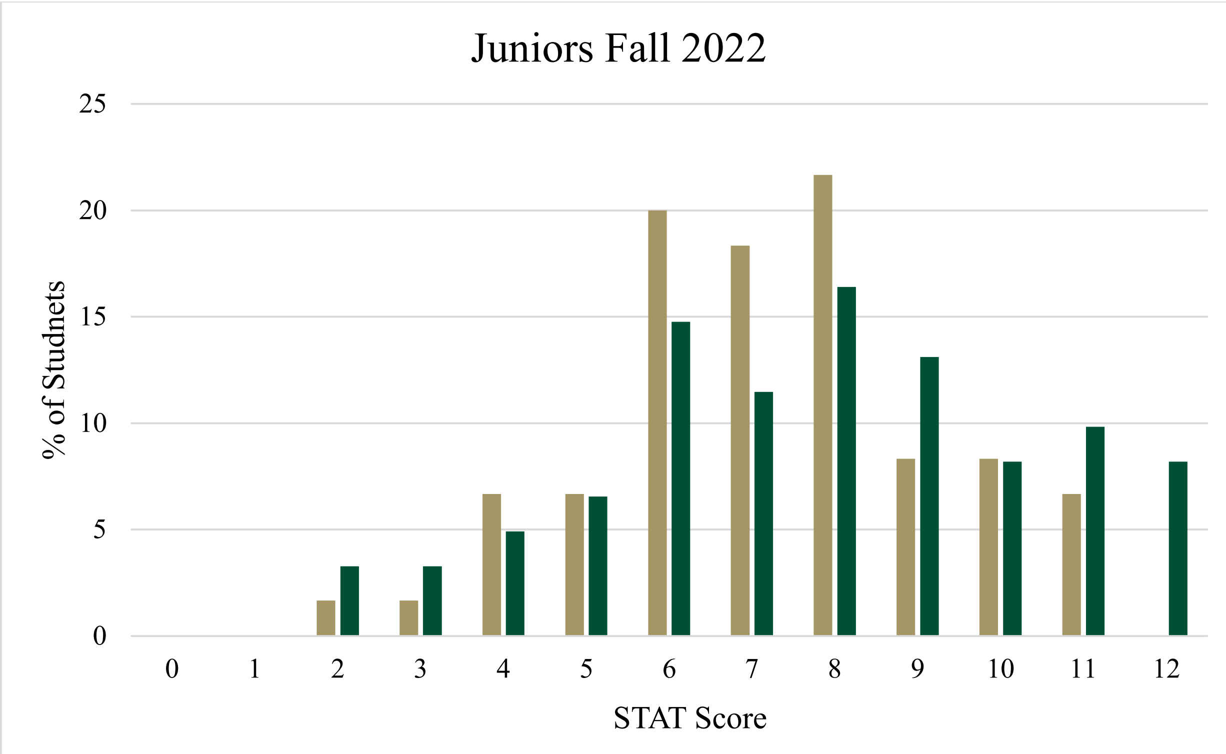


Figure 4. 31: *Frequency distribution of Juniors in the Fall 2022 semester. The graph shows the pre-test results in gold, and the post-test results in green.*

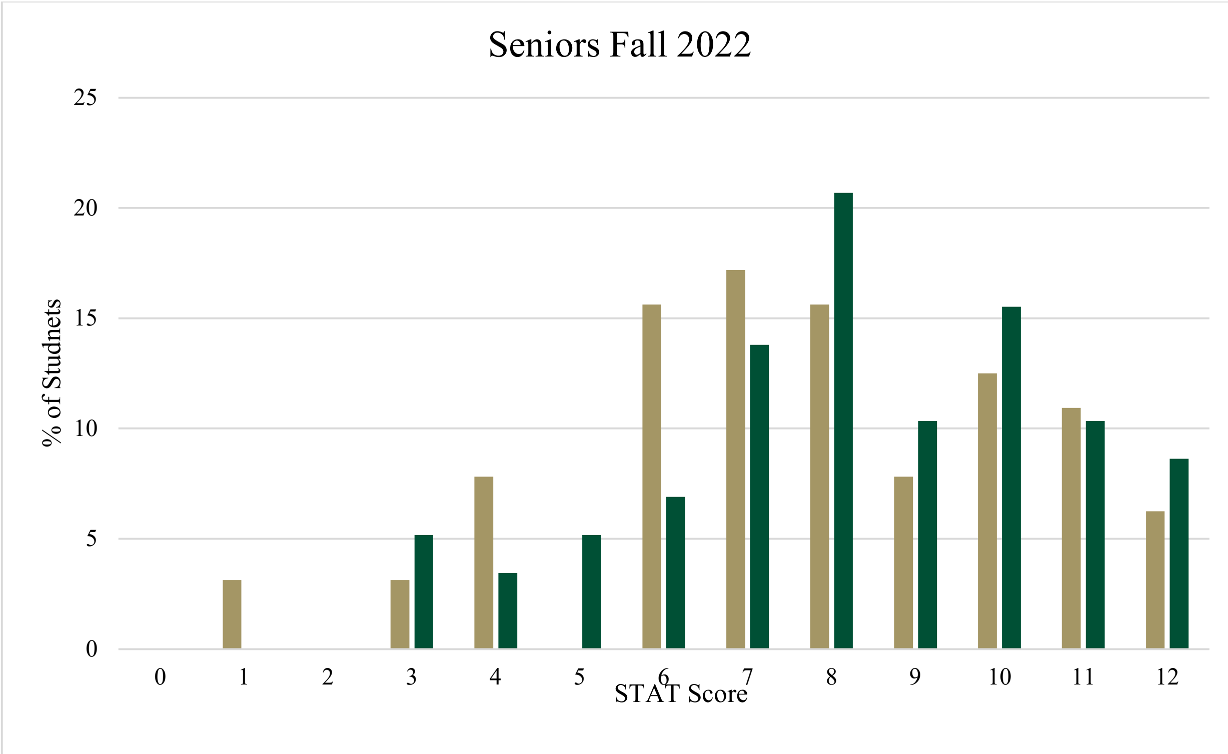


Figure 4. 32: *Frequency distribution of Senior in the Fall 2022 semester. The graph shows the pre-test results in gold, and the post-test results in green.*

Grade Levels in the Fall 2022 Semester								
	Freshmen		***Sophomores***		***Juniors***		***Seniors***	
Statistics	**Pre-Test** (n = 32)	**Post-Test** (n = 33)	**Pre-Test** (n = 83)	**Post-Test** (n = 83)	**Pre-Test** (n = 60)	**Post-Test** (n = 61)	**Pre-Test** (n = 64)	**Post-Test** (n = 58)
Mean	6.69	6.76	6.75	7.16	7.22	7.75	7.73	8.24
Median	7	7	7	7	7	8	8	8
Mode	7	5	7	6	8	8	7	8
Range	7	8	11	11	9	10	11	9
Skewness	-0.063	0.159	0.029	0.096	-0.117	-0.224	-0.430	-0.396
Standard Deviation	1.94	2.19	2.69	2.60	2.03	2.61	2.64	2.41

Table 4. 12: *Summary statistics on STAT performance for Freshmen, Sophomores, Juniors and Seniors in the Fall 2022 semester.*

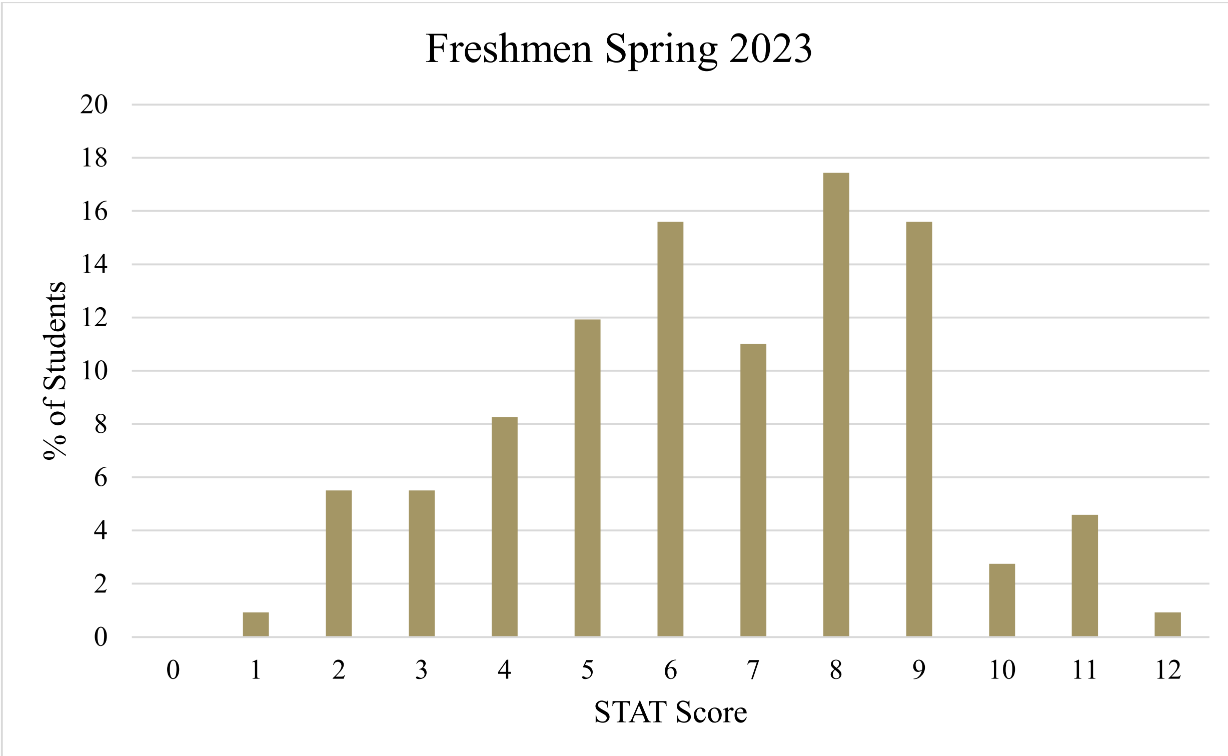


Figure 4. 33: *Frequency distribution for Freshmen pre-test in the Spring 2023 semester.*

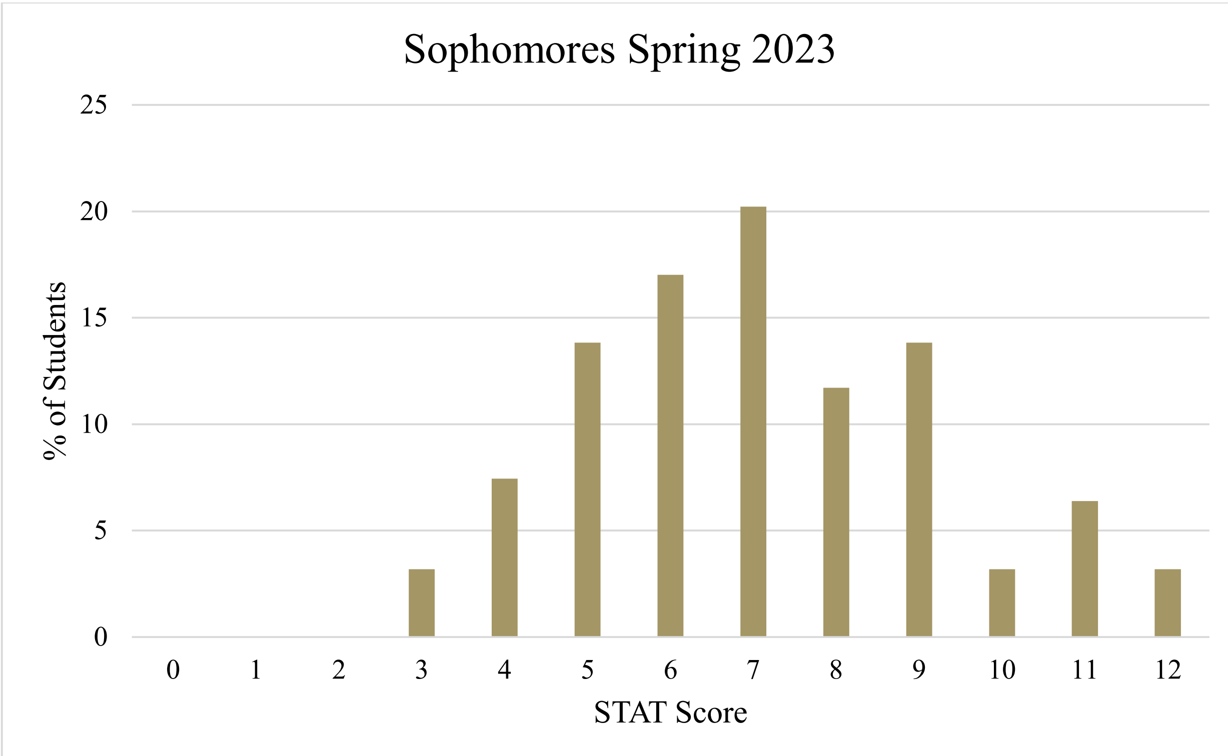


Figure 4. 34: *Frequency distribution for Sophomores pre-test in the Spring 2023 semester.*

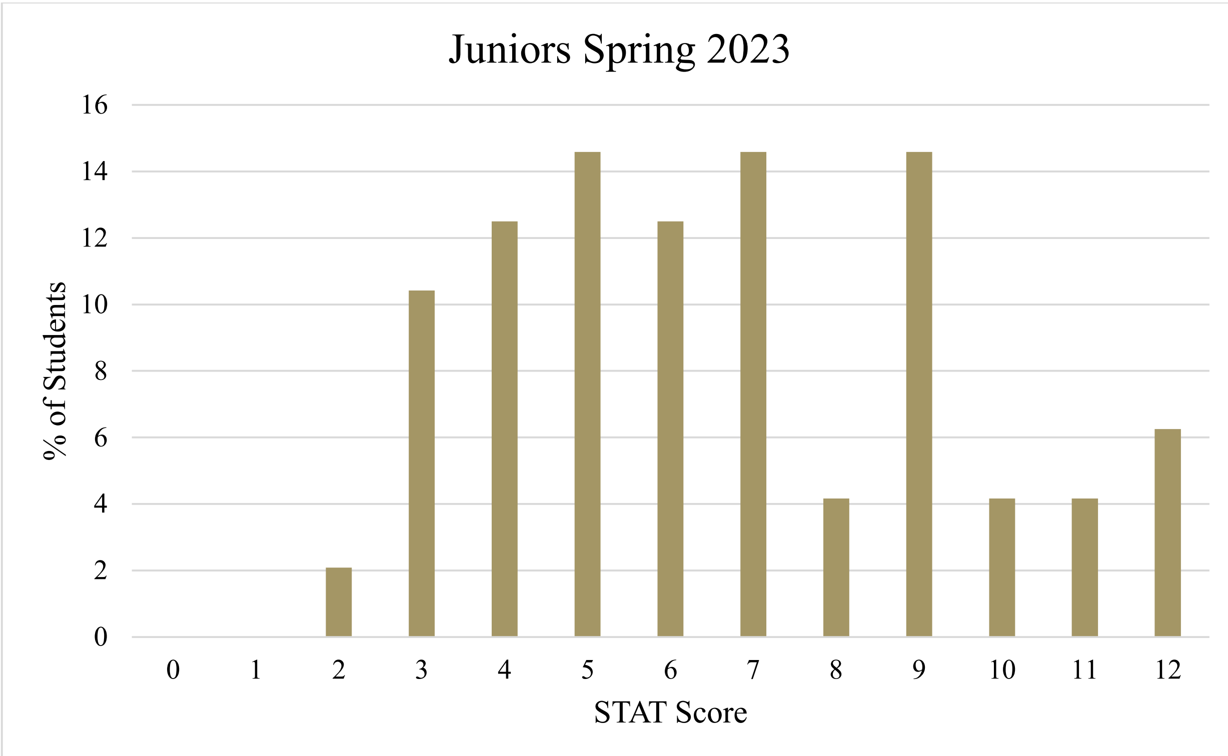


Figure 4. 35: *Frequency distribution for Juniors pre-test in the Spring 2023 semester.*

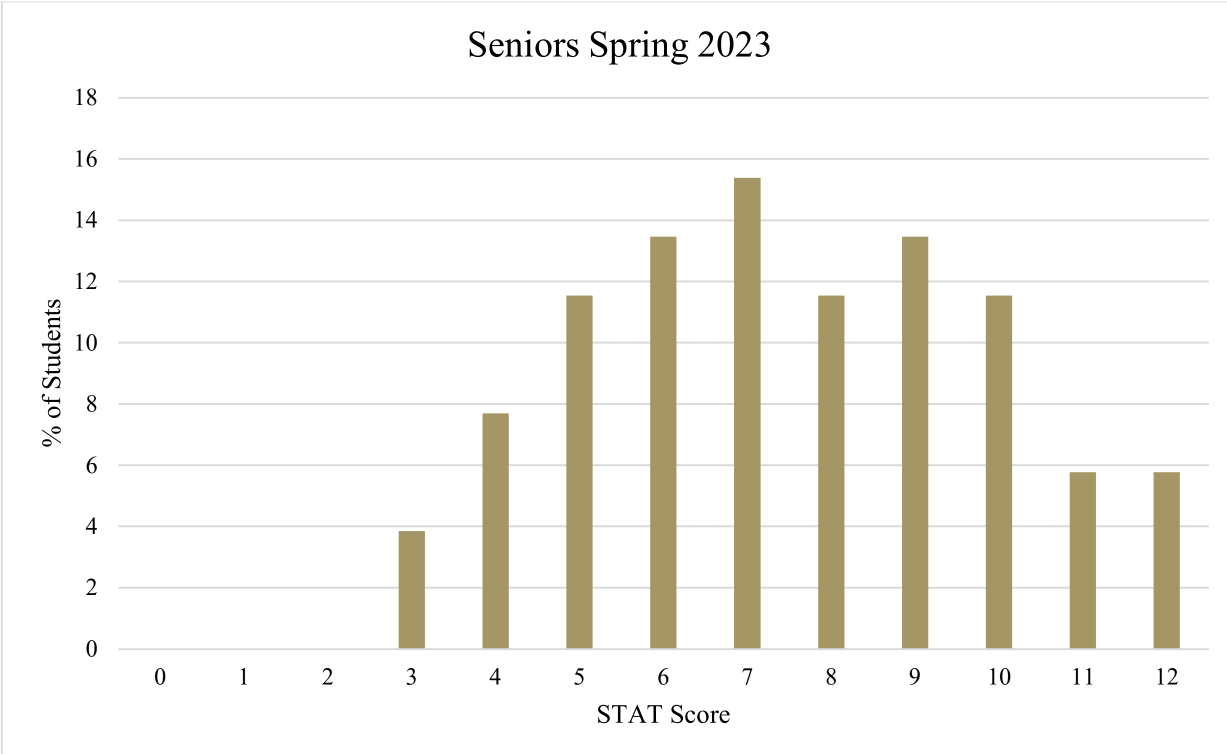


Figure 4. 36: *Frequency distribution for Seniors pre-test in the Spring 2023 semester.*

Grade Levels in the Spring 2023 Semester				
	Freshmen	***Sophomores***	***Juniors***	***Seniors***
Statistics	**Pre-Test** (n = 109)	**Pre-Test** (n = 94)	**Pre-Test** (n = 48)	**Pre-Test** (n = 52)
Mean	6.61	7.11	6.63	7.5
Median	7	7	6	7
Mode	8	7	5	7
Range	11	9	10	9
Skewness	-0.183	0.336	0.377	0.070
Standard Deviation	2.42	2.17	2.69	2.41

Table 4. 13: *Summary statistics on STAT performance for Freshmen, Sophomores, Juniors and Seniors in the Spring 2023 semester.*

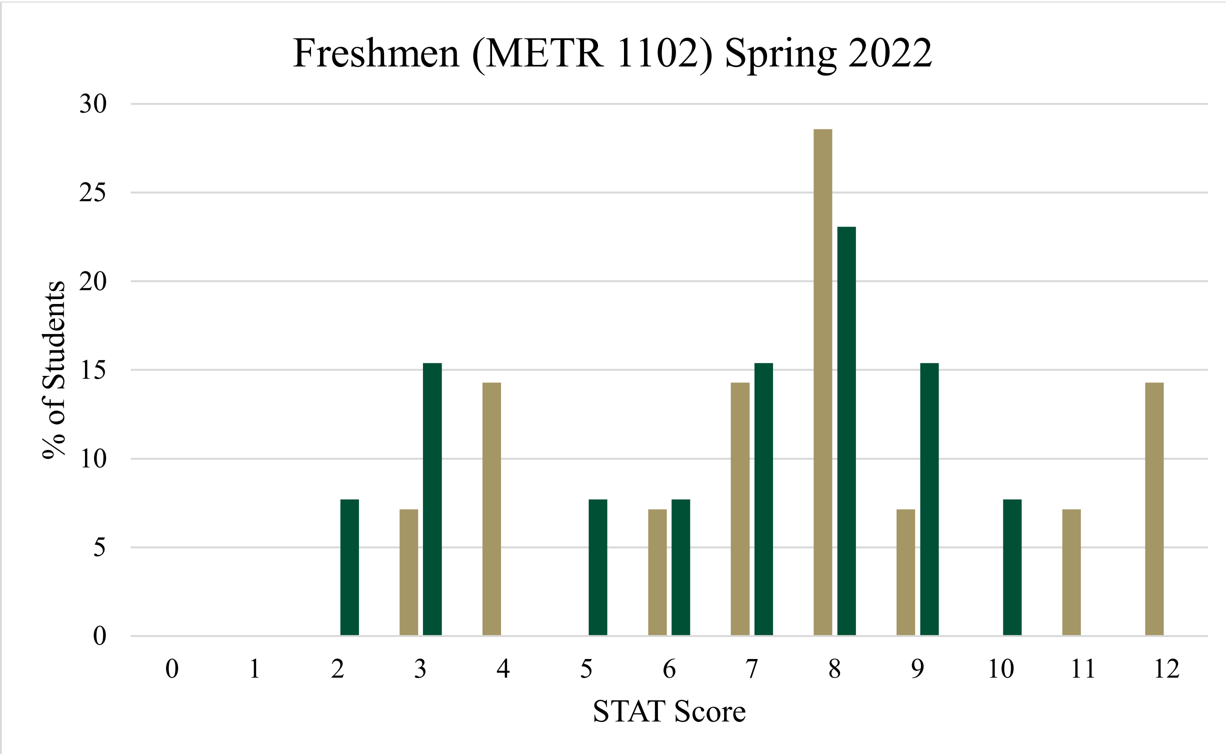


Figure 4. 37: *Frequency distribution of Freshmen (METR 1102) in the Spring 2022 semester. The graph shows the pre-test results in gold, and the post-test results in green.*

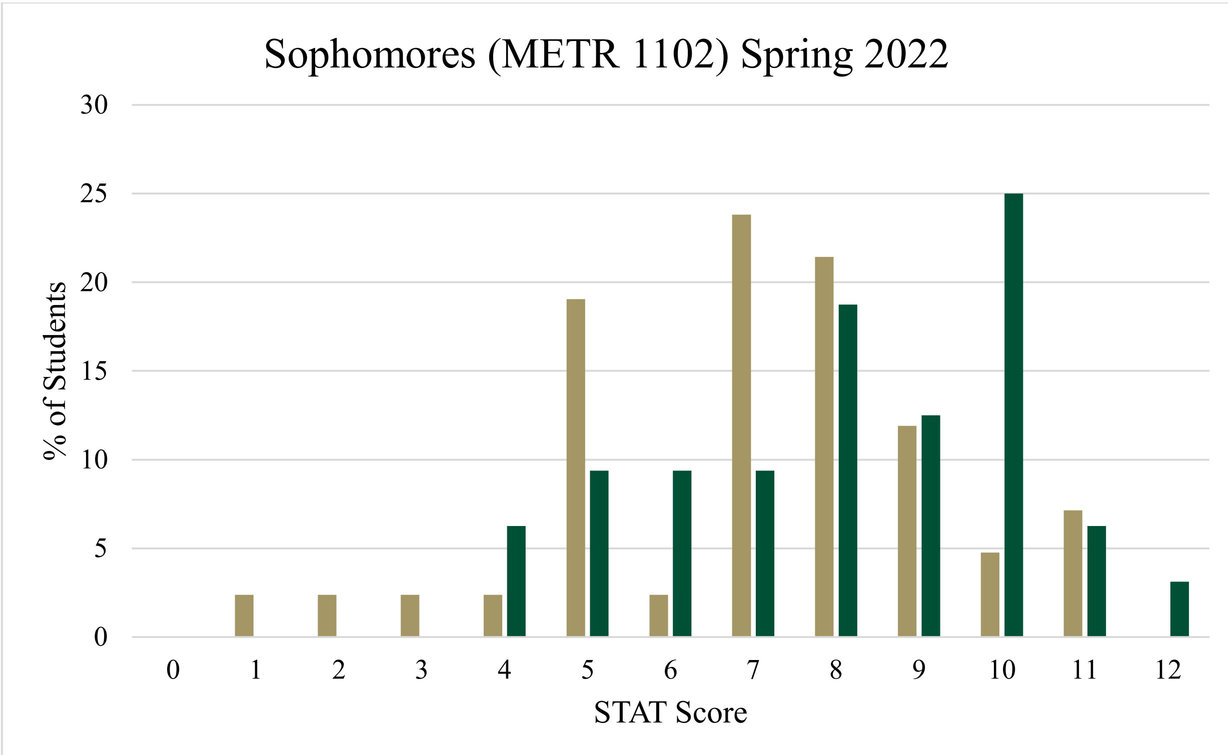


Figure 4. 38: *Frequency distribution of Sophomores (METR 1102) in the Spring 2022 semester. The graph shows the pre-test results in gold, and the post-test results in green.*

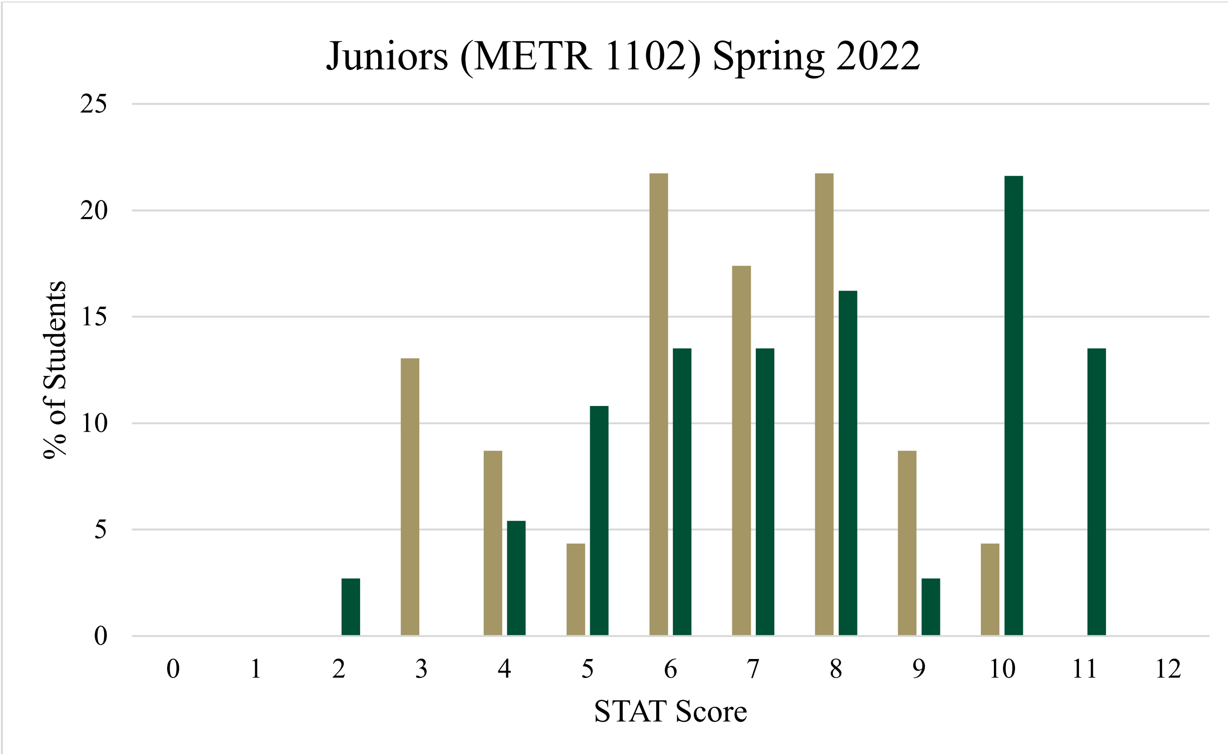


Figure 4. 39: *Frequency distribution of Junior (METR 1102) in the Spring 2022 semester. The graph shows the pre-test results in gold, and the post-test results in green.*

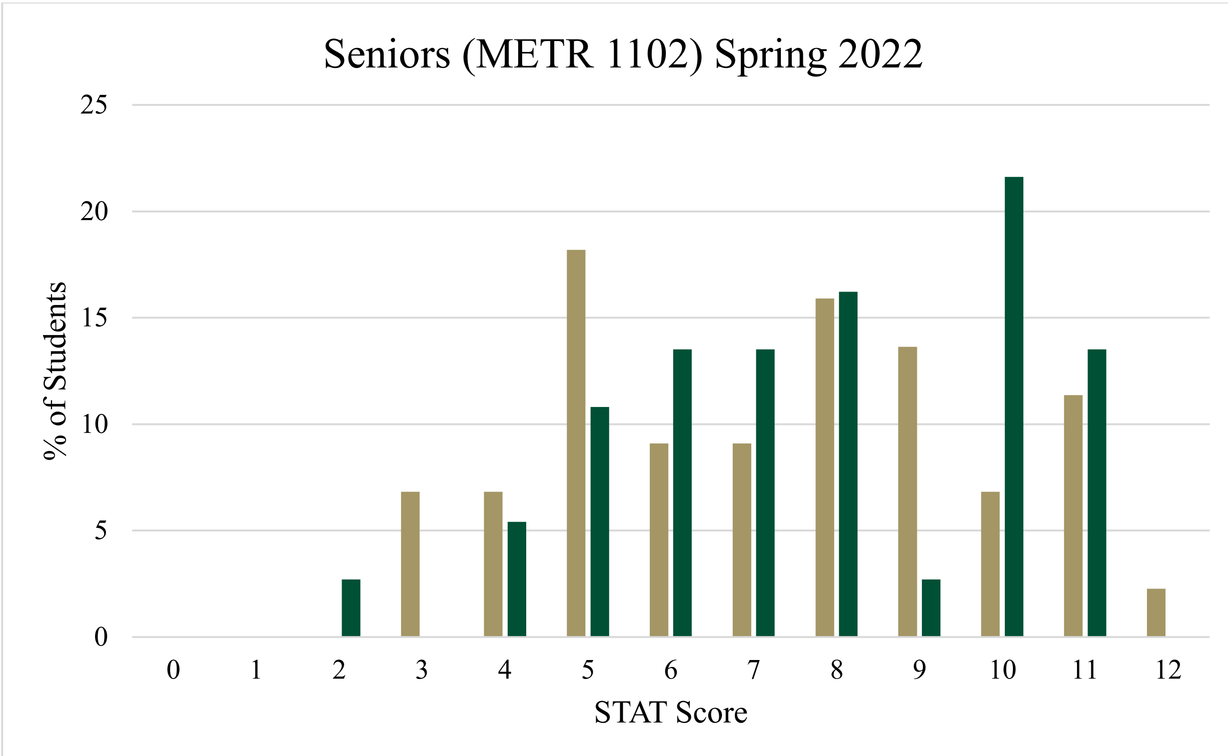


Figure 4. 40: *Frequency distribution of Seniors (METR 1102) in the Spring 2022 semester. The graph shows the pre-test results in gold, and the post-test results in green.*

METR 1102 Grade Levels in the Spring 2022 Semester								
	Freshmen		***Sophomores***		***Juniors***		***Seniors***	
Statistics	**Pre-Test** (n = 14)	**Post-Test** (n = 13)	**Pre-Test** (n = 42)	**Post-Test** (n = 32)	**Pre-Test** (n = 23)	**Post-Test** (n = 37)	**Pre-Test** (n = 44)	**Post-Test** (n = 37)
Mean	7.64	6.54	7.05	8.13	6.43	6.57	7.27	7.76
Median	8	7	7	8	7	6	7.5	8
Mode	8	8	7	10	6	6	5	10
Range	9	8	10	8	7	10	9	9
Skewness	0.017	-0.610	-0.50	-0.359	-0.332	-0.091	0.027	-0.318
Standard Deviation	2.82	2.57	2.28	2.15	2.02	2.92	2.51	2.39

Table 4. 14: *Summary statistics on STAT performance for Freshmen, Sophomores, Juniors and Seniors enrolled in Introduction to Meteorology (METR 1102) in the Spring 2022 semester.*

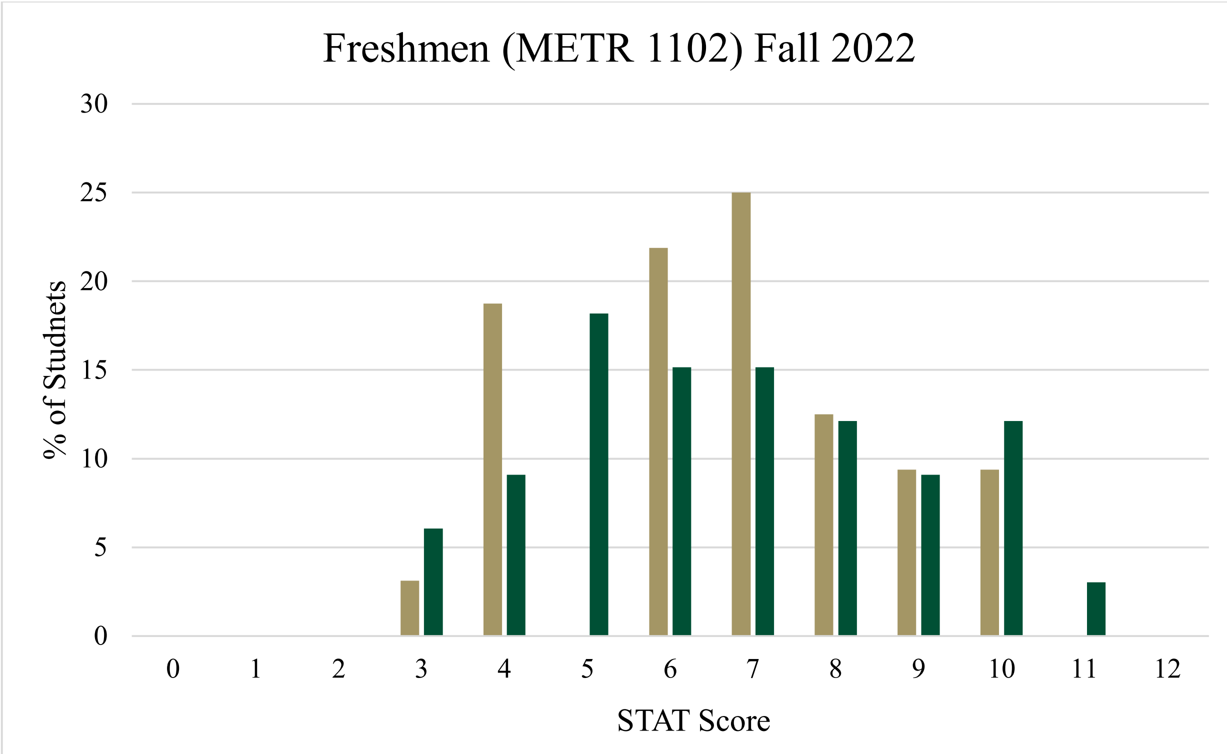


Figure 4. 41: *Frequency distribution of Freshmen (METR 1102) in the Fall 2022 semester. The graph shows the pre-test results in gold, and the post-test results in green.*

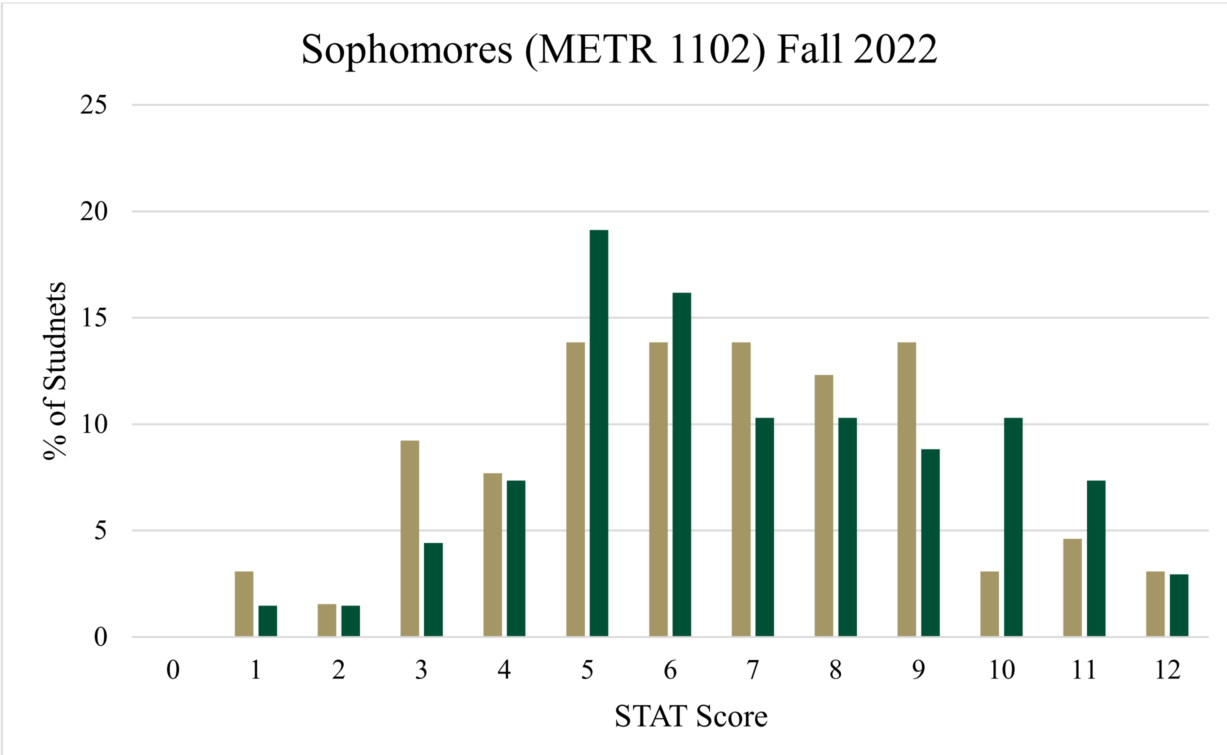


Figure 4. 42: *Frequency distribution of Sophomores (METR 1102) in the Fall 2022 semester. The graph shows the pre-test results in gold, and the post-test results in green.*

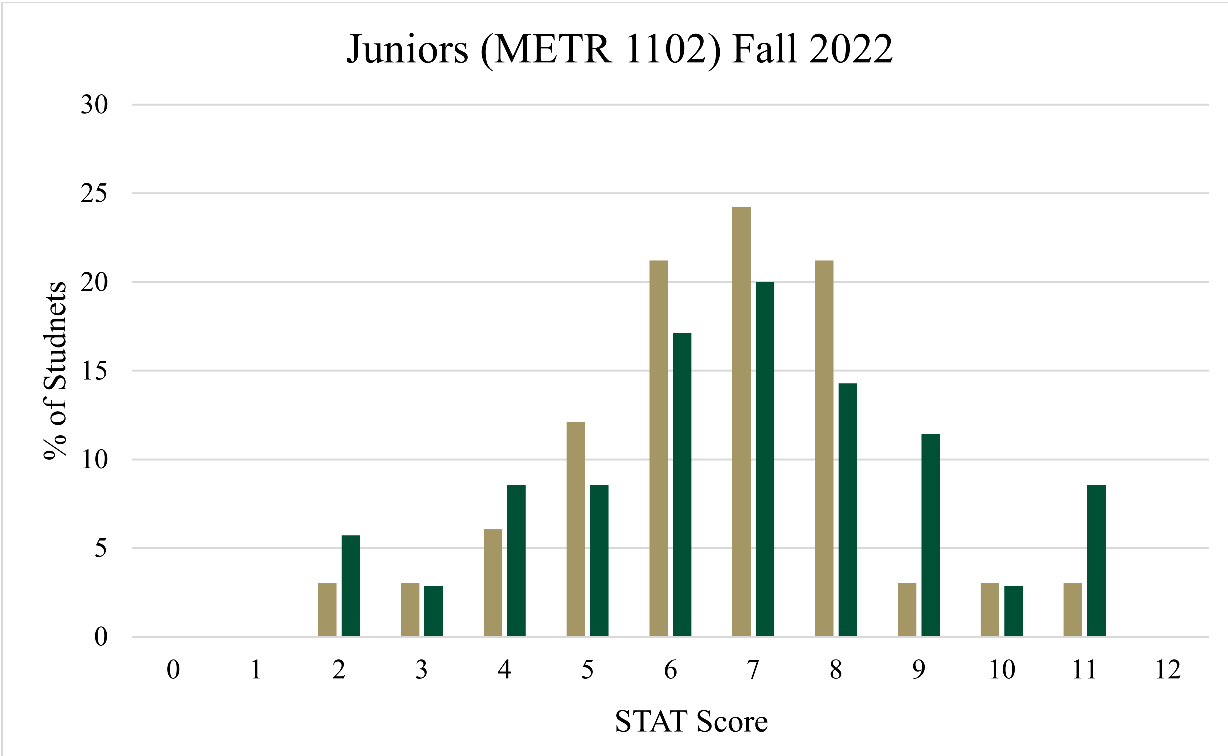


Figure 4. 43: *Frequency distribution of Juniors (METR 1102) in the Fall 2022 semester. The graph shows the pre-test results in gold, and the post-test results in green.*

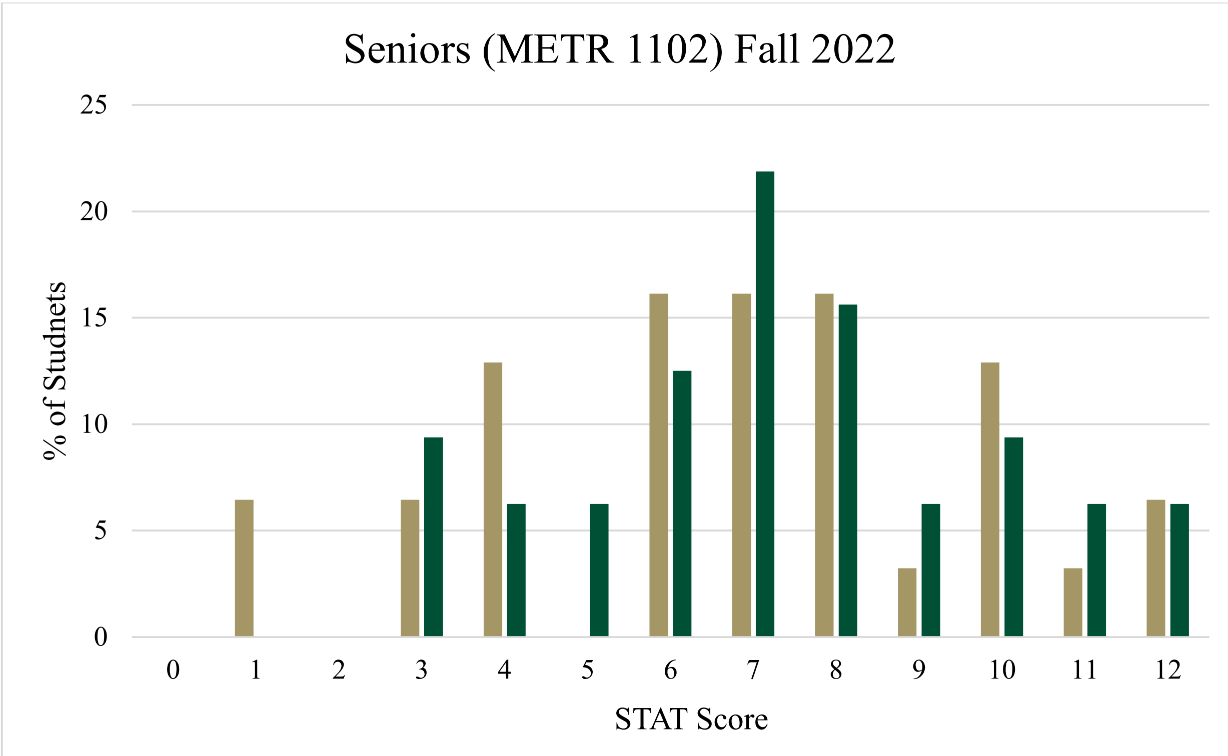


Figure 4. 44: *Frequency distribution of Seniors (METR 1102) in the Fall 2022 semester. The graph shows the pre-test results in gold, and the post-test results in green.*

METR 1102 Grade Levels in the Fall 2022 Semester								
	Freshmen		***Sophomores***		***Juniors***		***Seniors***	
Statistics	**Pre-Test** (n = 32)	**Post-Test** (n = 33)	**Pre-Test** (n = 65)	**Post-Test** (n = 68)	**Pre-Test** (n = 33)	**Post-Test** (n = 35)	**Pre-Test** (n = 31)	**Post-Test** (n = 32)
Mean	6.69	6.76	6.55	6.93	6.58	6.8	6.87	7.31
Median	7	7	7	6.5	7	7	7	7
Mode	7	5	7	5	7	7	6	7
Range	7	8	11	11	9	9	11	9
Skewness	-0.063	0.159	0.0004	0.117	-0.157	-0.135	-0.199	0.061
Standard Deviation	1.94	2.19	2.59	2.56	1.87	2.35	2.92	2.52

Table 4. 15: *Summary statistics on STAT performance for Freshmen, Sophomores, Juniors and Seniors enrolled in Introduction to Meteorology (METR 1102) in the Fall 2022 semester.*

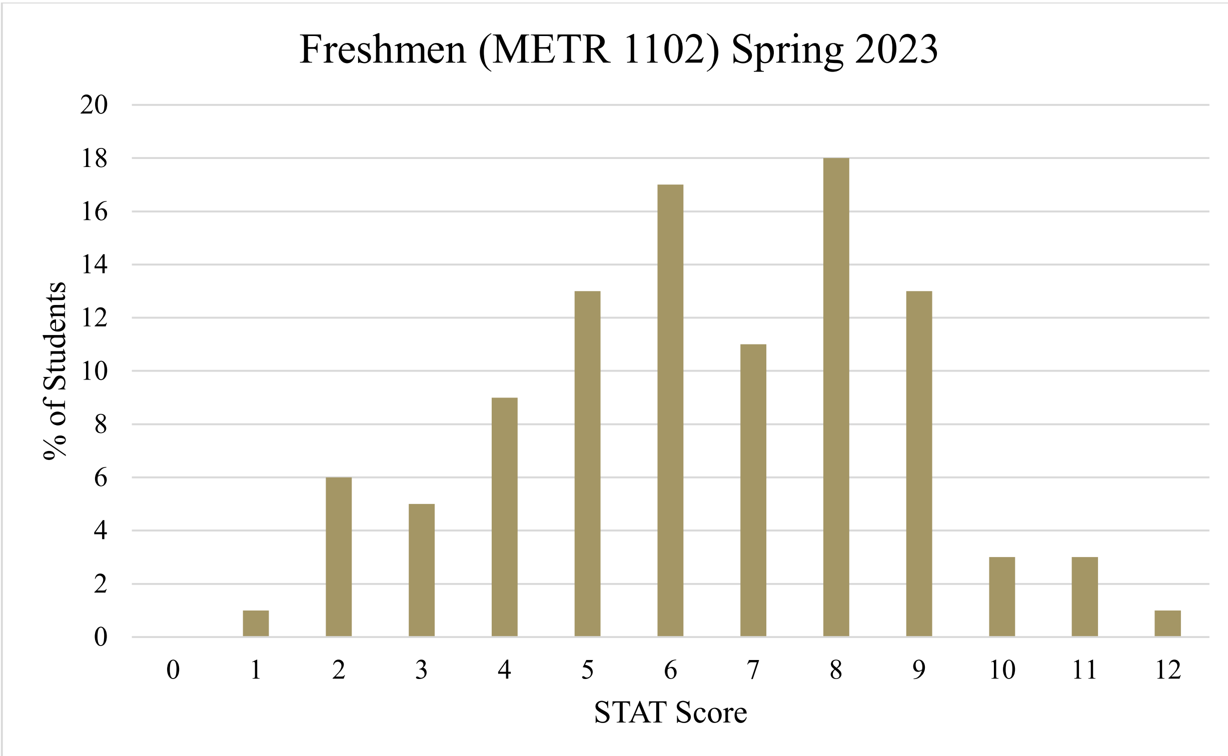


Figure 4. 45: *Frequency distribution for Freshmen (METR 1102) pre-test in the Spring 2023 semester.*

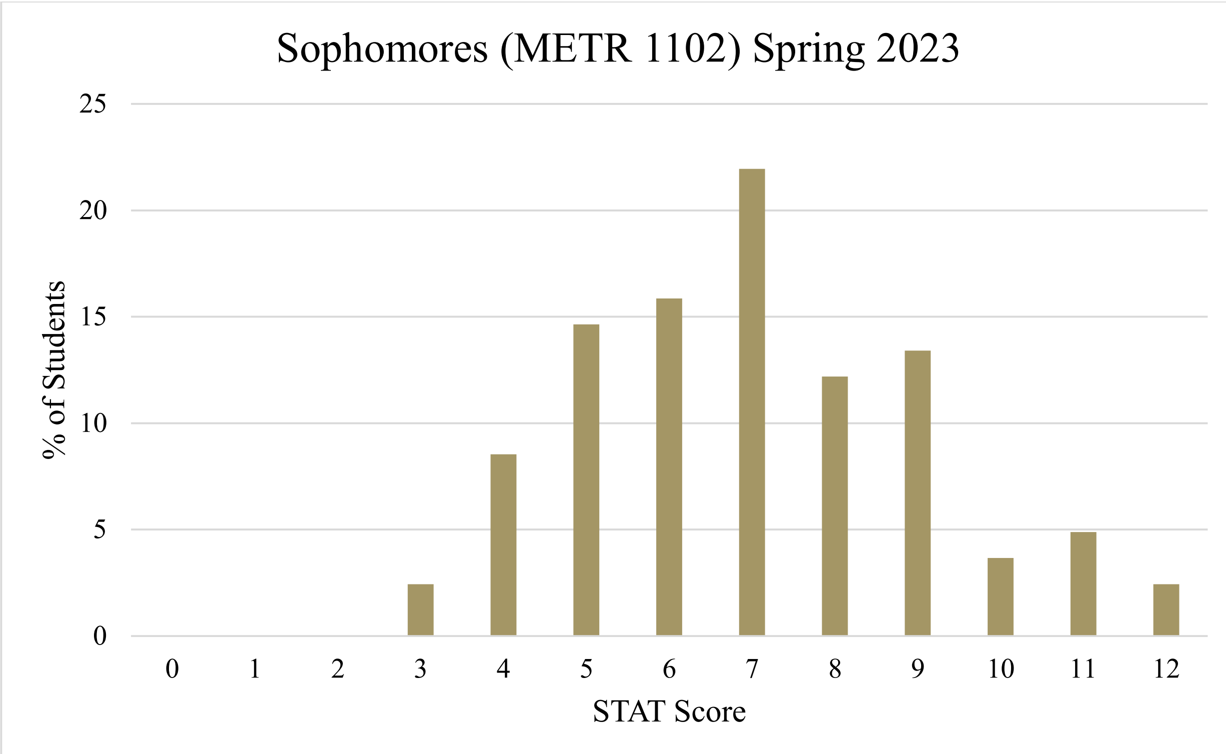


Figure 4. 46: *Frequency distribution for Sophomores (METR 1102) pre-test in the Spring 2023 semester.*

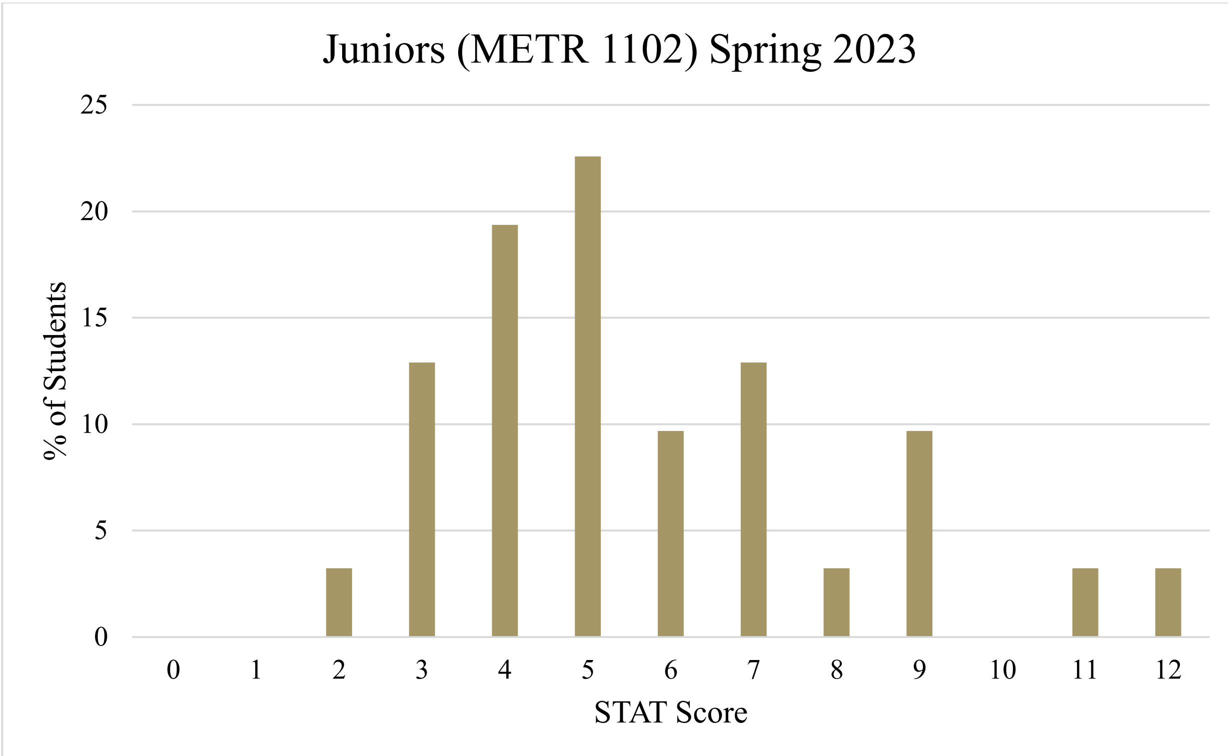


Figure 4. 47: *Frequency distribution for Juniors (METR 1102) pre-test in the Spring 2023 semester.*

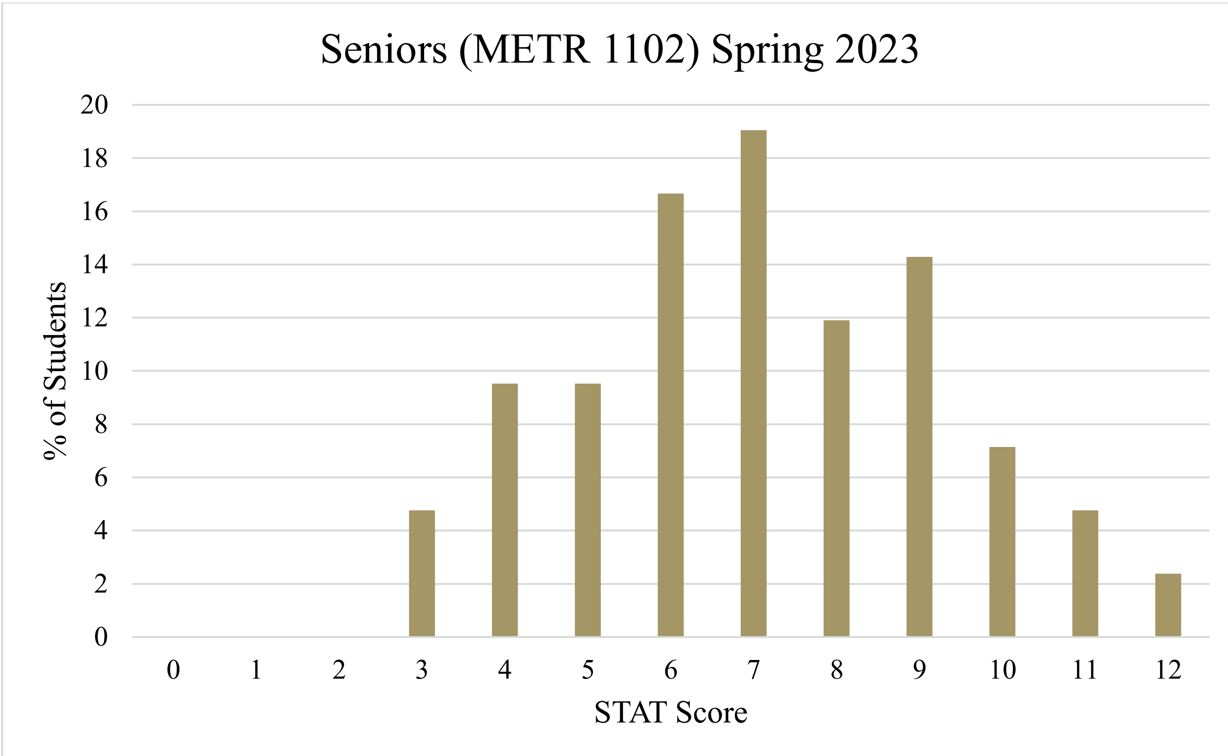


Figure 4. 48: *Frequency distribution for Seniors (METR 1102) pre-test in the Spring 2023 semester.*

METR 1102 Grade Levels in the Spring 2023 Semester				
	Freshmen	***Sophomores***	***Juniors***	***Seniors***
Statistics	**Pre-Test** (n = 100)	**Pre-Test** (n = 82)	**Pre-Test** (n = 31)	**Pre-Test** (n = 42)
Mean	6.44	7.01	5.71	7.10
Median	6	7	5	7
Mode	8	7	5	7
Range	11	9	10	9
Skewness	-0.140	0.345	0.903	0.124
Standard Deviation	2.37	2.08	2.42	2.23

Table 4. 16: *Summary statistics on STAT performance for Freshmen, Sophomores, Juniors and Seniors enrolled in Introduction to Meteorology (METR 1102) in the Spring 2023 semester.*

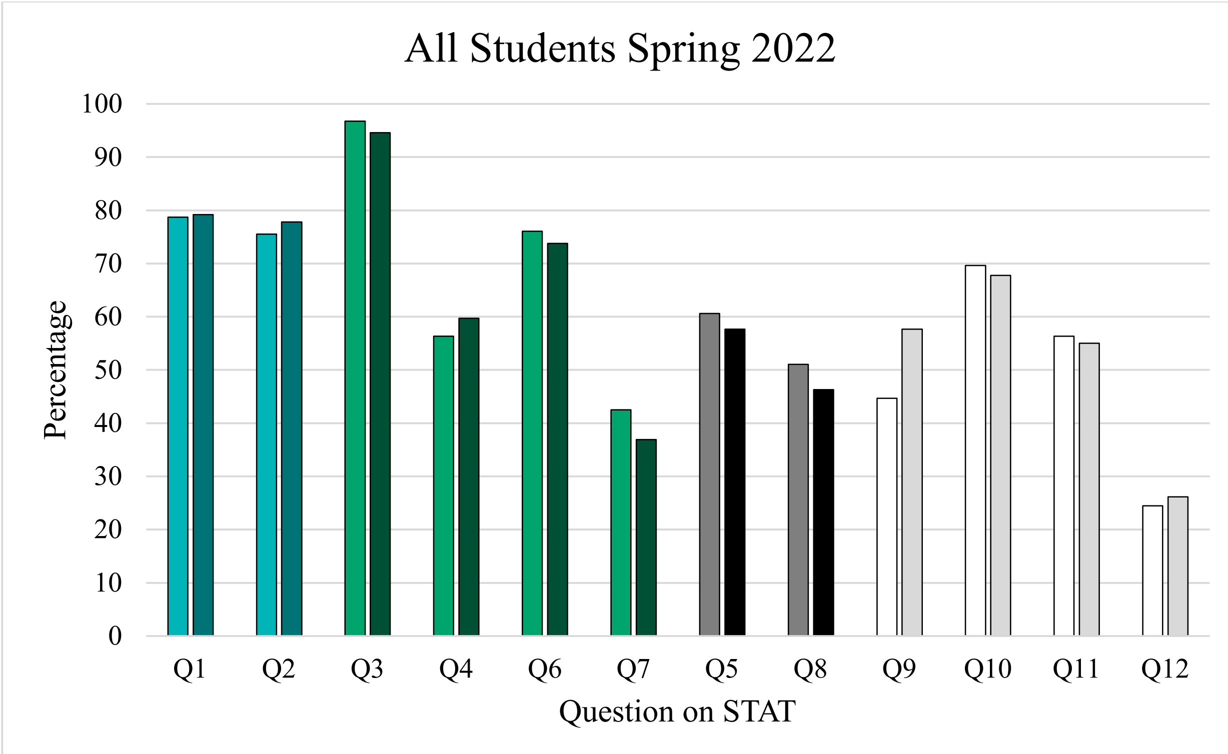


Figure 4. 49: *Shows what percentage of students correctly answered each question for All Students in the Spring 2022 semester. The lighter shades are the pre-test, while the darker shades are the post-test.*

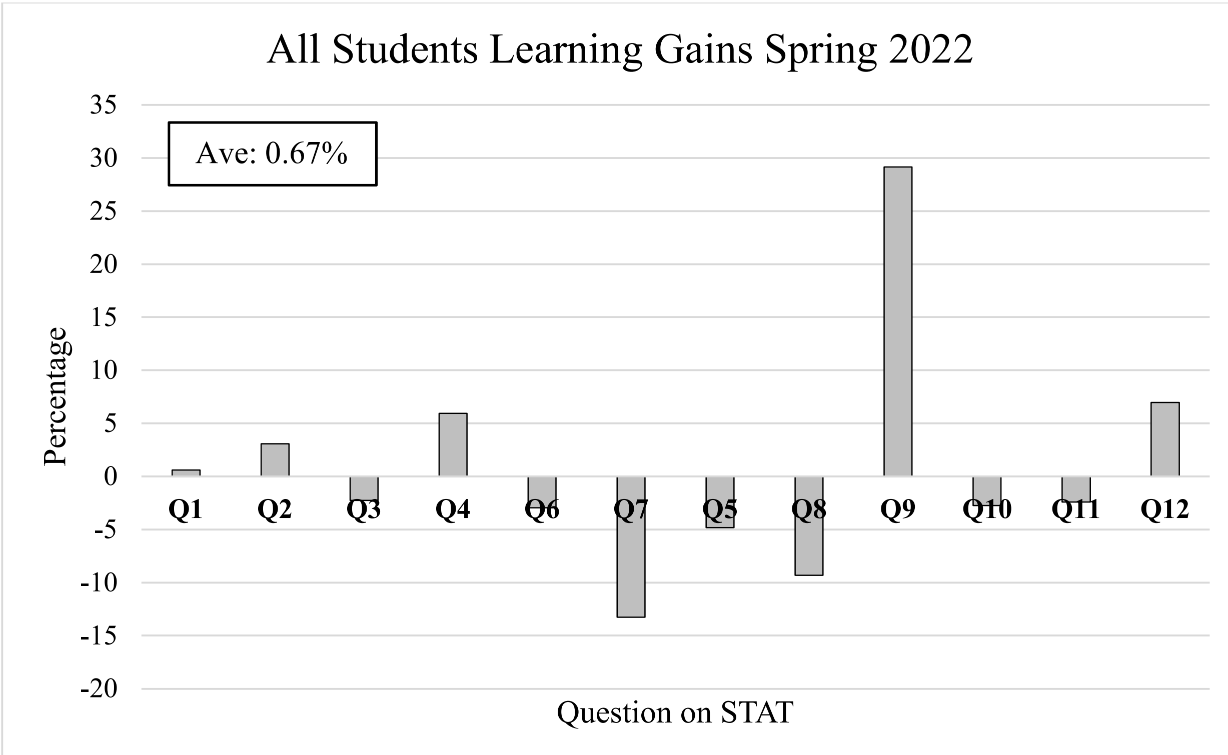


Figure 4. 50: *Shows the normalized learning gains between the STAT pre-test and post-test for each question for All Students in the Spring 2022 semester.*

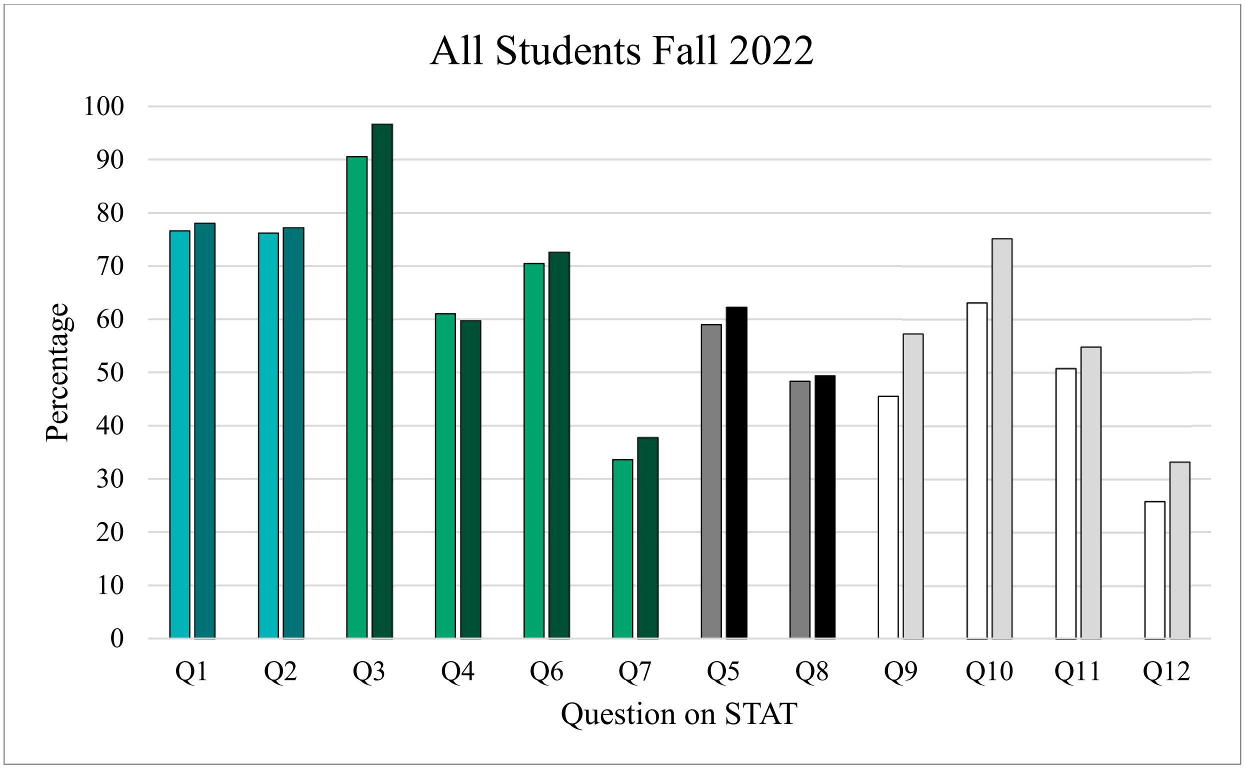


Figure 4.51: *Shows what percentage of students correctly answered each question for All Students in the Fall 2022 semester. The lighter shades are the pre-test, while the darker shades are the post-test.*

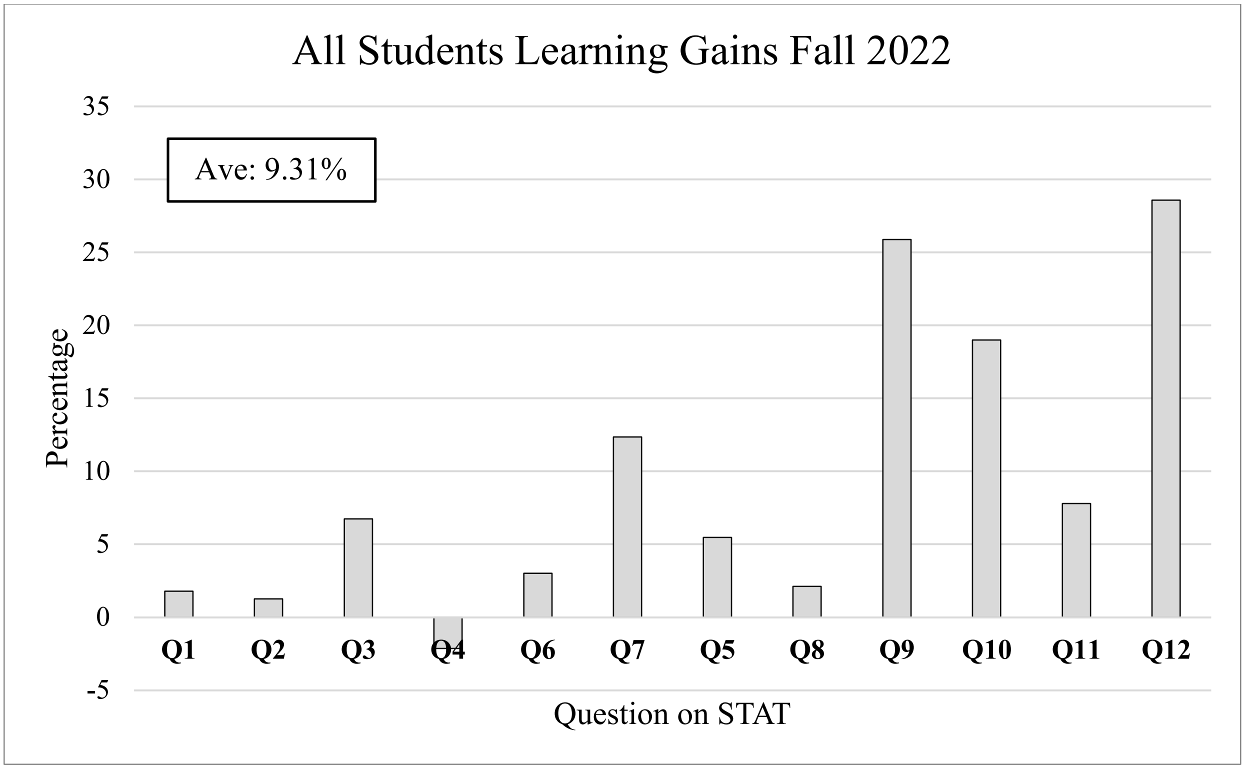


Figure 4. 52: *Shows the normalized learning gains between the STAT pre-test and post-test for each question for All Students in the Fall 2022 semester.*

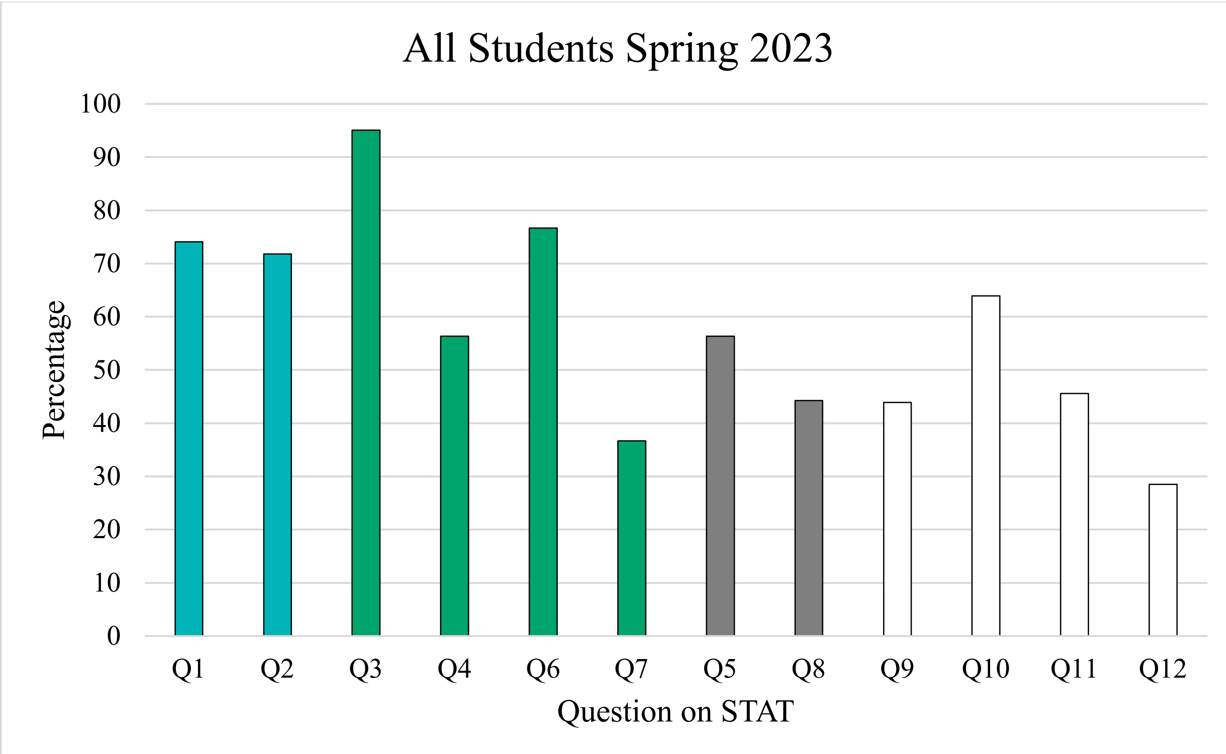


Figure 4.53: *Shows what percentage of students correctly answered each question for the pre-test for All Students in the Spring 2023 semester.*

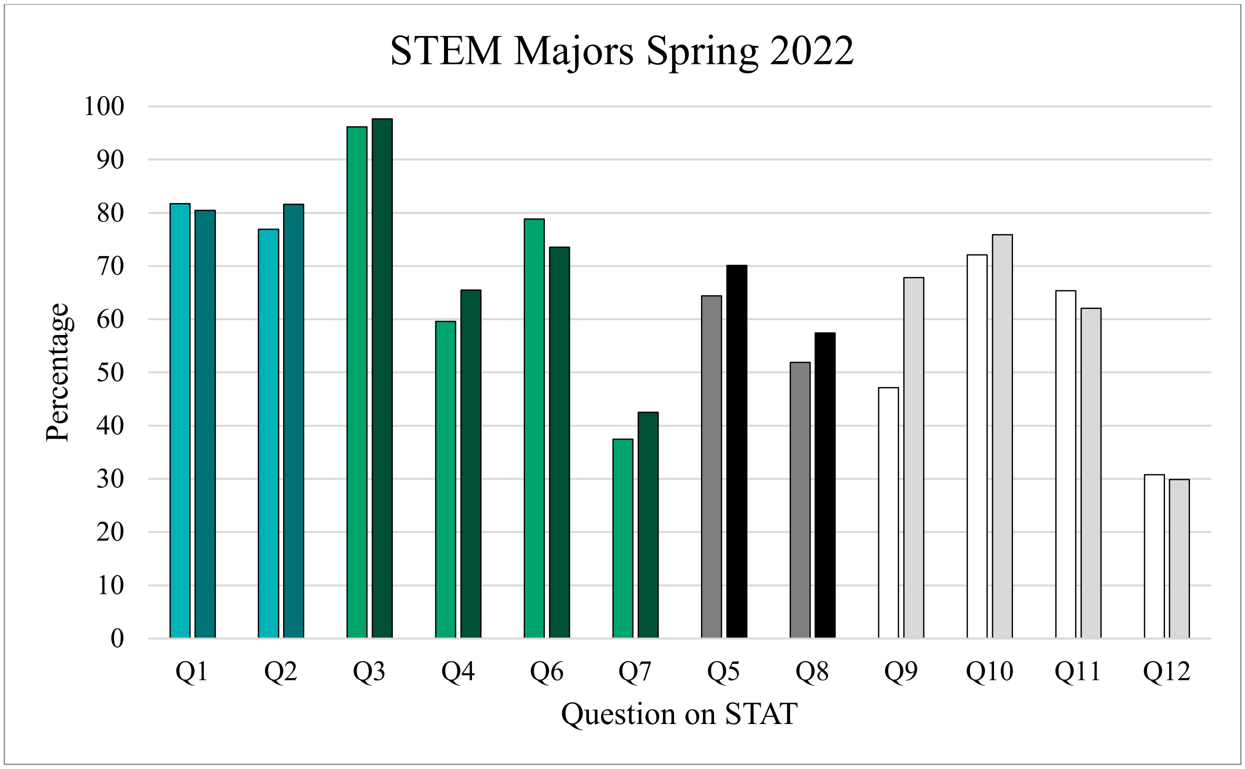


Figure 4.54: *Shows what percentage of students correctly answered each question for STEM Majors in the Spring 2022 semester. The lighter shades are the pre-test, while the darker shades are the post-test.*

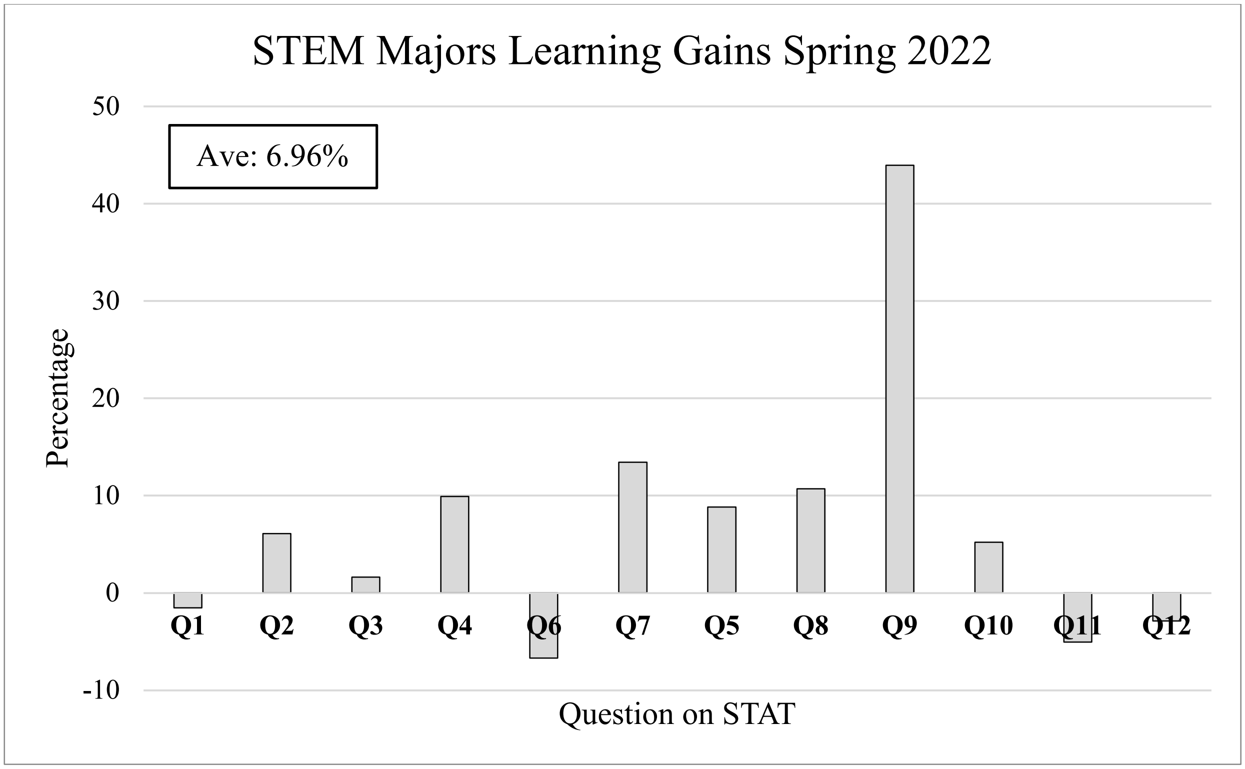


Figure 4.55: *Shows the normalized learning gains between the STAT pre-test and post-test for each question for STEM Majors in the Spring 2022 semester.*

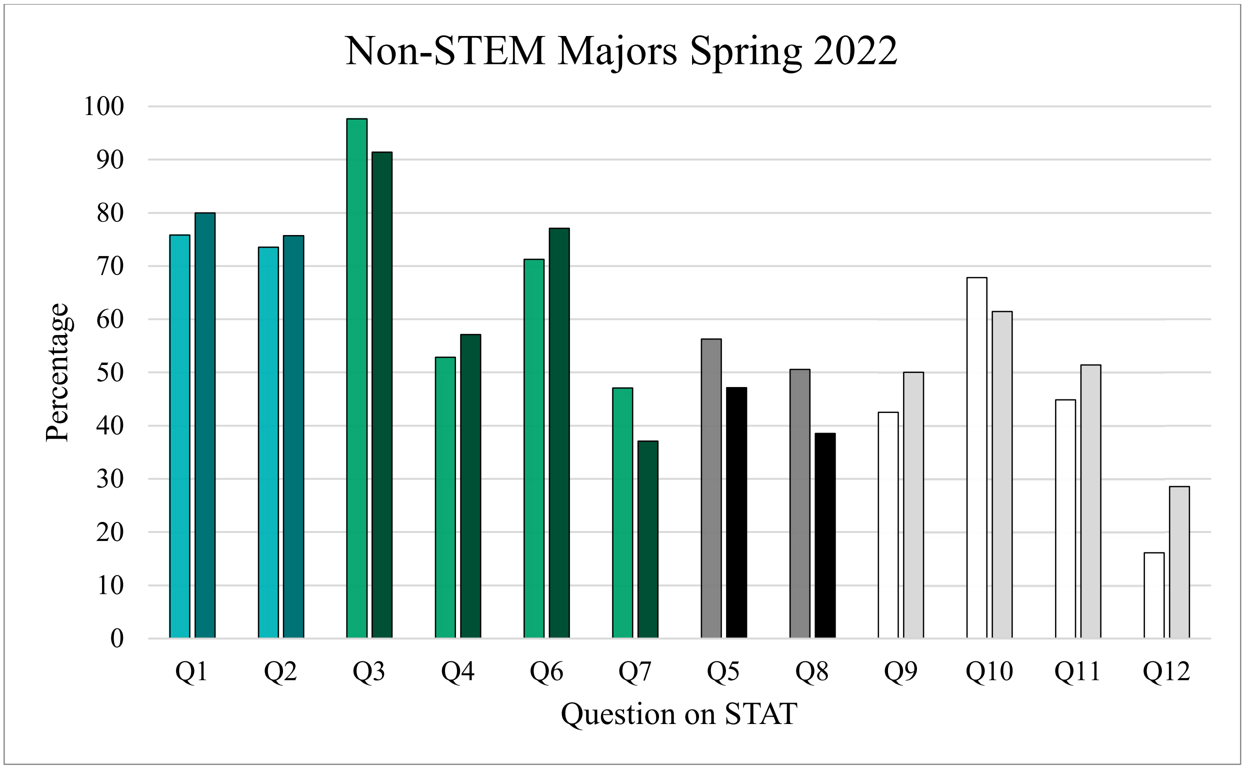


Figure 4. 56: *Shows what percentage of students correctly answered each question for Non-STEM Majors in the Spring 2022 semester. The lighter shades are the pre-test, while the darker shades are the post-test.*

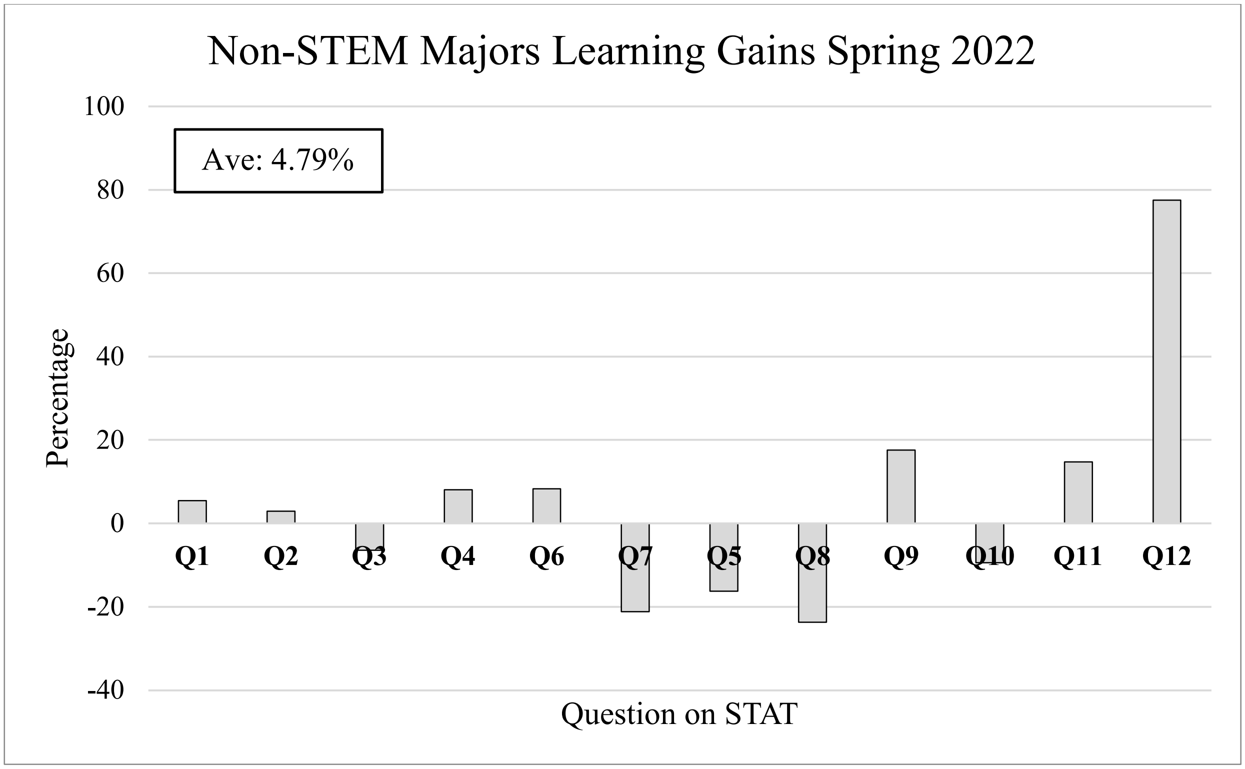


Figure 4.57: *Shows the normalized learning gains between the STAT pre-test and post-test for each question for Non-STEM Majors in the Spring 2022 semester.*

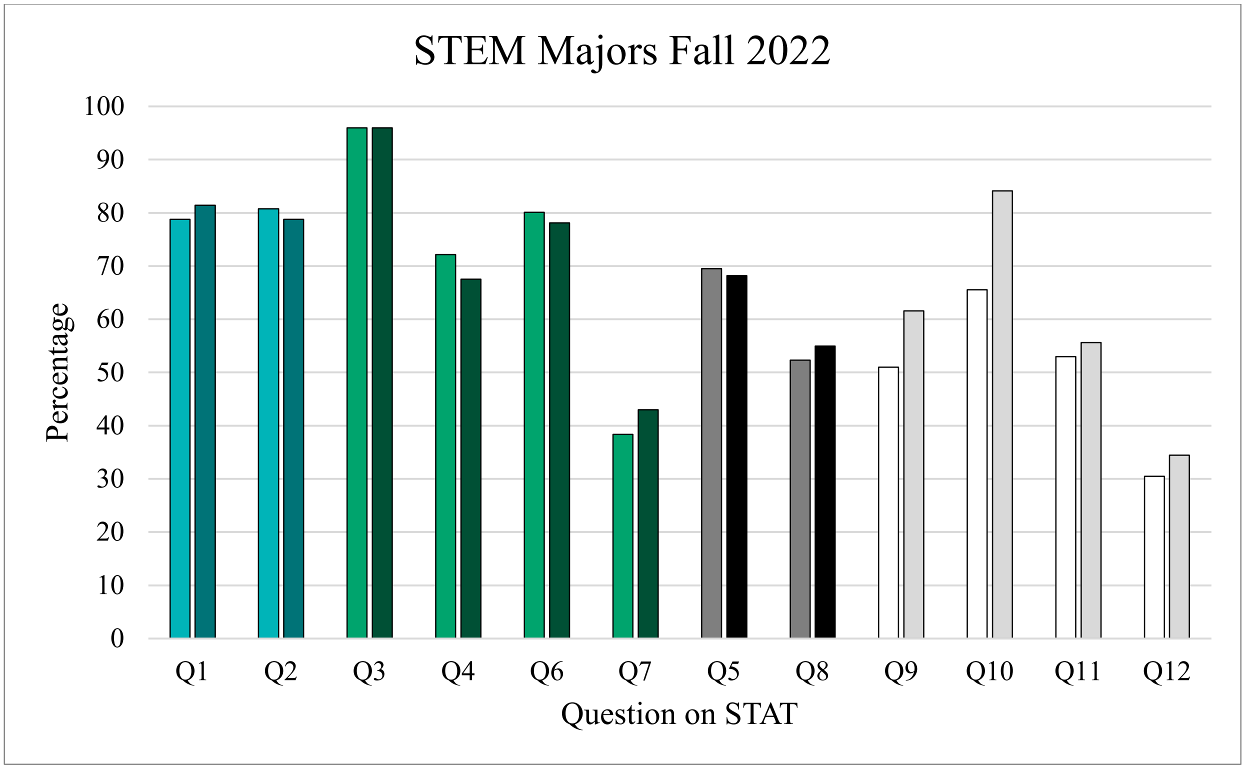


Figure 4.58: *Shows what percentage of students correctly answered each question for STEM Majors in the Fall 2022 semester. The lighter shades are the pre-test, while the darker shades are the post-test.*

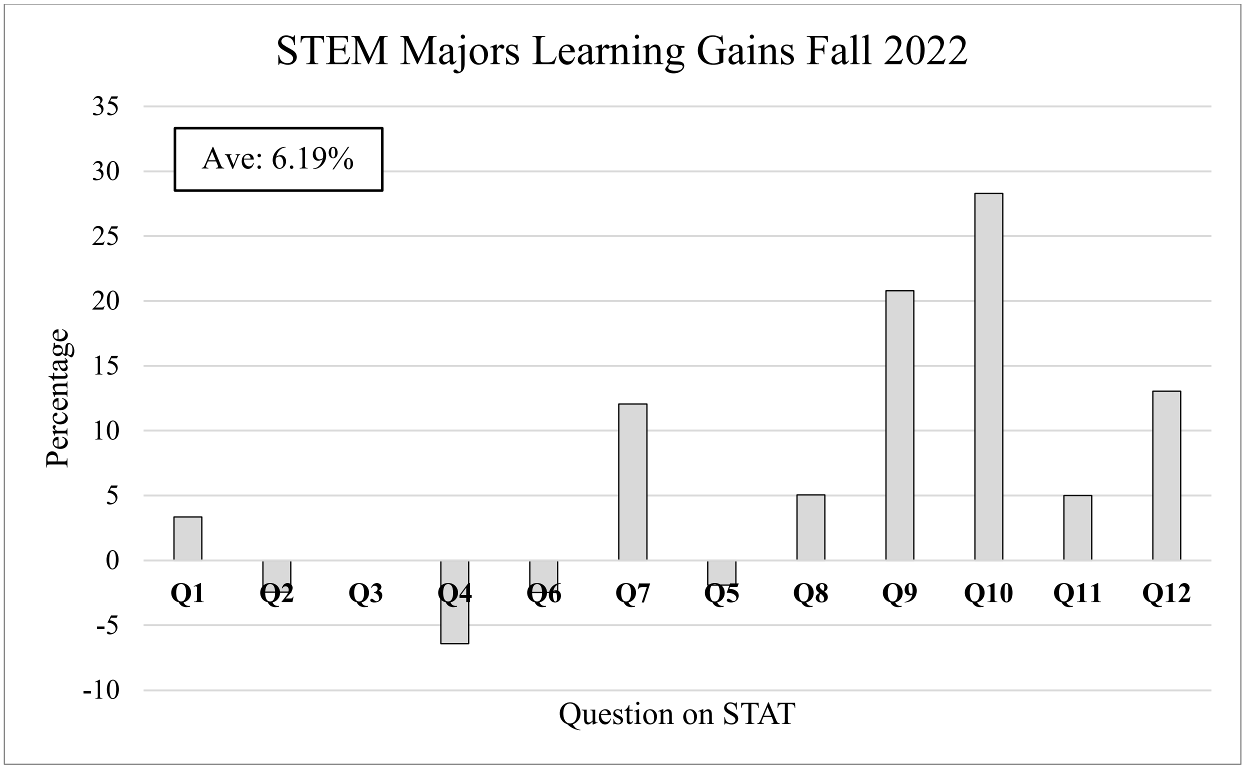


Figure 4.59: *Shows the normalized learning gains between the STAT pre-test and post-test for each question for STEM Majors in the Fall 2022 semester.*

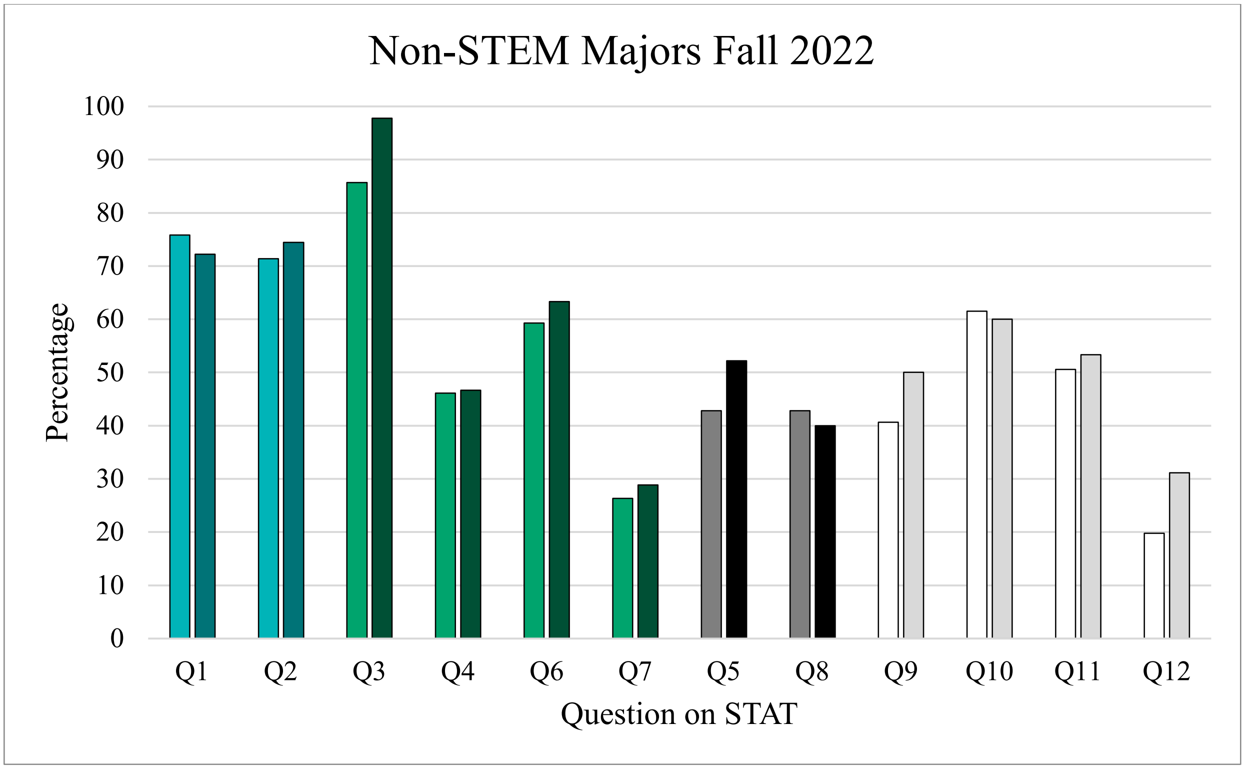


Figure 4.60: *Shows what percentage of students correctly answered each question for Non-STEM Majors in the Fall 2022 semester. The lighter shades are the pre-test, while the darker shades are the post-test.*

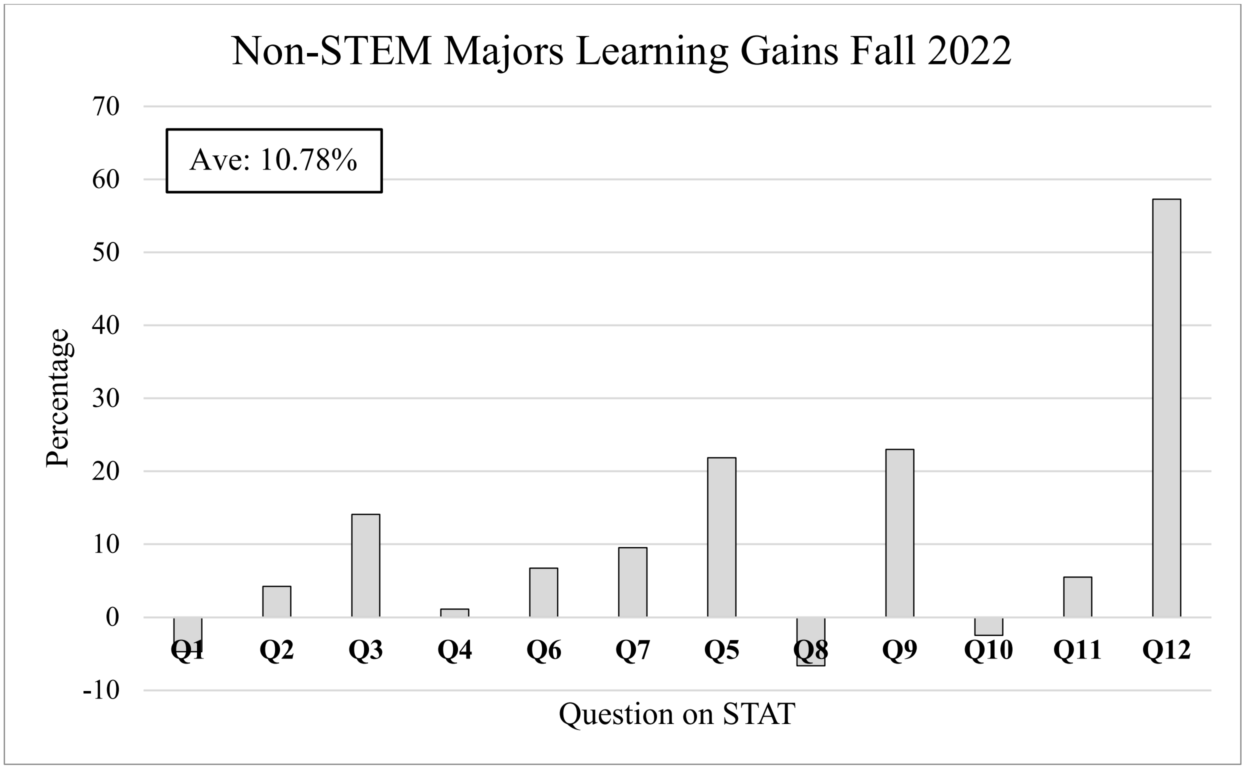


Figure 4.61: *Shows the normalized learning gains between the STAT pre-test and post-test for each question for Non-STEM Majors in the Fall 2022 semester.*

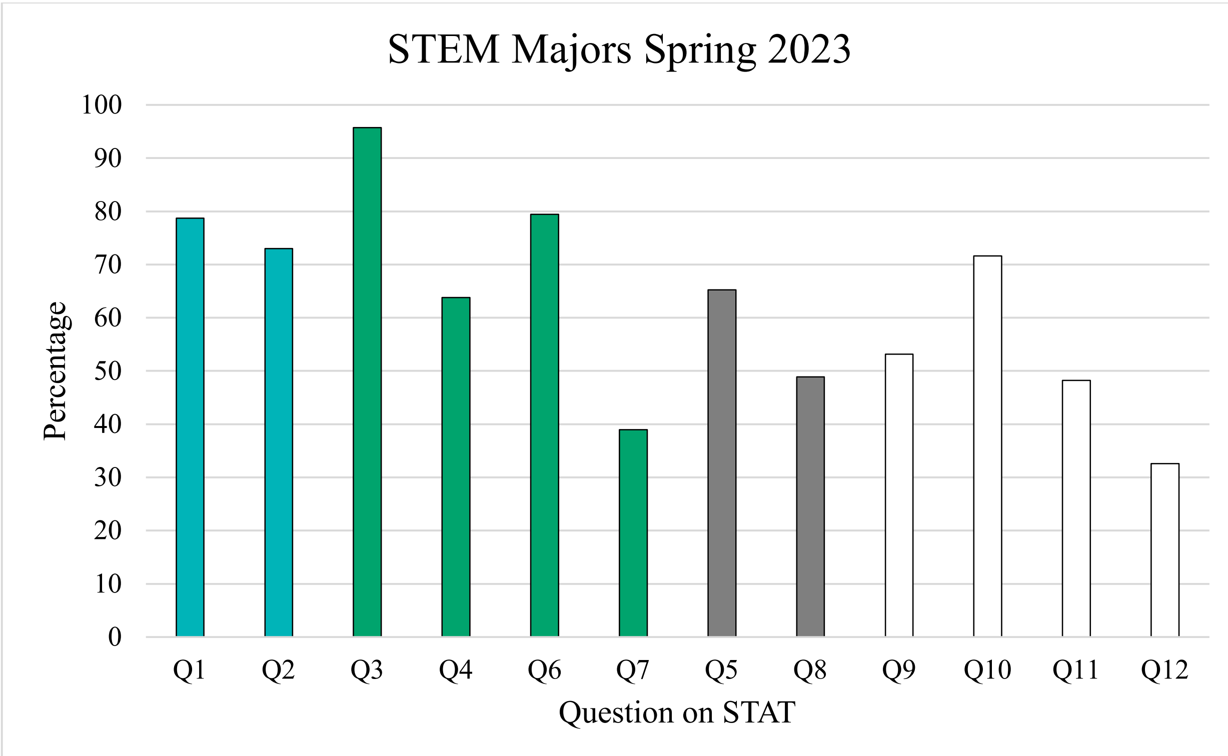


Figure 4.62: *Shows what percentage of students correctly answered each question for the pre-test for STEM Majors in the Spring 2023 semester.*

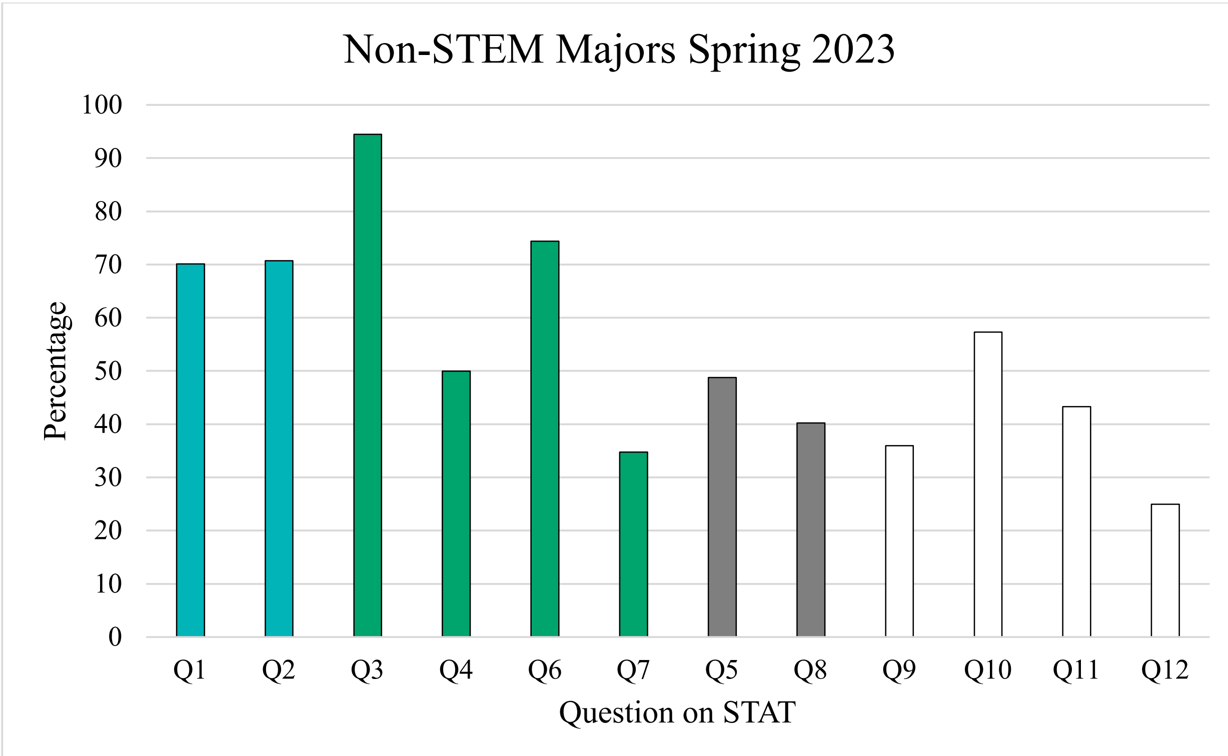


Figure 4.63: *Shows what percentage of students correctly answered each question for the pre-test for Non-STEM Majors in the Spring 2023 semester.*

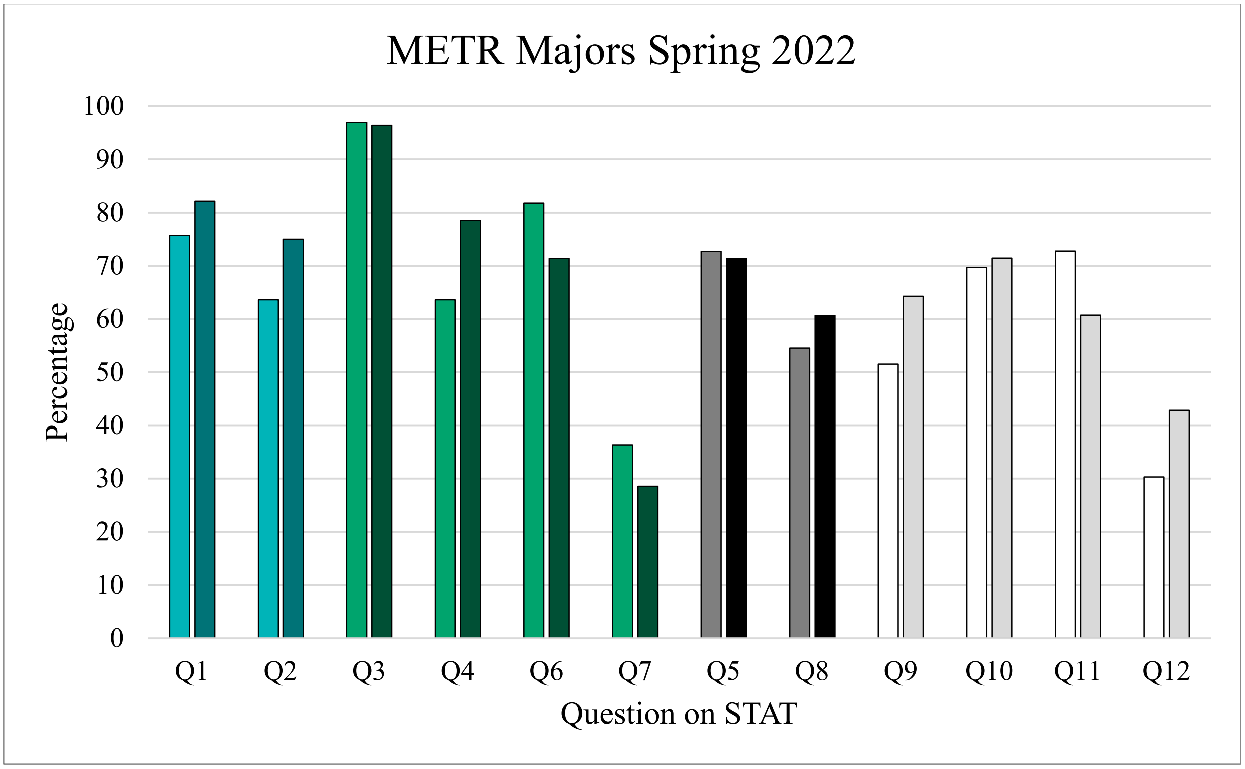


Figure 4.64: *Shows what percentage of students correctly answered each question for Meteorology Majors in the Spring 2022 semester. The lighter shades are the pre-test, while the darker shades are the post-test.*

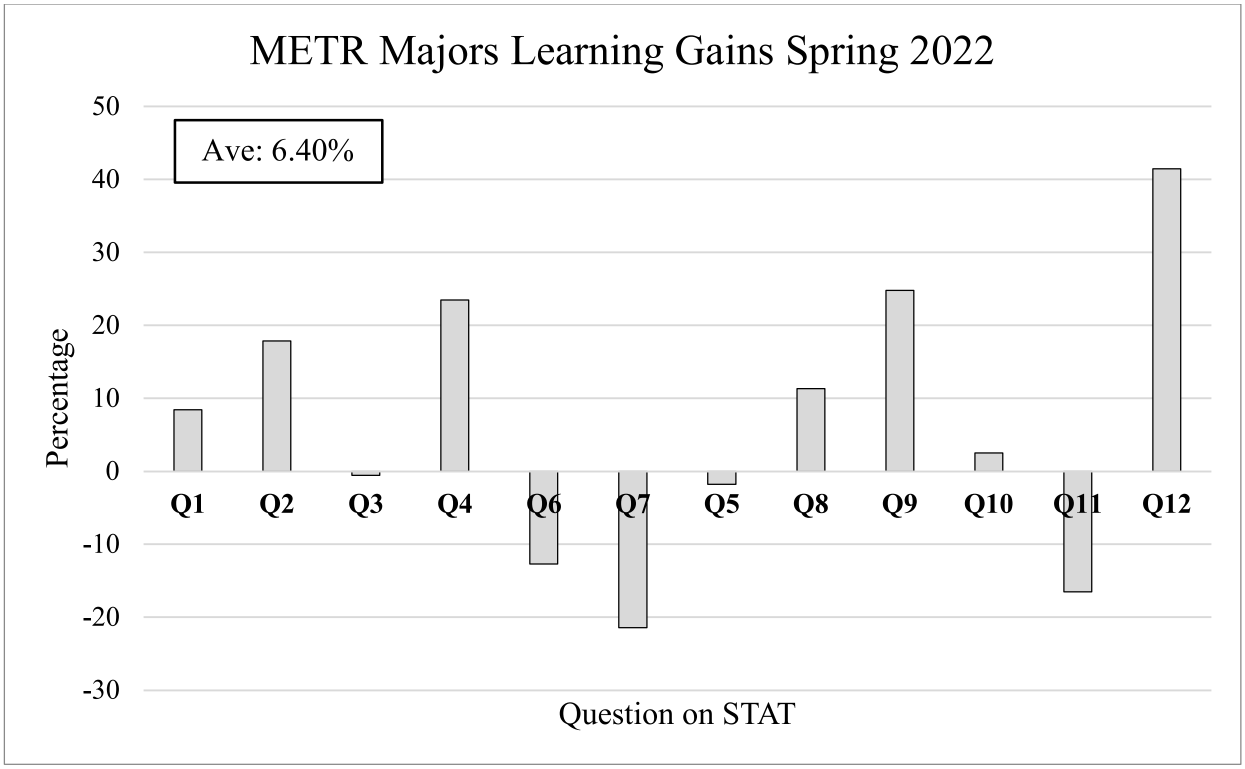


Figure 4.65: *Shows the normalized learning gains between the STAT pre-test and post-test for each question for Meteorology Majors in the Spring 2022 semester.*

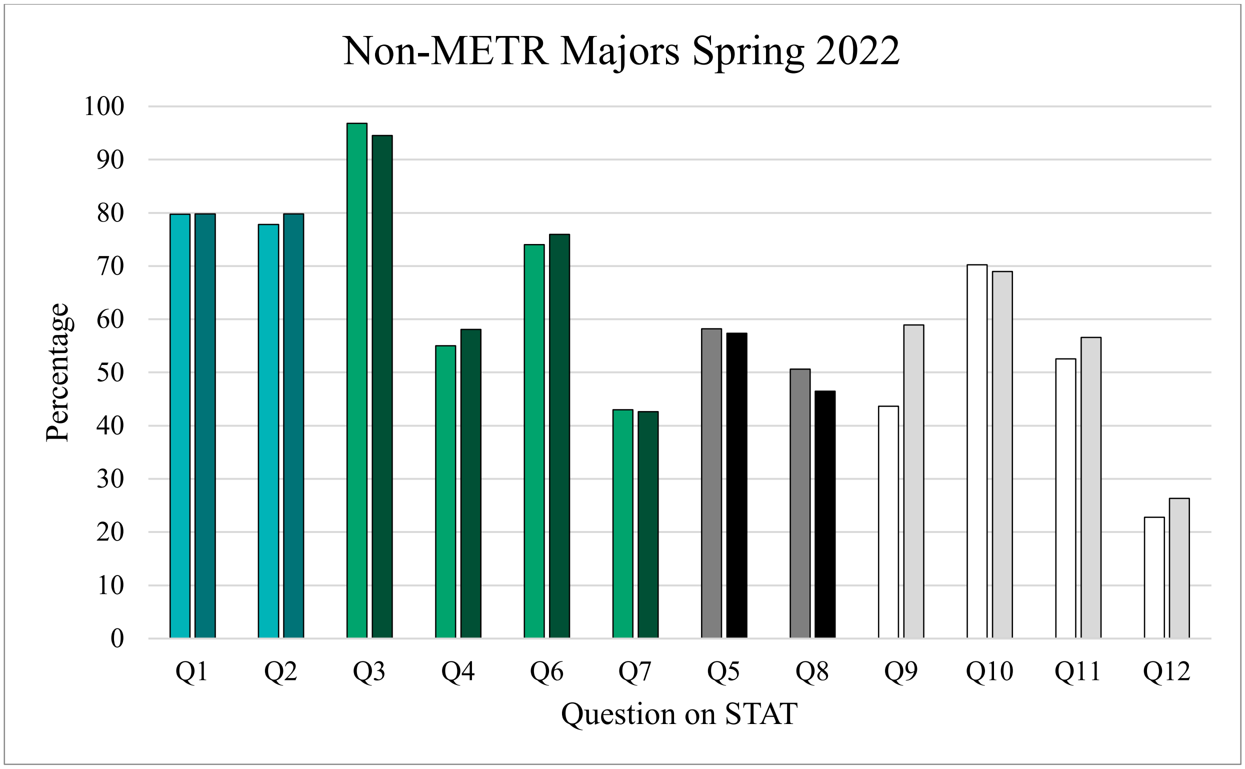


Figure 4.66: *Shows what percentage of students correctly answered each question for Non-Meteorology Majors in the Spring 2022 semester. The lighter shades are the pre-test, while the darker shades are the post-test.*

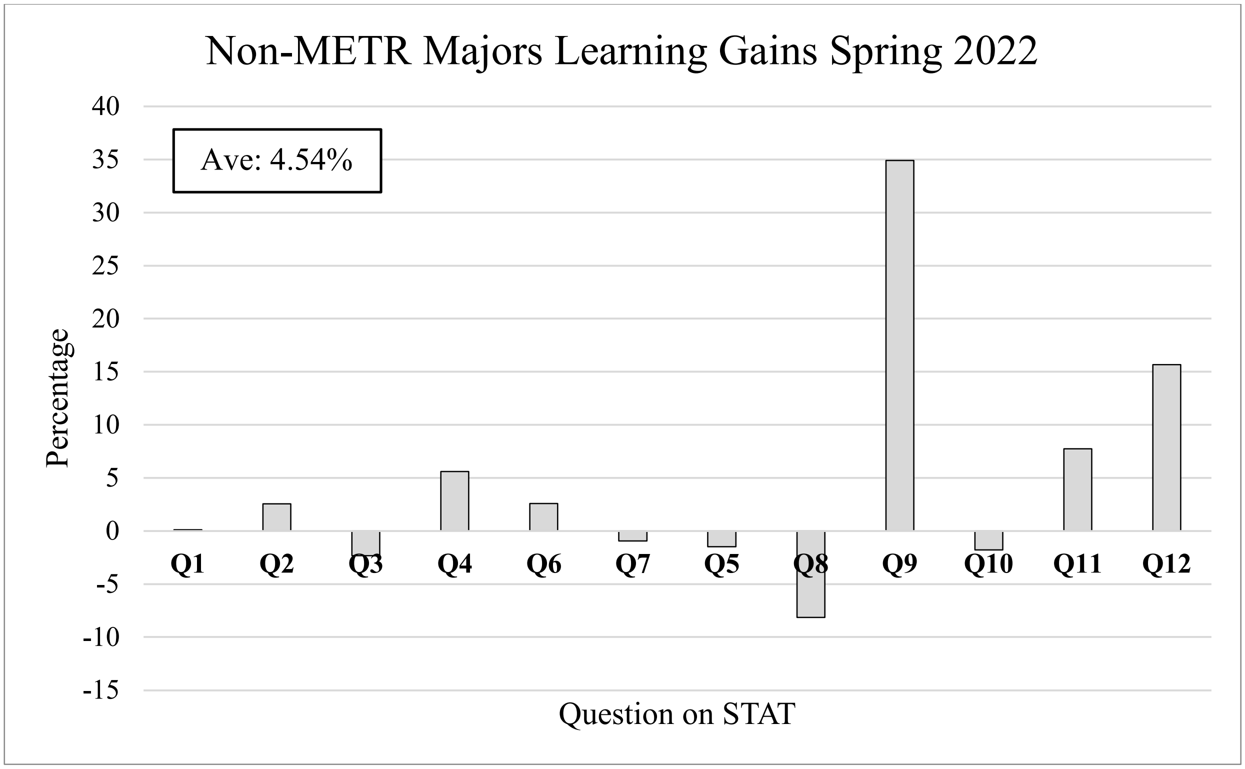


Figure 4.67: *Shows the normalized learning gains between the STAT pre-test and post-test for each question for Non-Meteorology Majors in the Spring 2022 semester.*

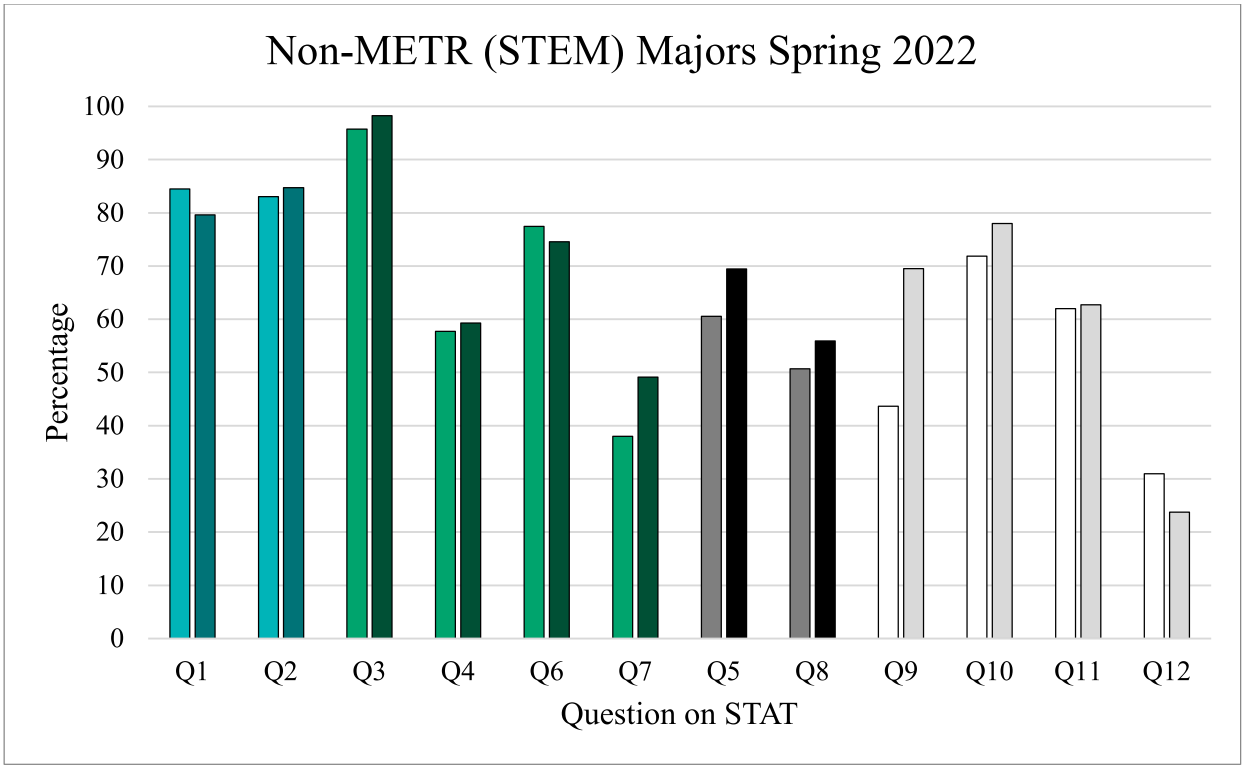


Figure 4.68: *Shows what percentage of students correctly answered each question for Non-Meteorology (STEM) Majors in the Spring 2022 semester. The lighter shades are the pre-test, while the darker shades are the post-test.*

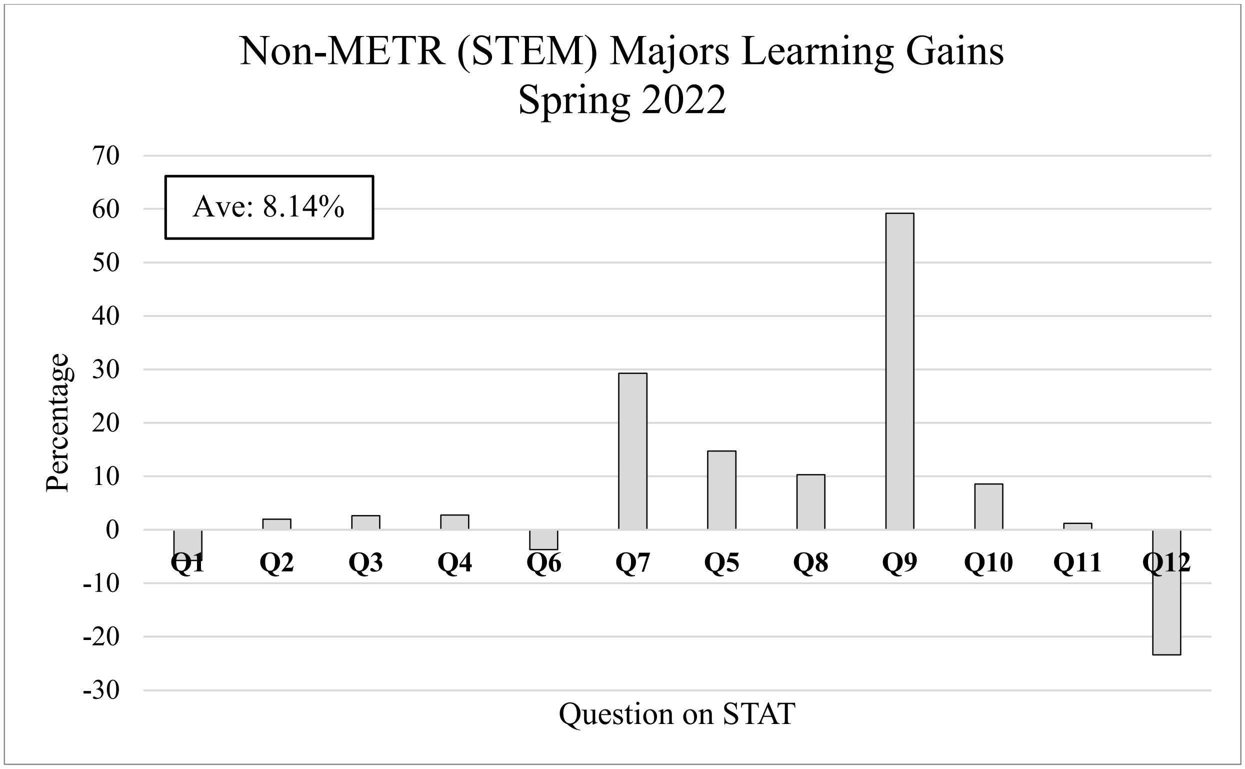


Figure 4.69: *Shows the normalized learning gains between the STAT pre-test and post-test for each question for Non-Meteorology (STEM) Majors in the Spring 2022 semester.*

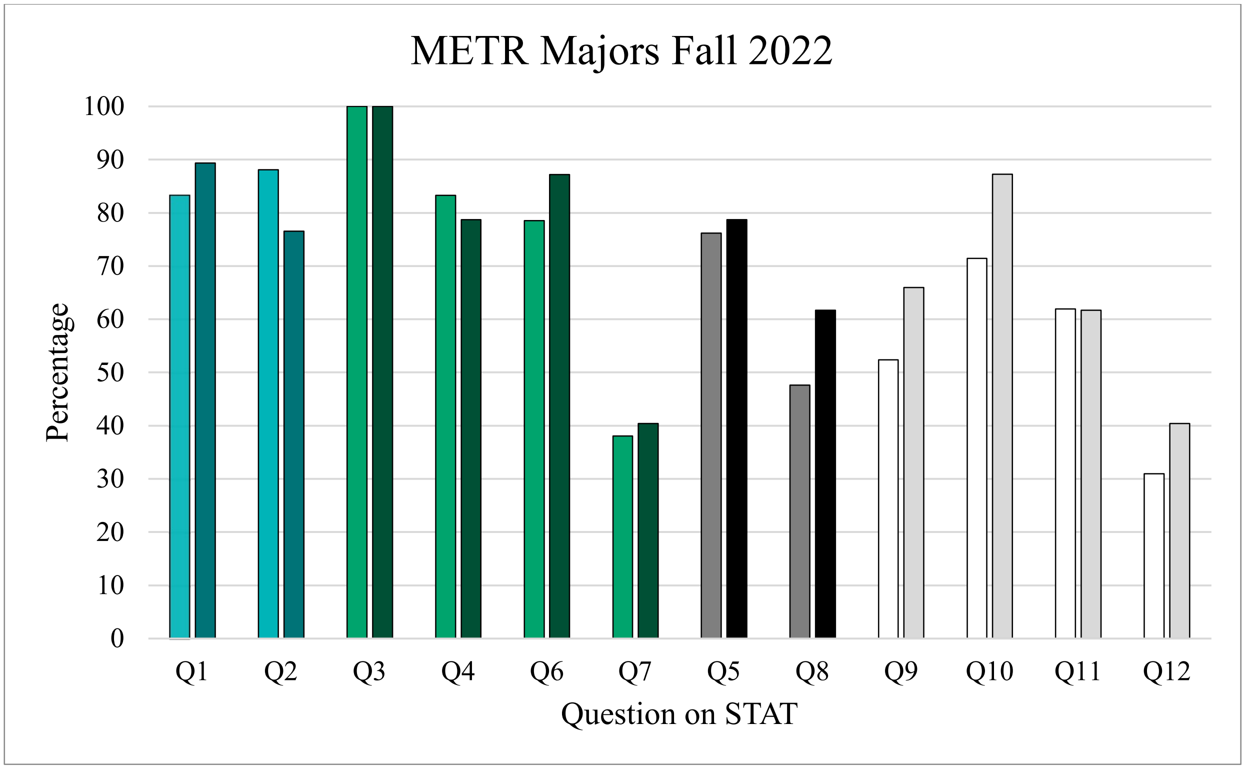


Figure 4.70: *Shows what percentage of students correctly answered each question for Meteorology Majors in the Fall 2022 semester. The lighter shades are the pre-test, while the darker shades are the post-test.*

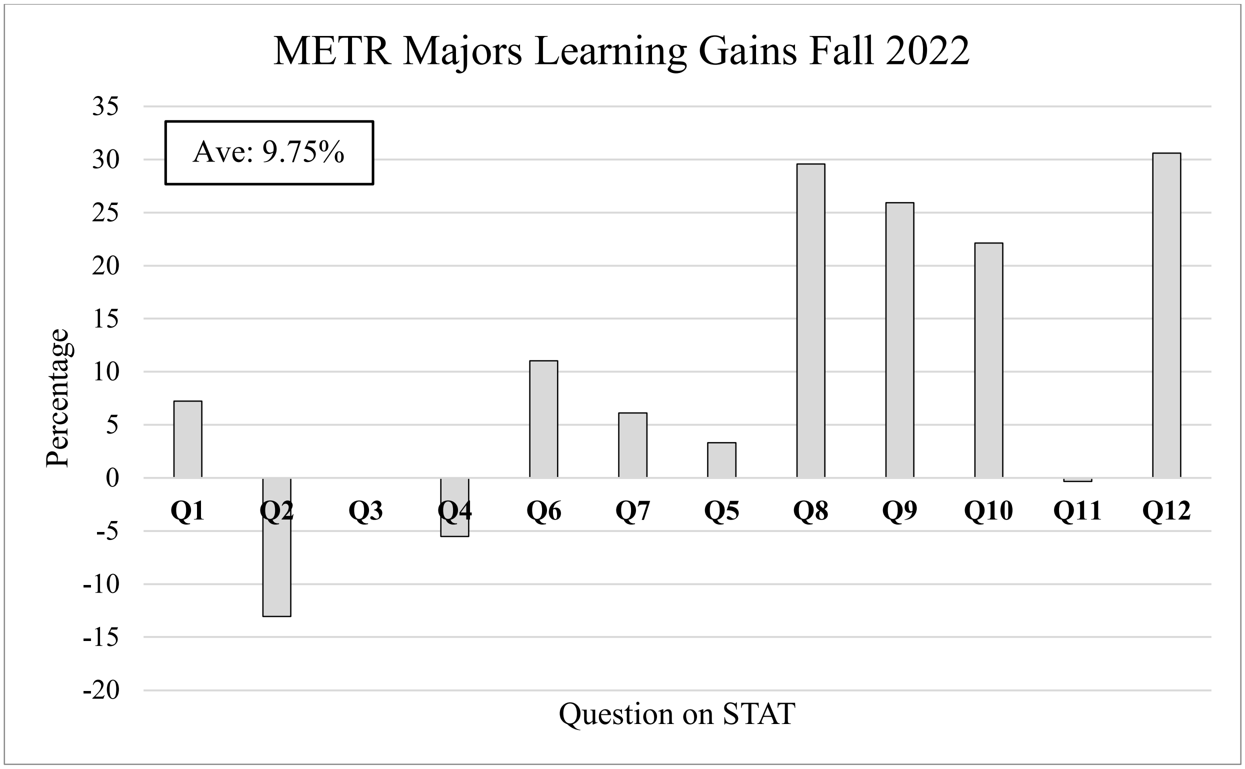


Figure 4.71: *Shows the normalized learning gains between the STAT pre-test and post-test for each question for Meteorology Majors in the Fall 2022 semester.*

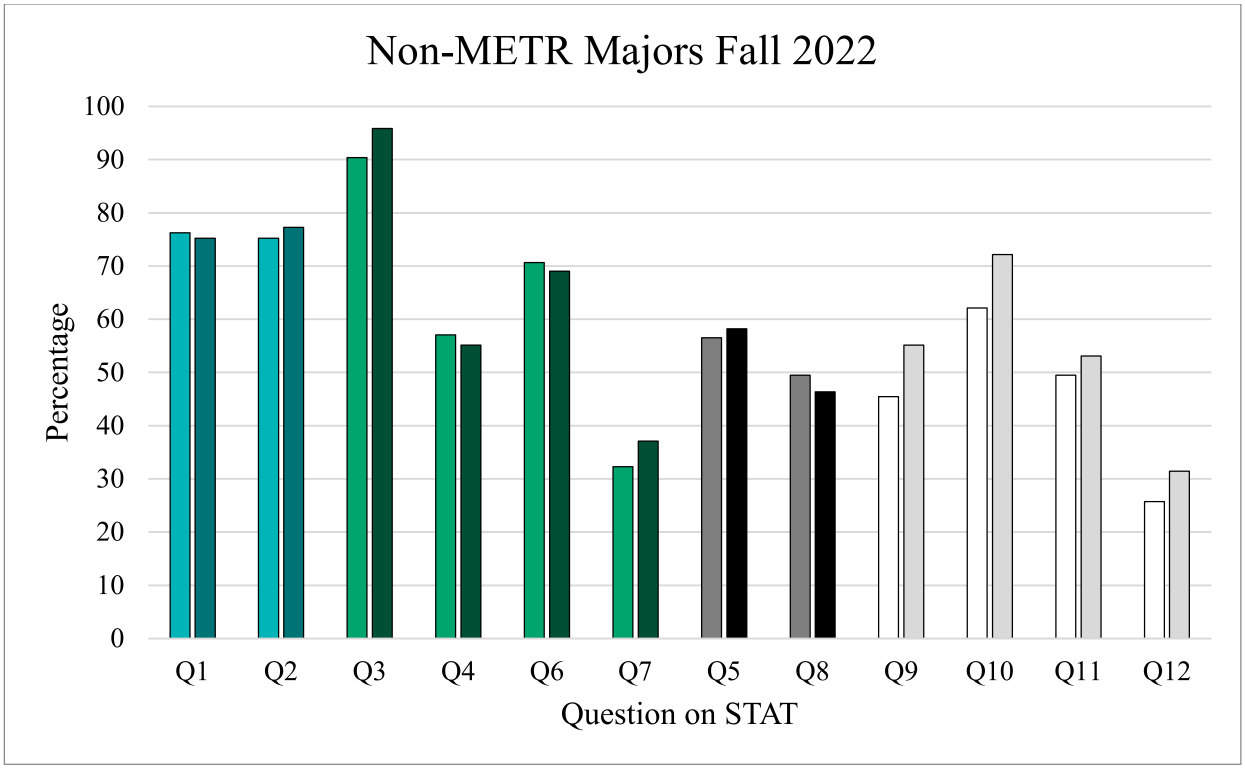


Figure 4.72: *Shows what percentage of students correctly answered each question for Non-Meteorology Majors in the Fall 2022 semester. The lighter shades are the pre-test, while the darker shades are the post-test.*

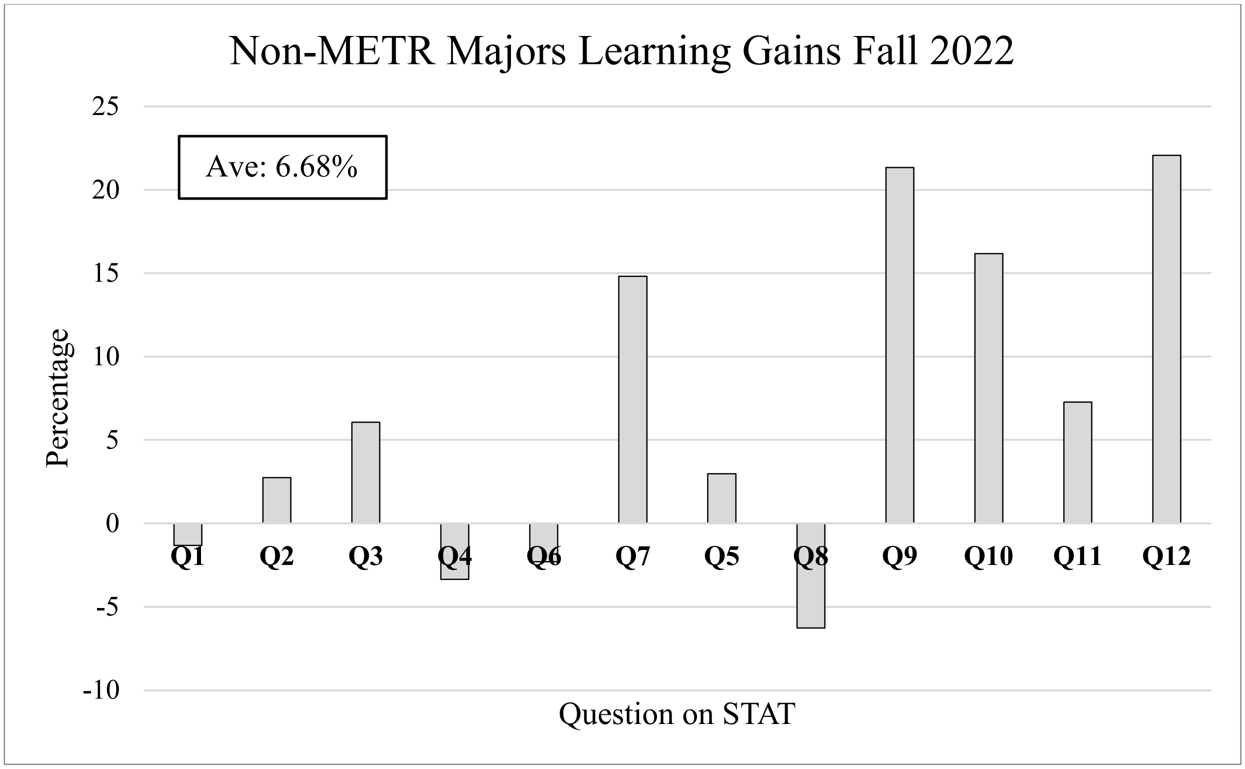


Figure 4.73: *Shows the normalized learning gains between the STAT pre-test and post-test for each question for Non-Meteorology Majors in the Fall 2022 semester.*

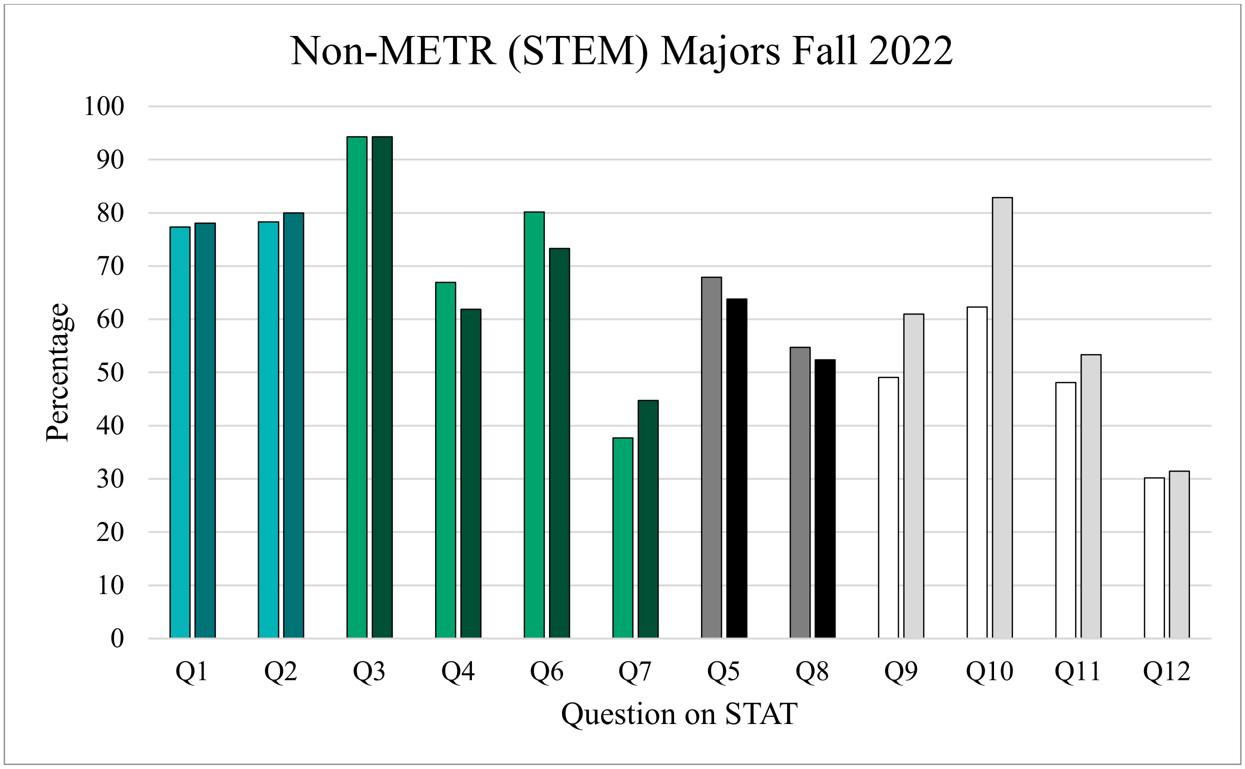


Figure 4.74: *Shows what percentage of students correctly answered each question for Non-Meteorology (STEM) Majors in the Fall 2022 semester. The lighter shades are the pre-test, while the darker shades are the post-test.*

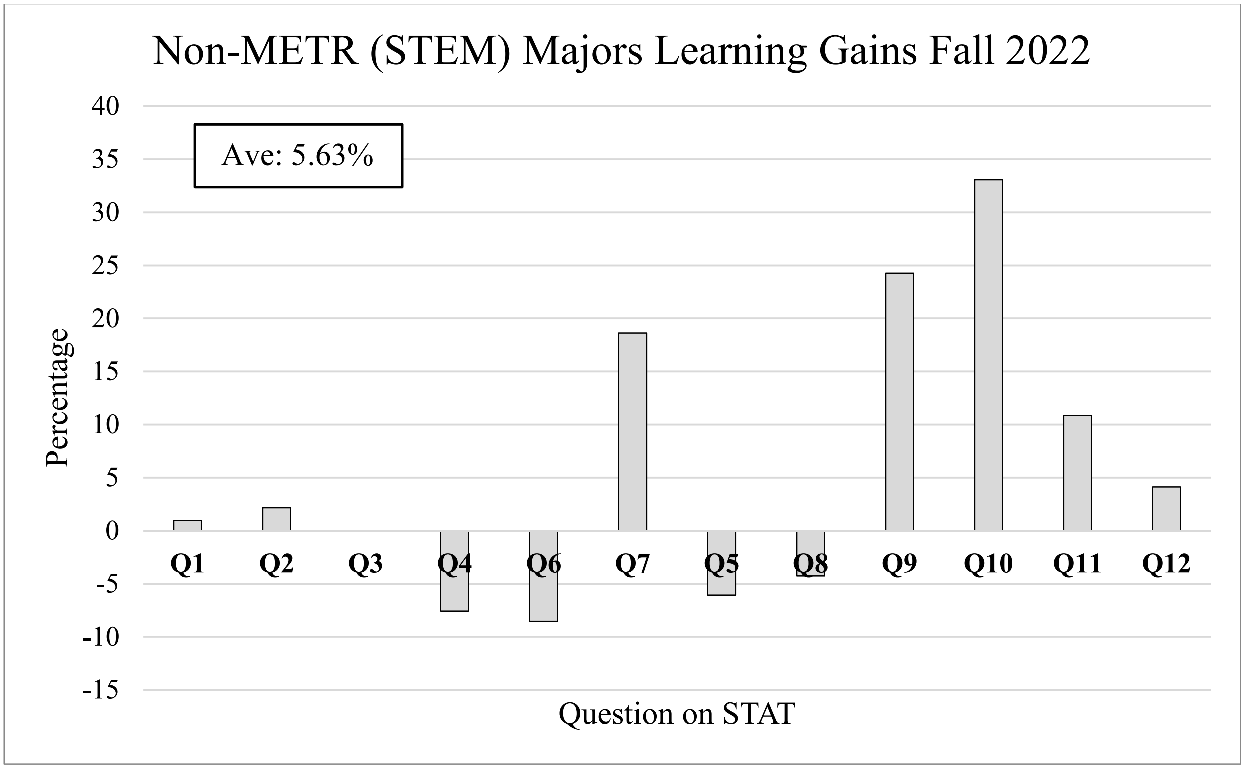


Figure 4.75: *Shows the normalized learning gains between the STAT pre-test and post-test for each question for Non-Meteorology (STEM) Majors in the Fall 2022 semester.*

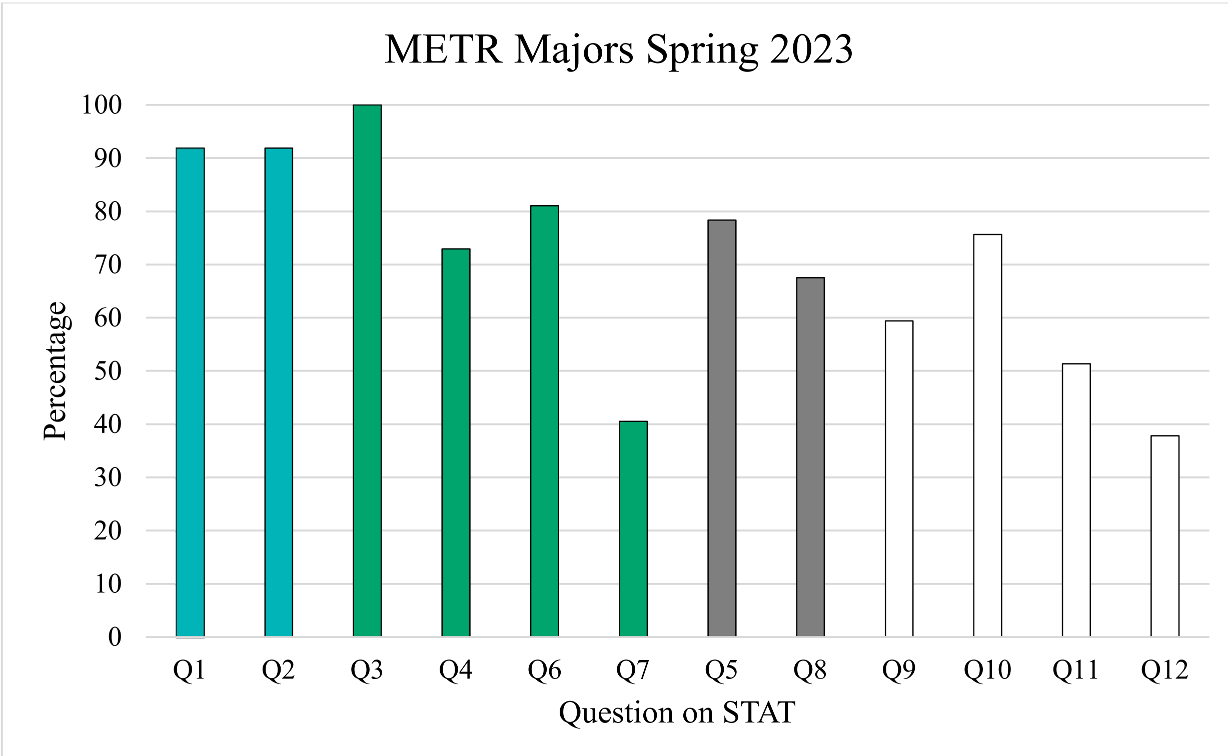


Figure 4.76: *Shows what percentage of students correctly answered each question for the pre-test for Meteorology Majors in the Spring 2023 semester.*

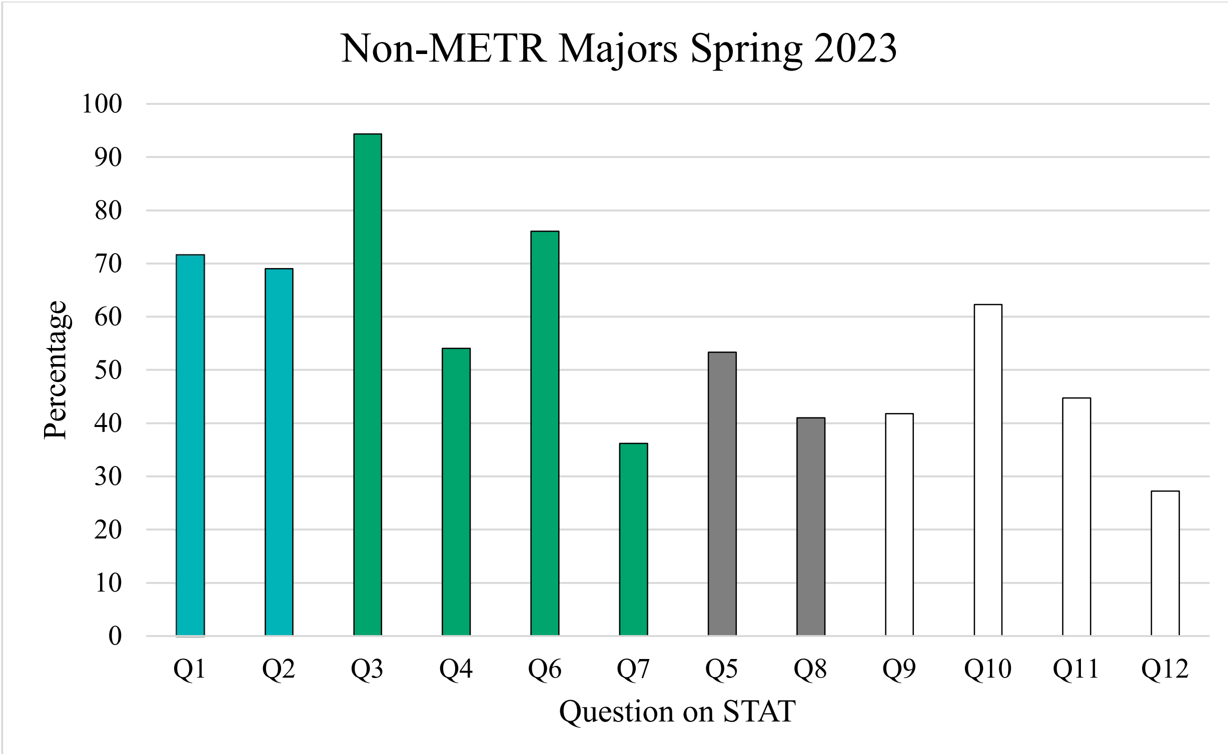


Figure 4.77: *Shows what percentage of students correctly answered each question for the pre-test for Non-Meteorology Majors in the Spring 2023 semester.*

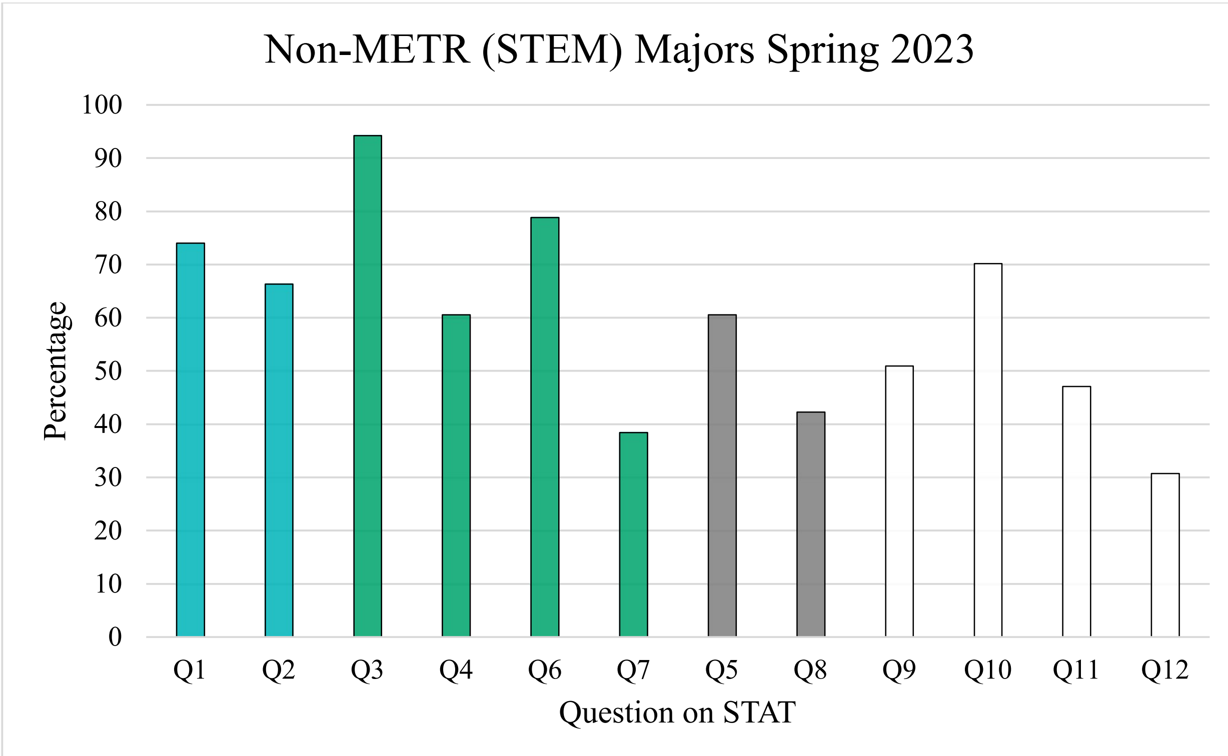


Figure 4.78: *Shows what percentage of students correctly answered each question for the pre-test for Non-Meteorology (STEM) Majors in the Spring 2023 semester.*

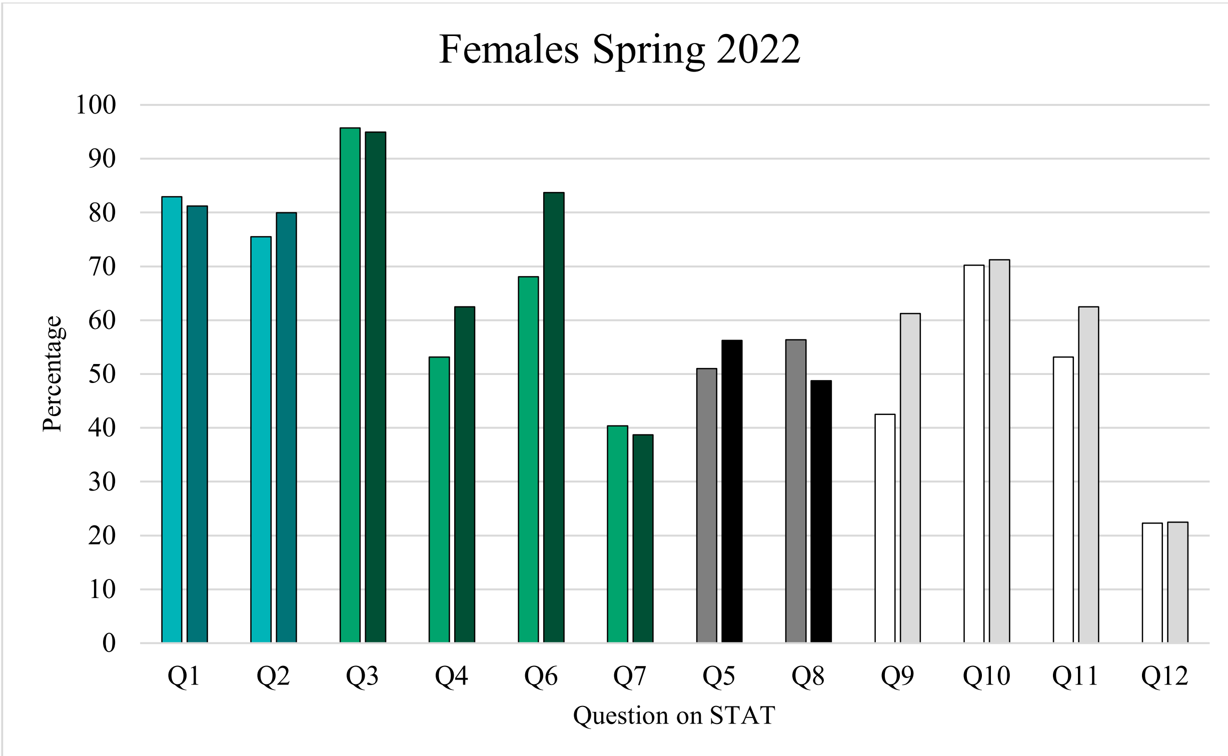


Figure 4.79: *Shows what percentage of students correctly answered each question for Females in the Spring 2022 semester. The lighter shades are the pre-test, while the darker shades are the post-test.*

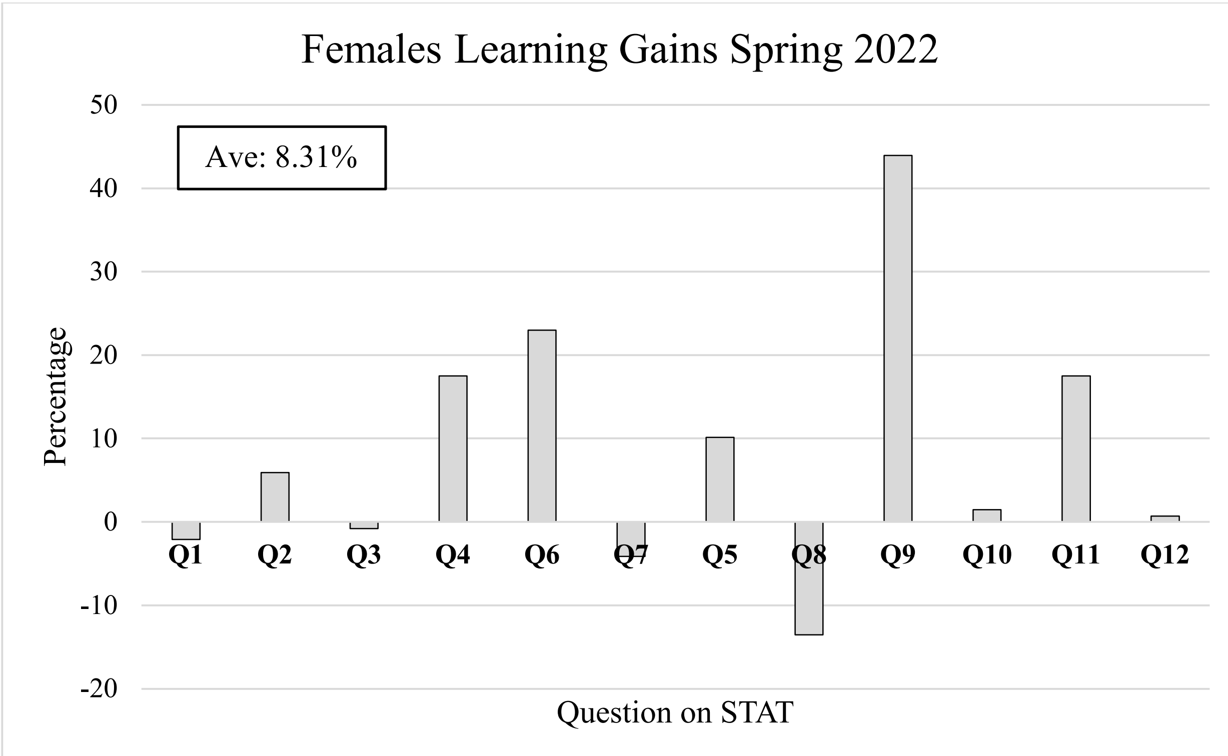


Figure 4.80: *Shows the normalized learning gains between the STAT pre-test and post-test for each question for Females in the Spring 2022 semester.*

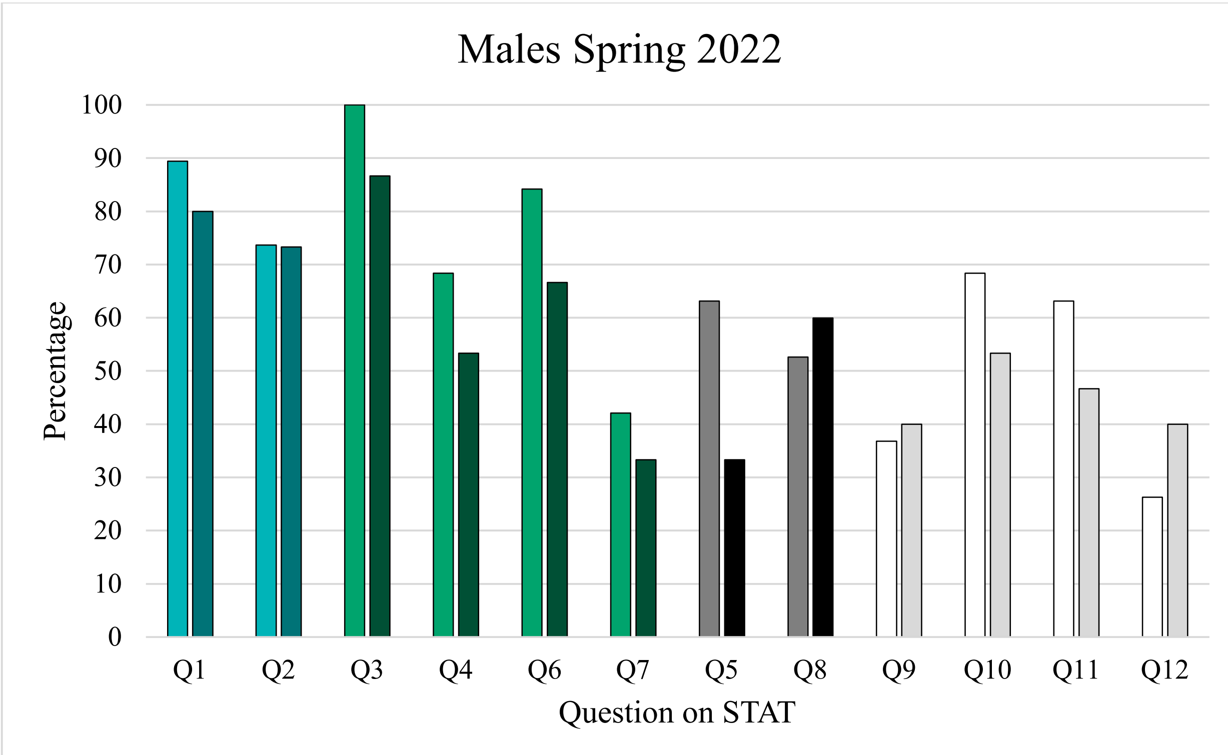


Figure 4. 81: *Shows what percentage of students correctly answered each question for Males in the Spring 2022 semester. The lighter shades are the pre-test, while the darker shades are the post-test.*

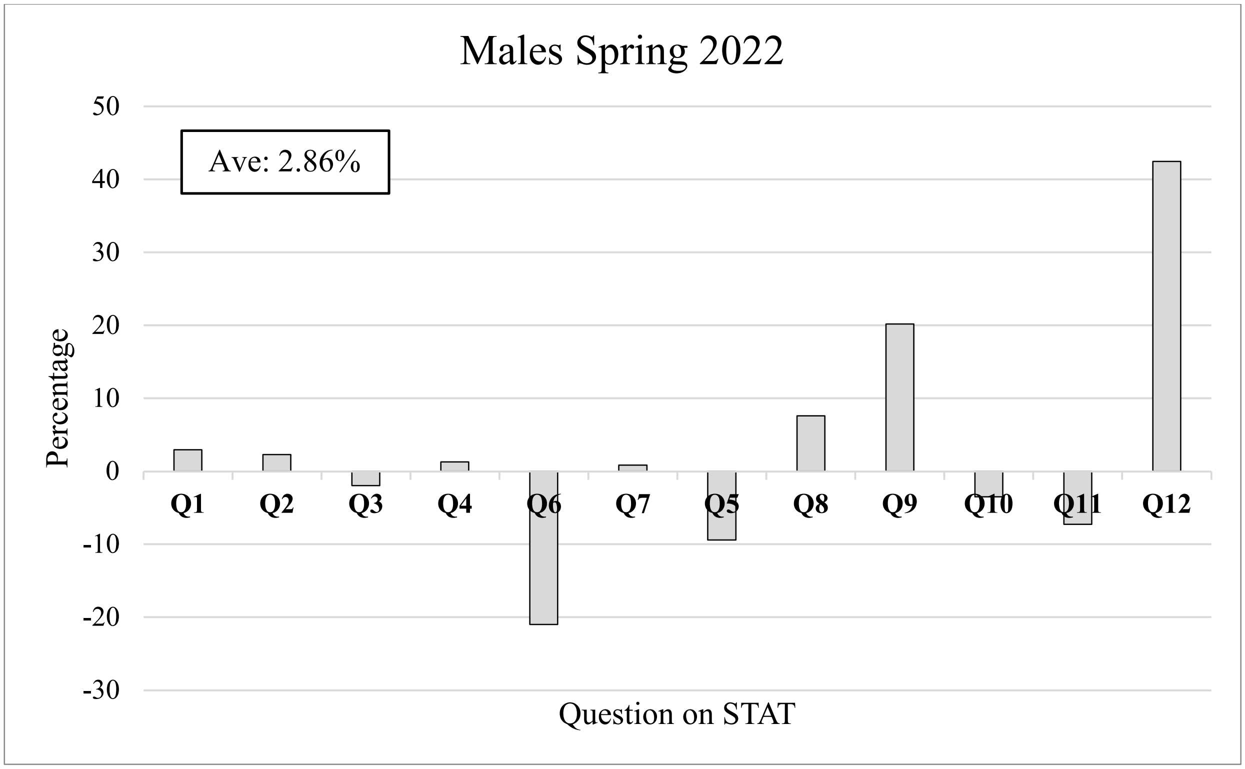


Figure 4.82: *Shows the normalized learning gains between the STAT pre-test and post-test for each question for Males in the Spring 2022 semester.*

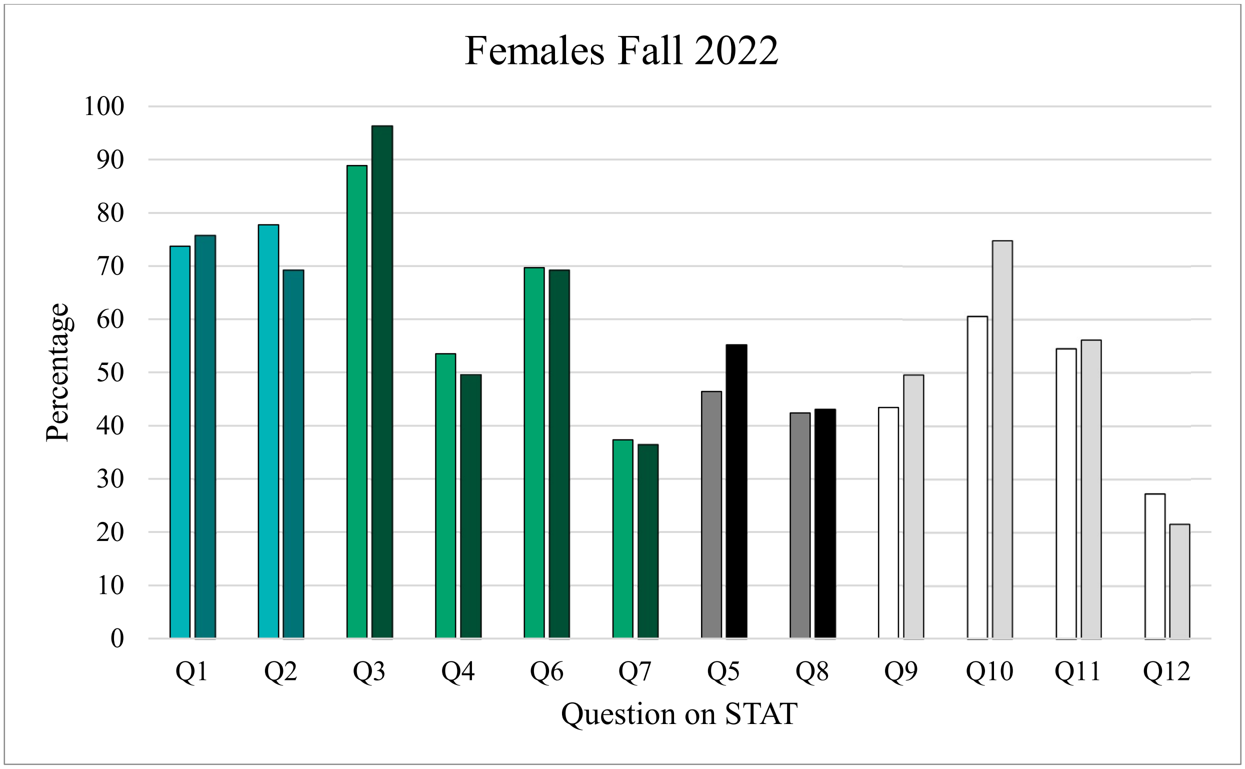


Figure 4. 83: *Shows what percentage of students correctly answered each question for Females in the Fall 2022 semester. The lighter shades are the pre-test, while the darker shades are the post-test.*

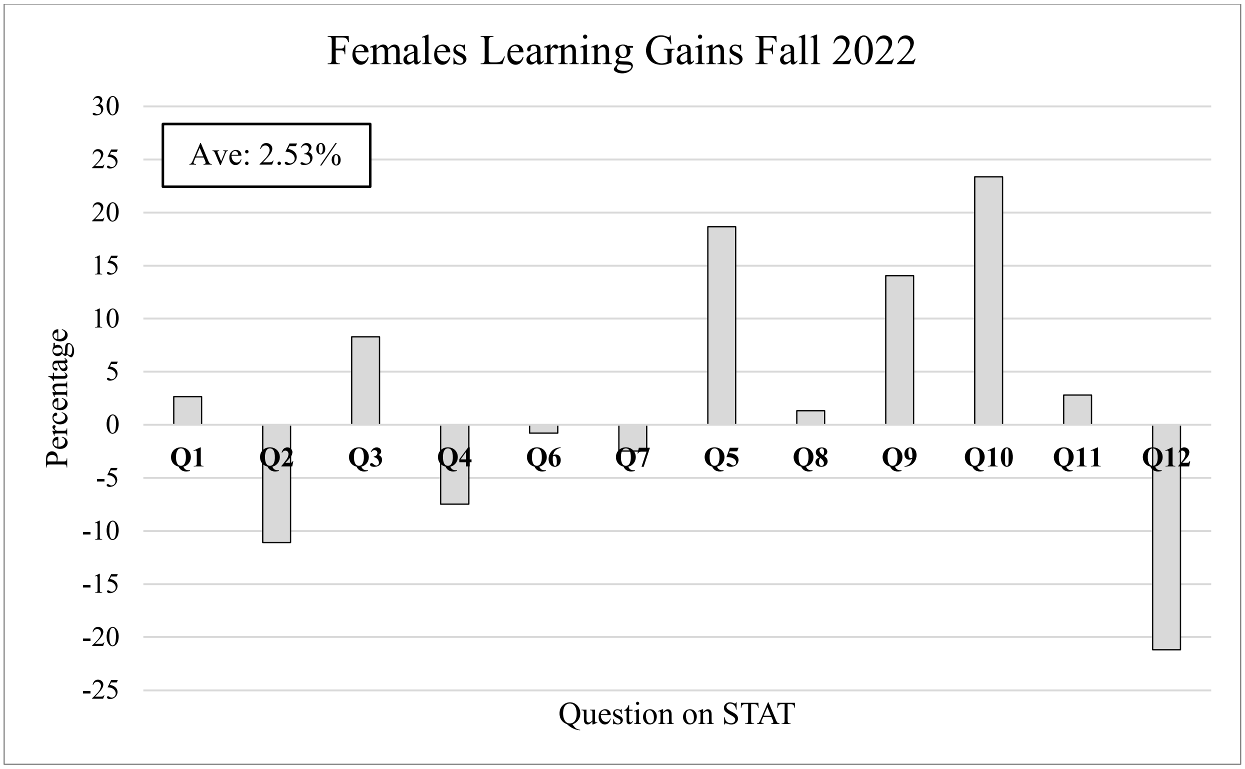


Figure 4. 84: *Shows the normalized learning gains between the STAT pre-test and post-test for each question for Females in the Fall 2022 semester.*

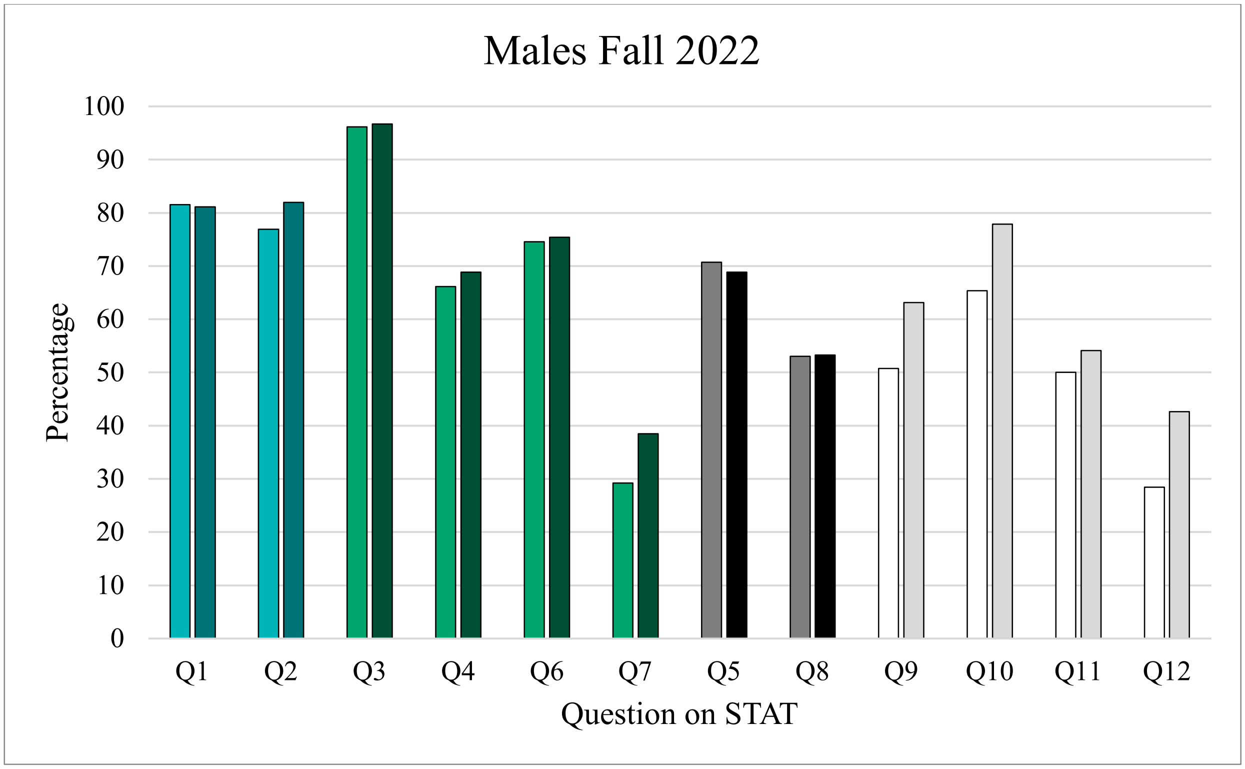


Figure 4. 85: *Shows what percentage of students correctly answered each question for Males in the Fall 2022 semester. The lighter shades are the pre-test, while the darker shades are the post-test.*

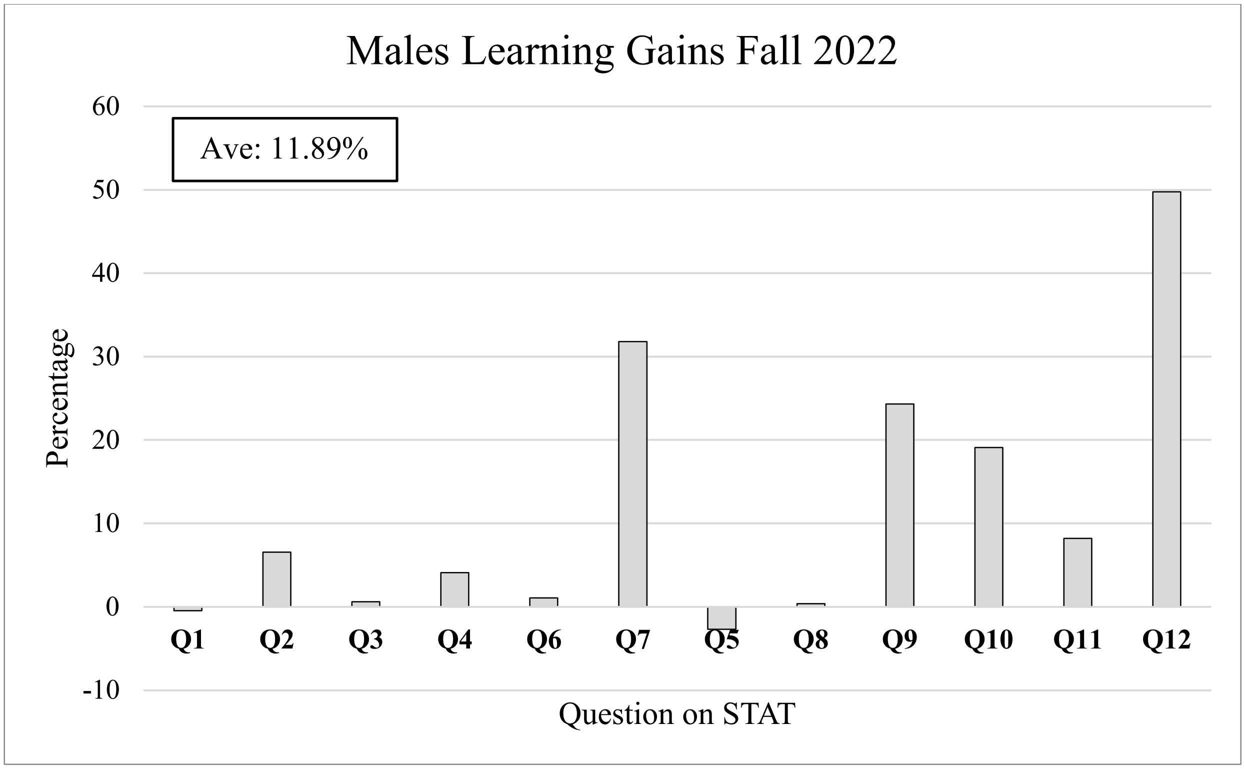


Figure 4. 86: *Shows the normalized learning gains between the STAT pre-test and post-test for each question for Males in the Fall 2022 semester.*

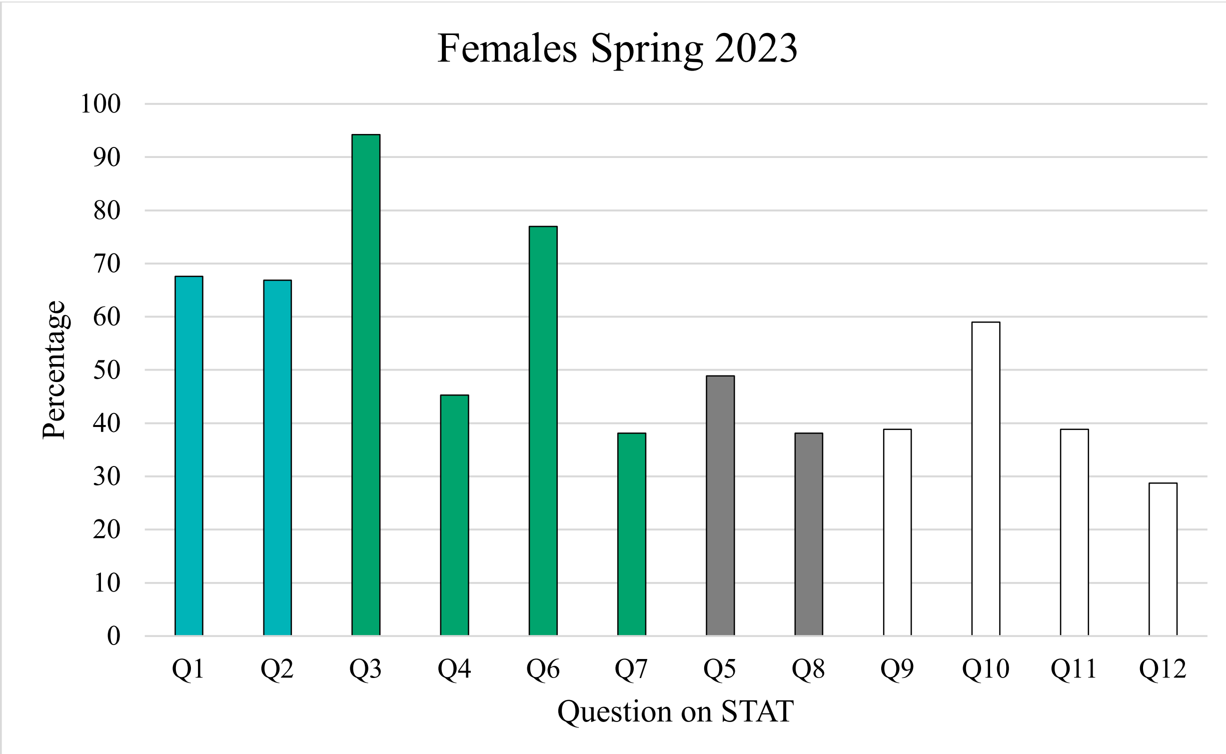


Figure 4.87: *Shows what percentage of students correctly answered each question for the pre-test for Females in the Spring 2023 semester.*

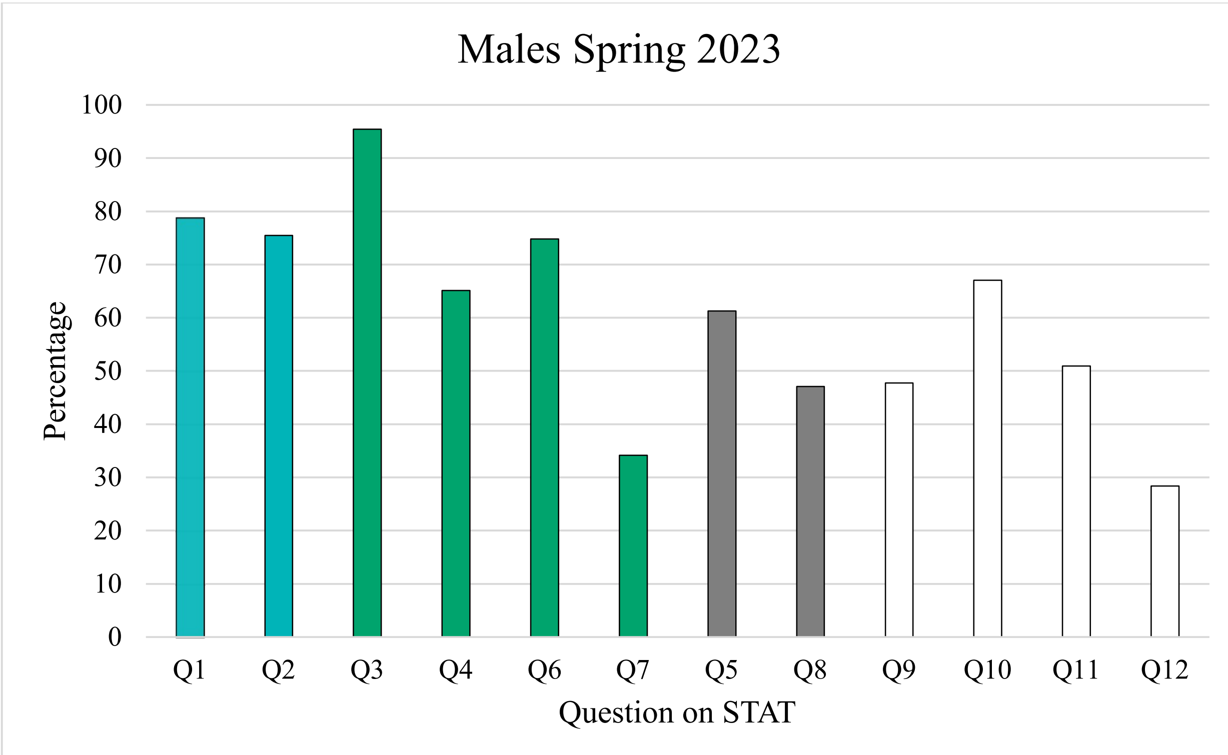


Figure 4.88: *Shows what percentage of students correctly answered each question for the pre-test for Males in the Spring 2023 semester.*

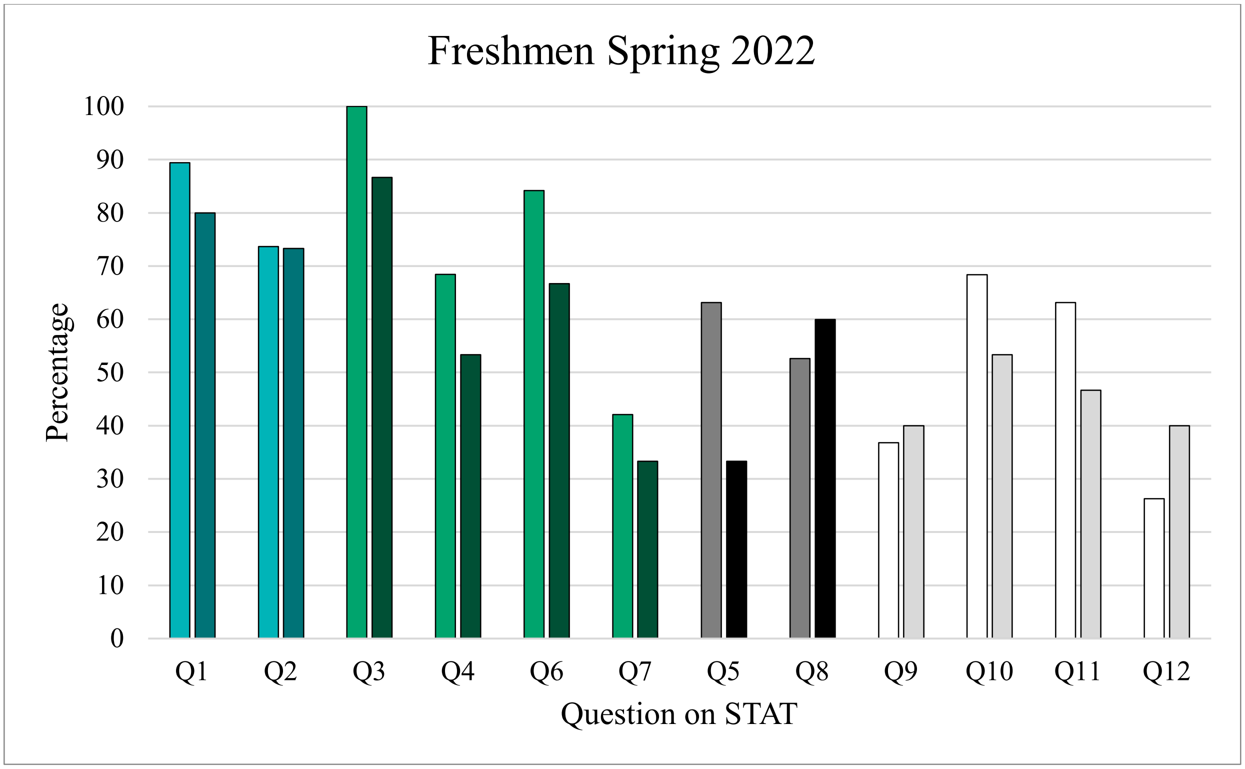


Figure 4.89: *Shows what percentage of students correctly answered each question for Freshmen in the Spring 2022 semester. The lighter shades are the pre-test, while the darker shades are the post-test.*

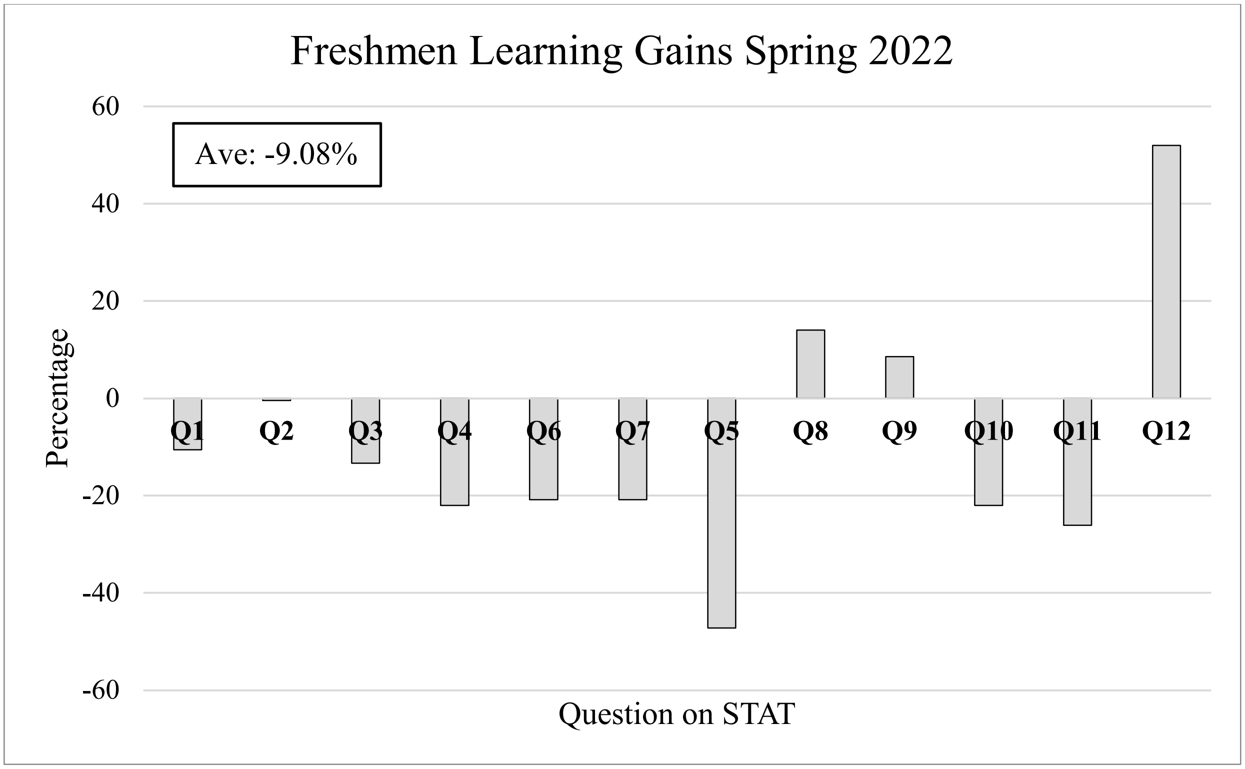


Figure 4.90: *Shows the normalized learning gains between the STAT pre-test and post-test for each question for Freshmen in the Spring 2022 semester.*

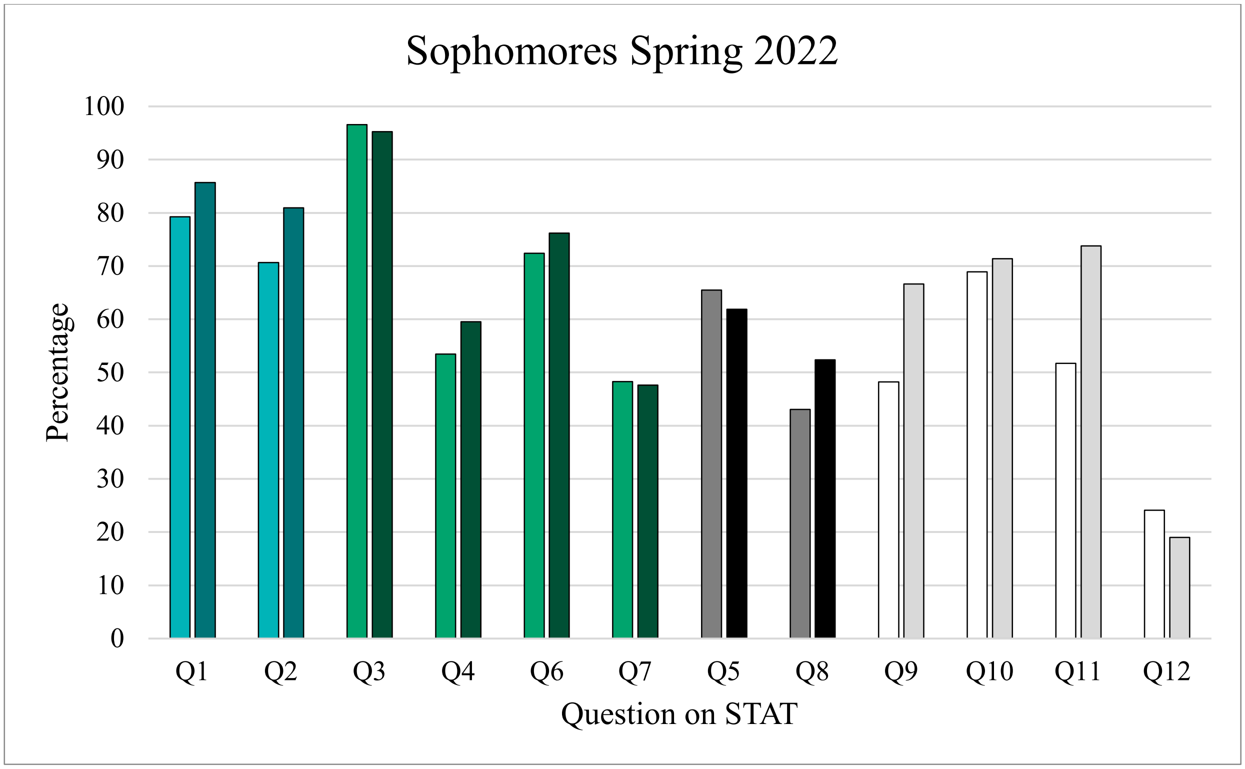


Figure 4.91: *Shows what percentage of students correctly answered each question for Sophomores in the Spring 2022 semester. The lighter shades are the pre-test, while the darker shades are the post-test.*

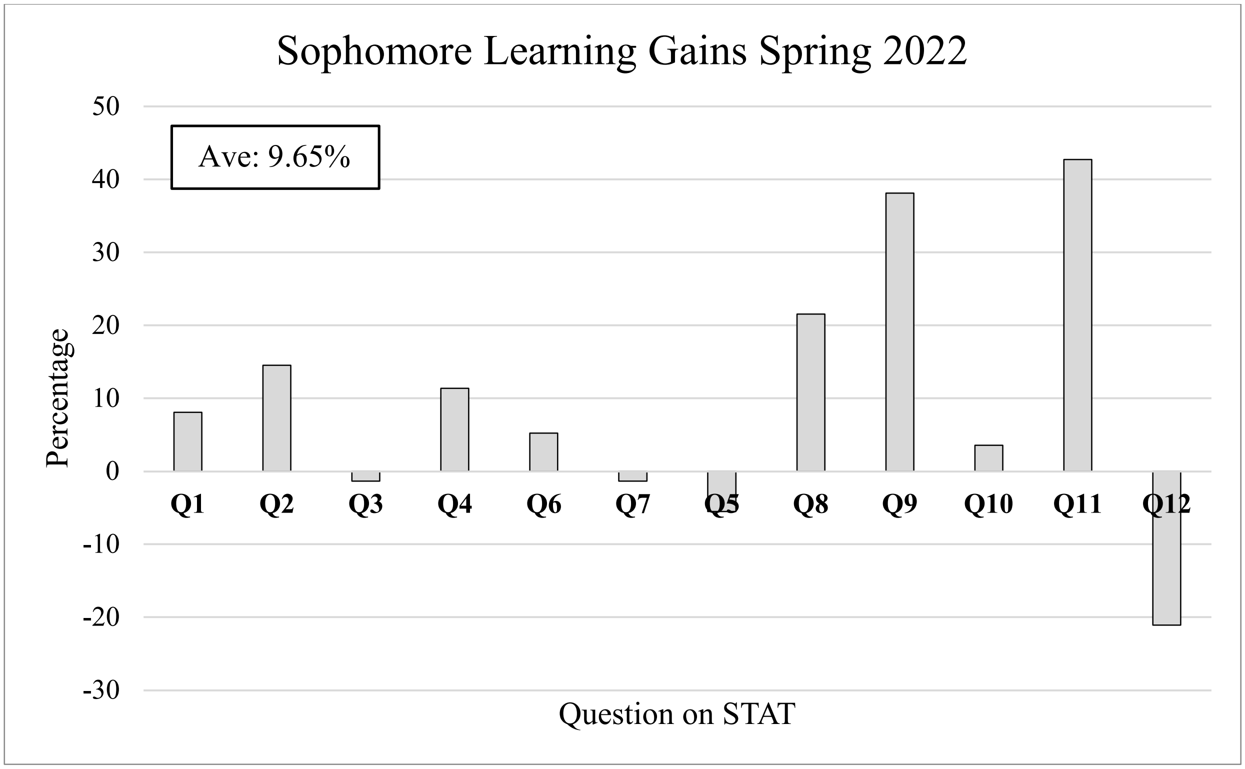


Figure 4. 92: *Shows the normalized learning gains between the STAT pre-test and post-test for each question for Sophomores in the Spring 2022 semester*

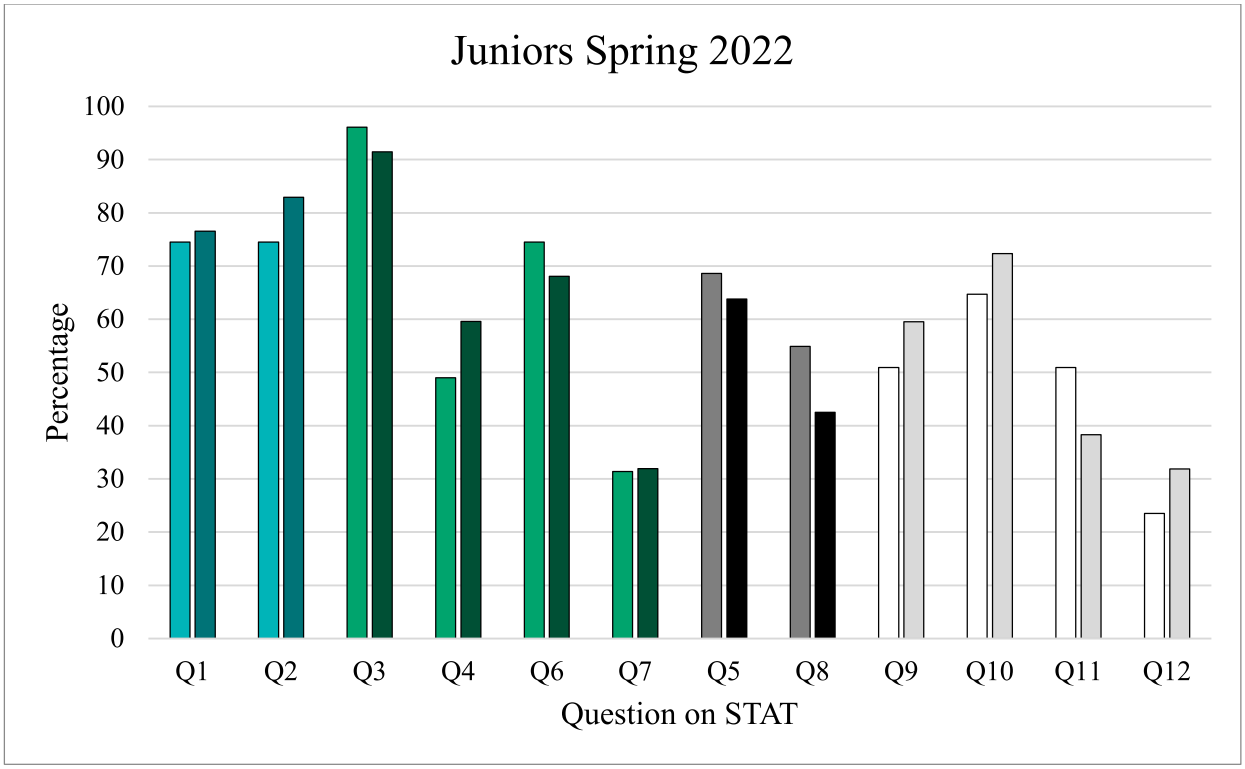


Figure 4.93: *Shows what percentage of students correctly answered each question for Juniors in the Spring 2022 semester. The lighter shades are the pre-test, while the darker shades are the post-test.*

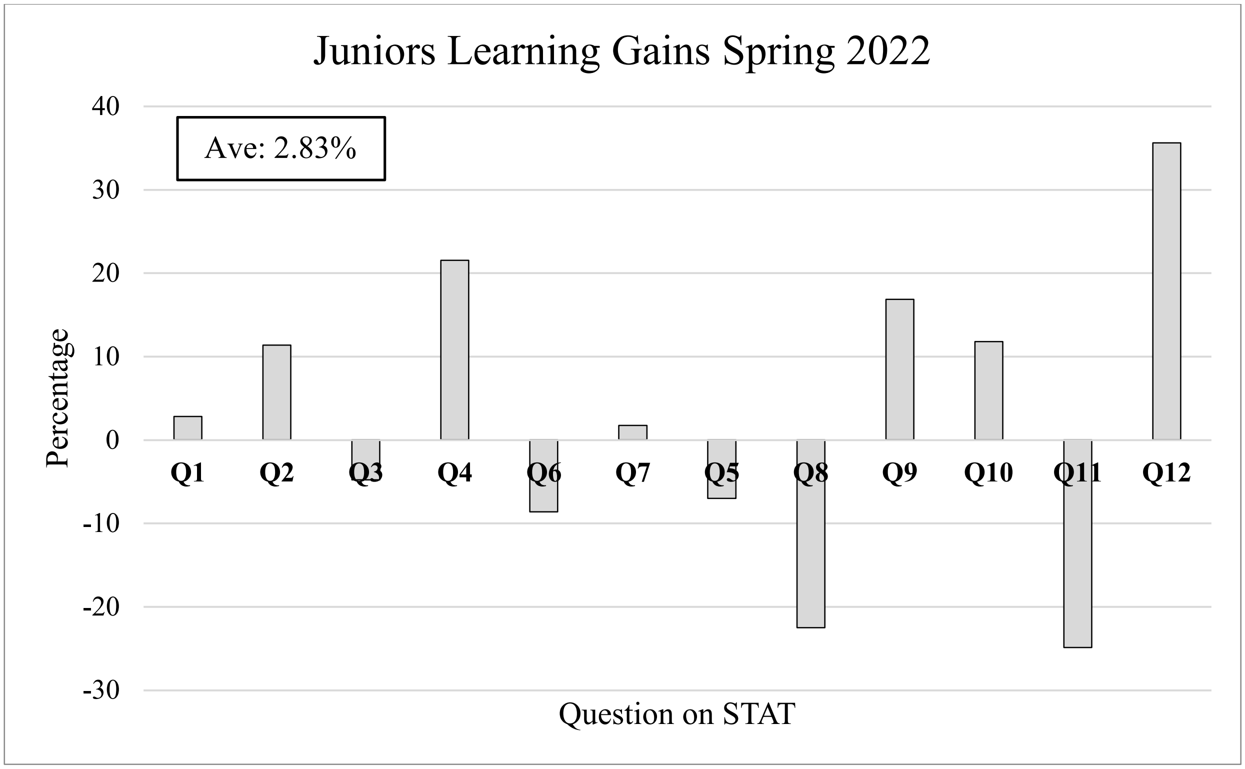


Figure 4.94: *Shows the normalized learning gains between the STAT pre-test and post-test for each question for Juniors in the Spring 2022 semester.*

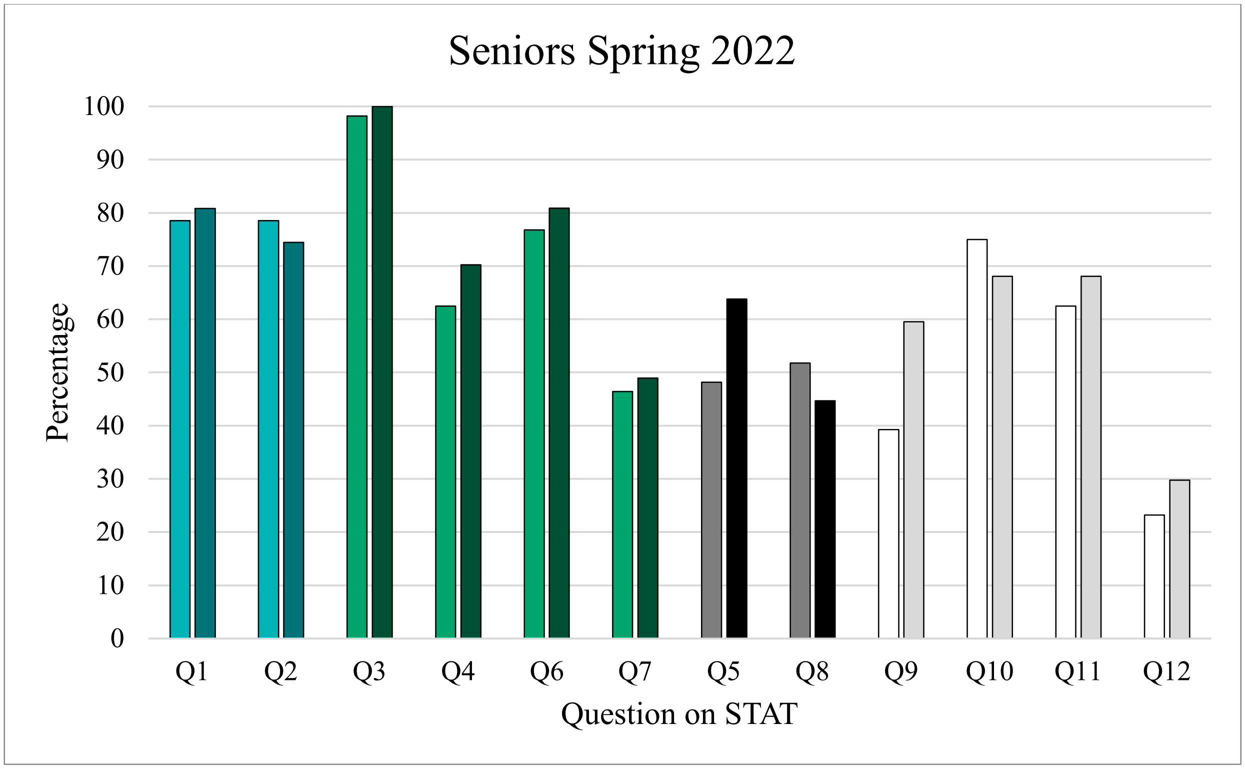


Figure 4.95: *Shows what percentage of students correctly answered each question for Seniors in the Spring 2022 semester. The lighter shades are the pre-test, while the darker shades are the post-test.*

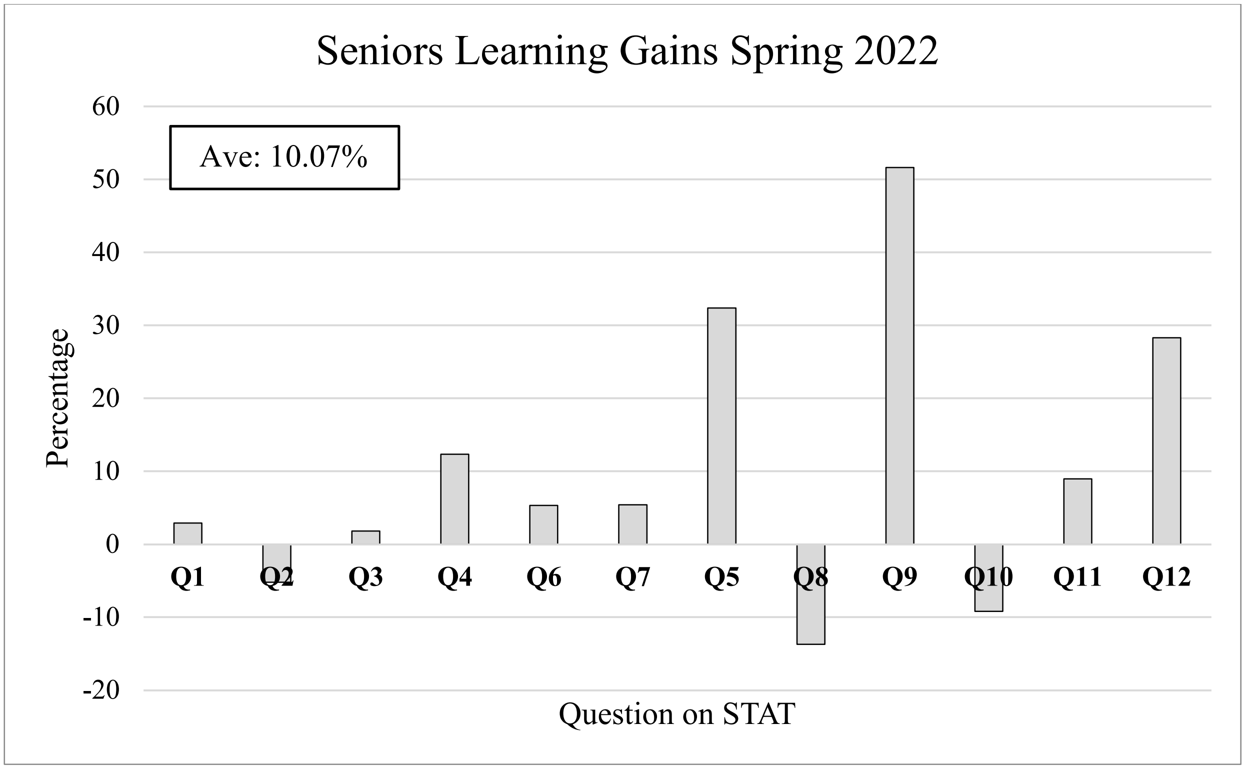


Figure 4.96: *Shows the normalized learning gains between the STAT pre-test and post-test for each question for Seniors in the Spring 2022 semester.*

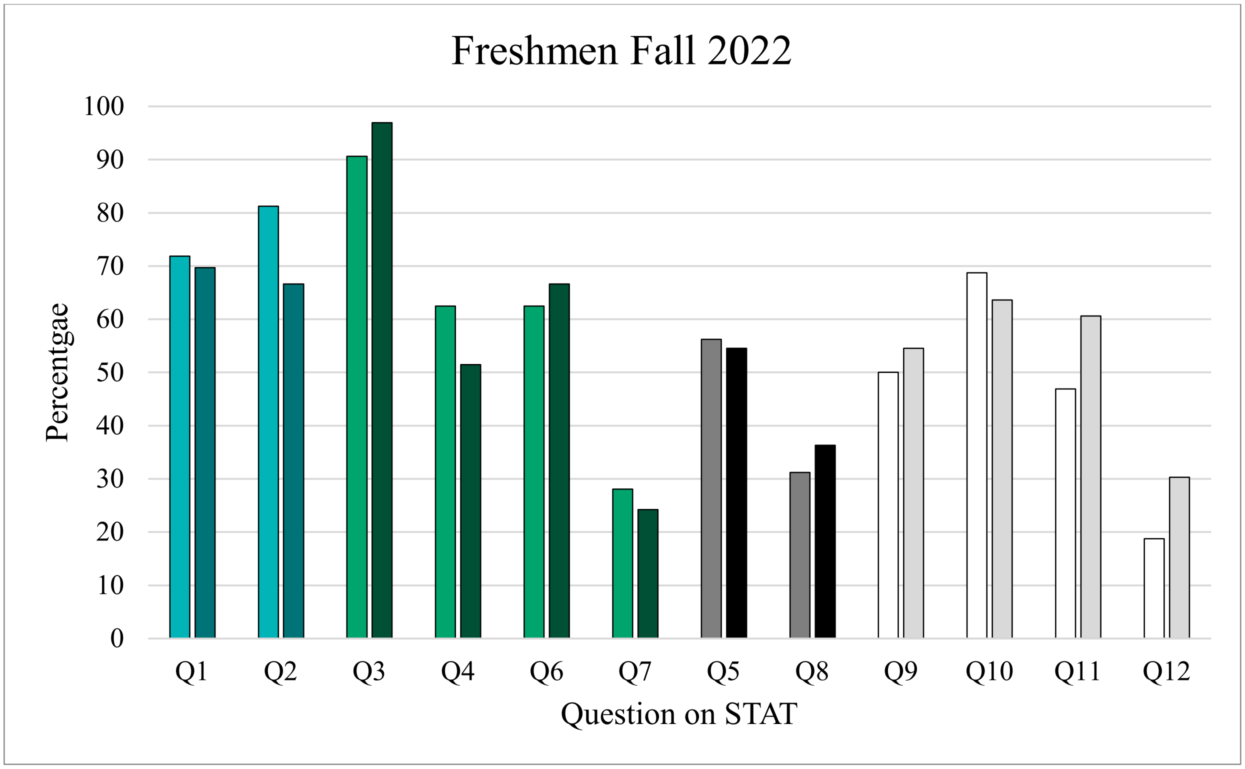


Figure 4.97: *Shows what percentage of students correctly answered each question for Freshmen in the Fall 2022 semester. The lighter shades are the pre-test, while the darker shades are the post-test.*

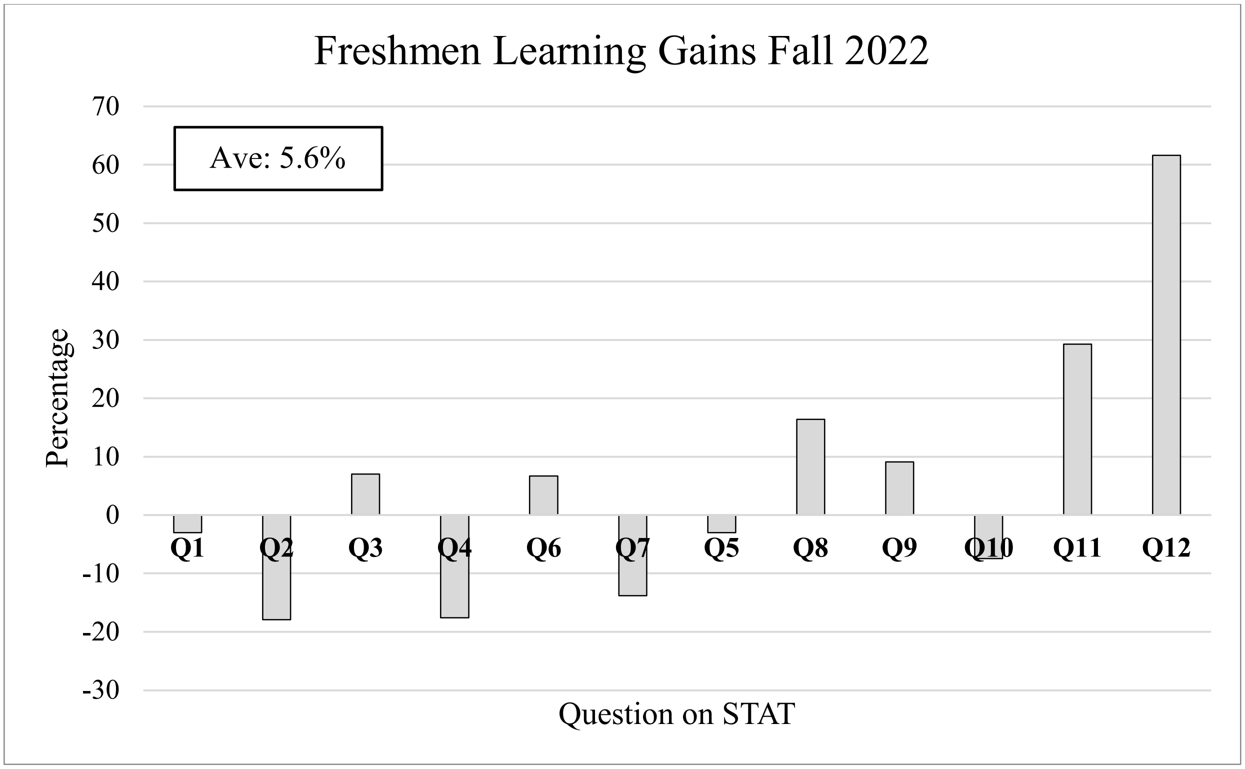


Figure 4.98: *Shows the normalized learning gains between the STAT pre-test and post-test for each question for Freshmen in the Fall 2022 semester.*

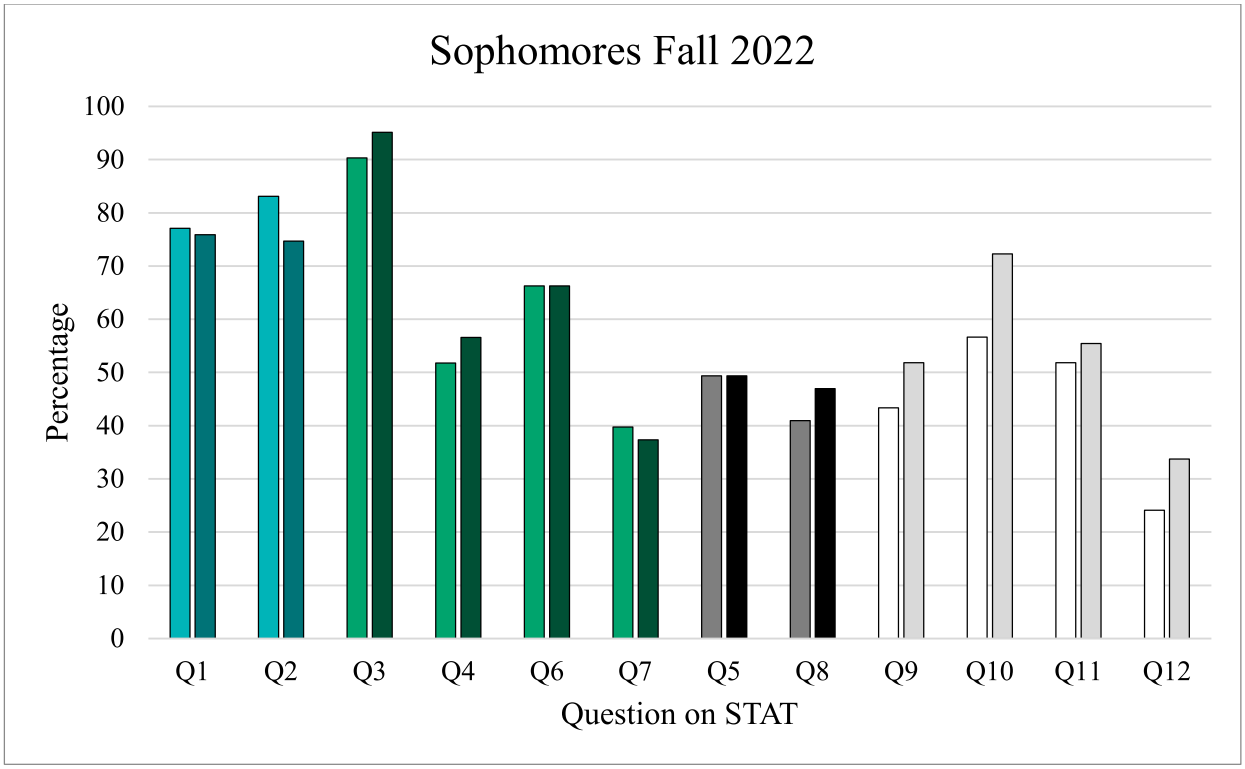


Figure 4.99: *Shows what percentage of students correctly answered each question for Sophomores in the Fall 2022 semester. The lighter shades are the pre-test, while the darker shades are the post-test.*

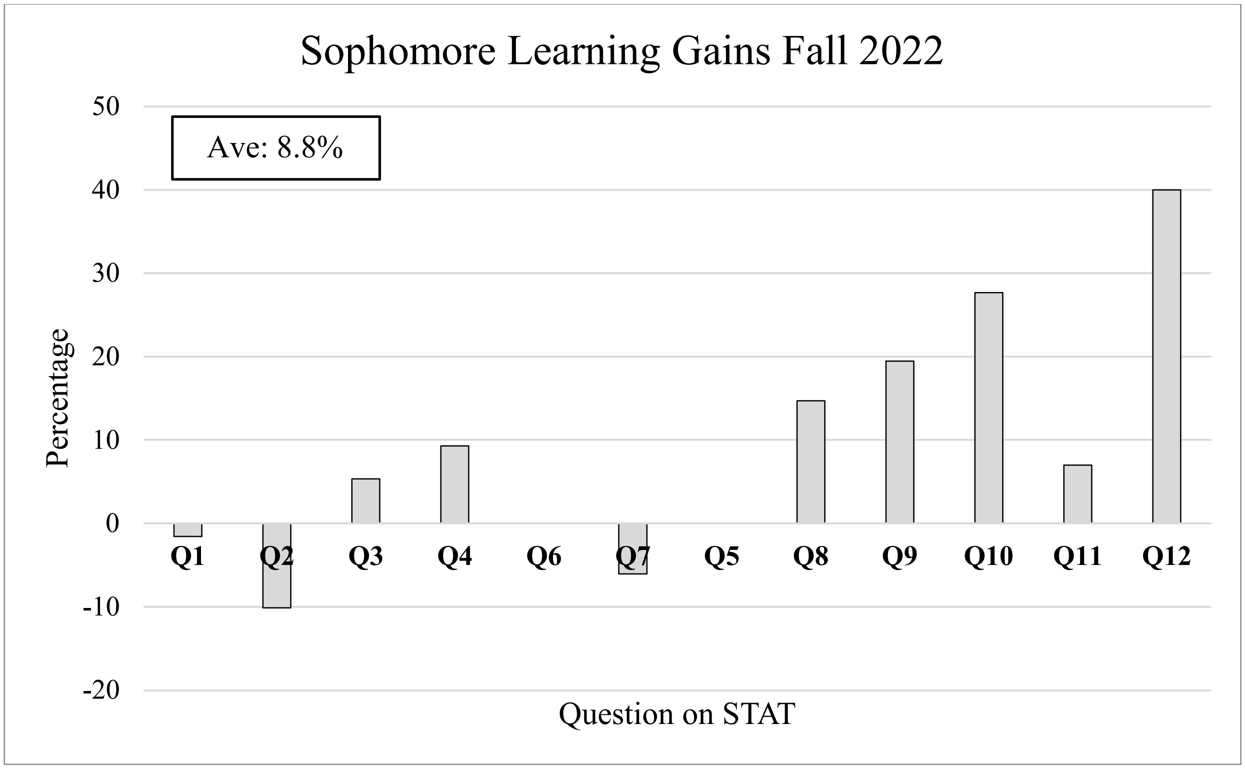


Figure 4.100: *Shows the normalized learning gains between the STAT pre-test and post-test for each question for Sophomore in the Fall 2022 semester.*

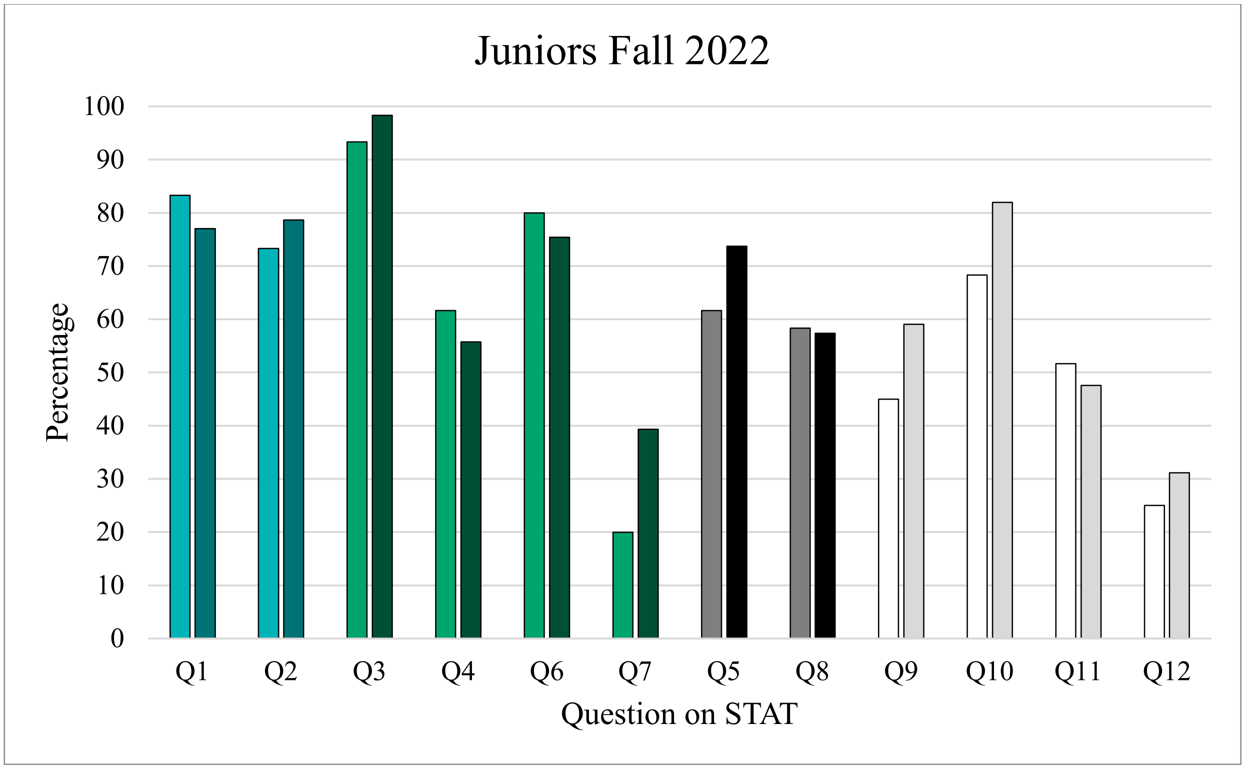


Figure 4.101: *Shows what percentage of students correctly answered each question for Juniors in the Fall 2022 semester. The lighter shades are the pre-test, while the darker shades are the post-test.*

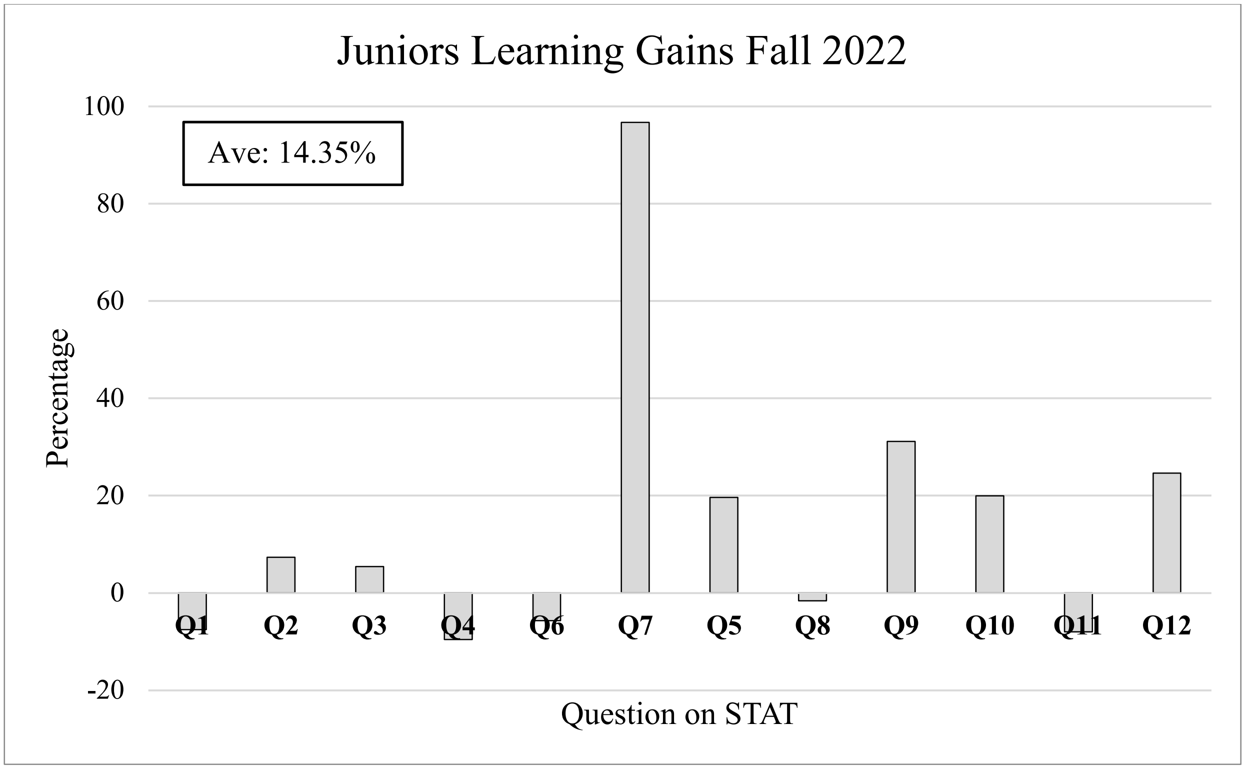


Figure 4.102: *Shows the normalized learning gains between the STAT pre-test and post-test for each question for Juniors in the Fall 2022 semester.*

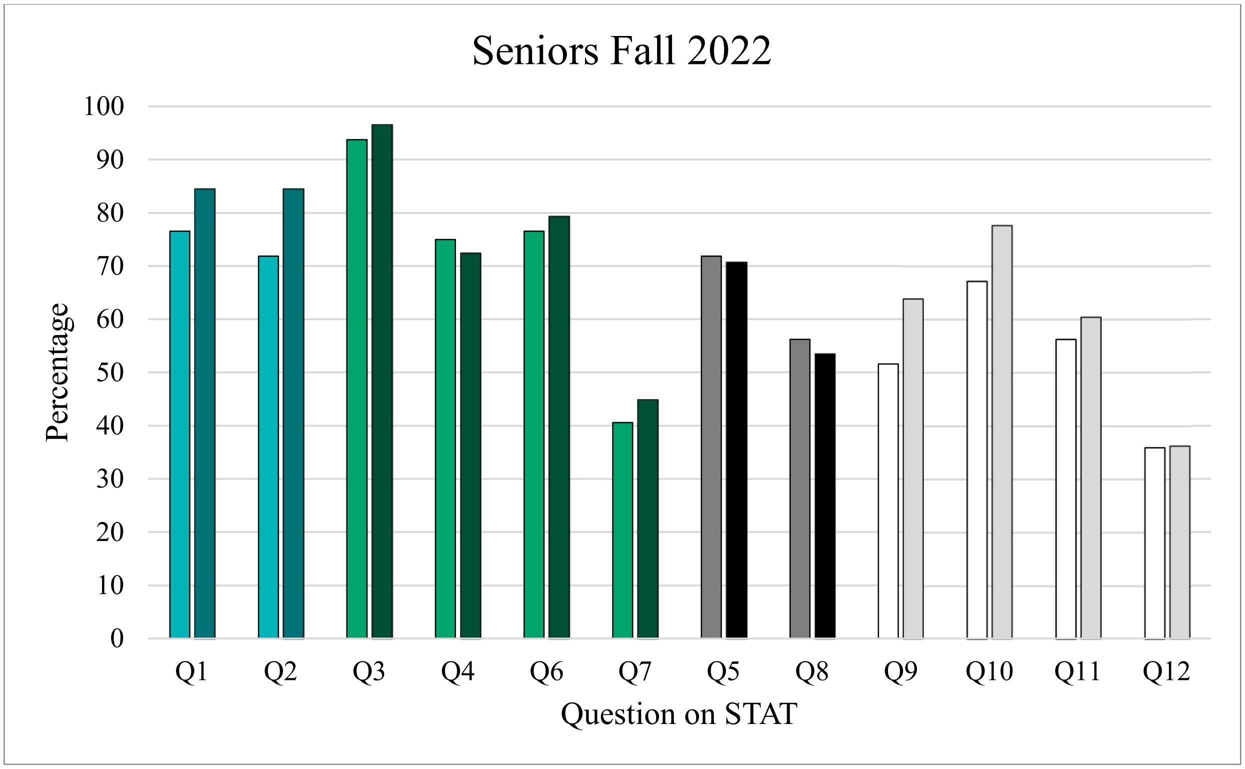


Figure 4. 103: *Shows what percentage of students correctly answered each question for Seniors in the Fall 2022 semester. The lighter shades are the pre-test, while the darker shades are the post-test.*

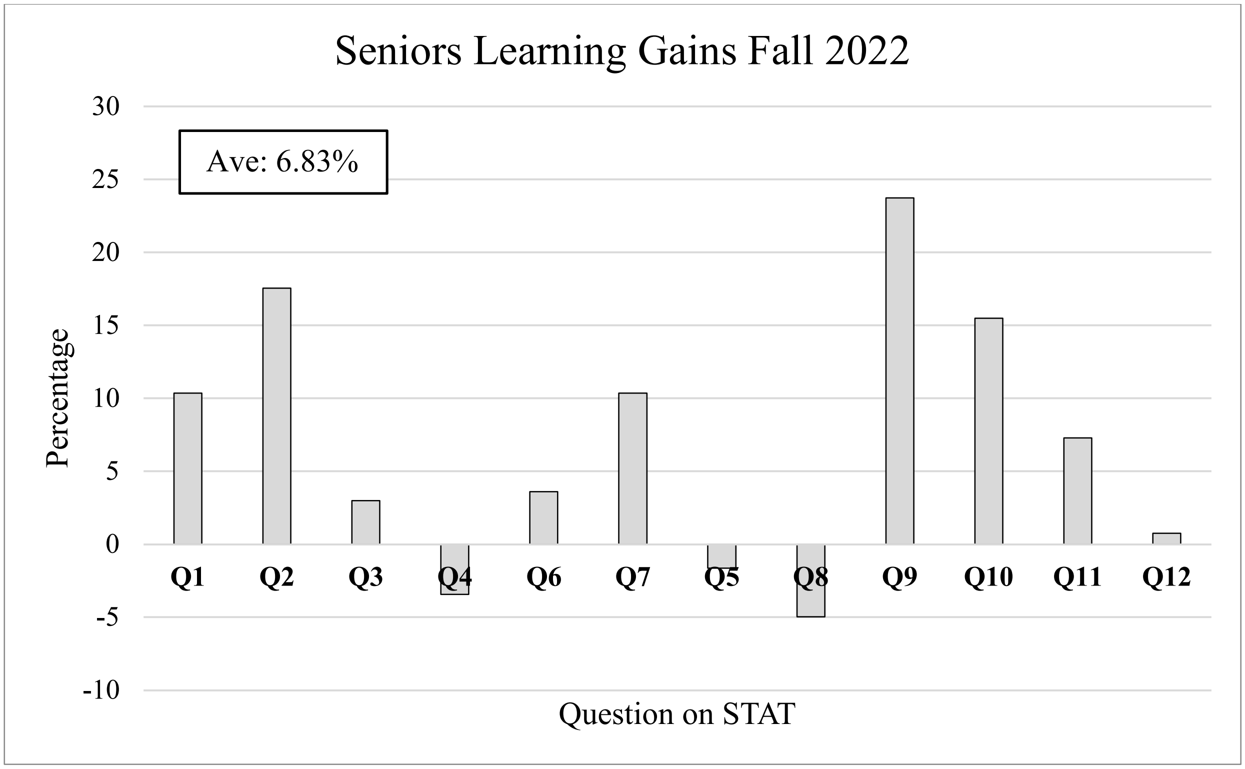


Figure 4. 104: *Shows the normalized learning gains between the STAT pre-test and post-test for each question for Seniors in the Fall 2022 semester.*

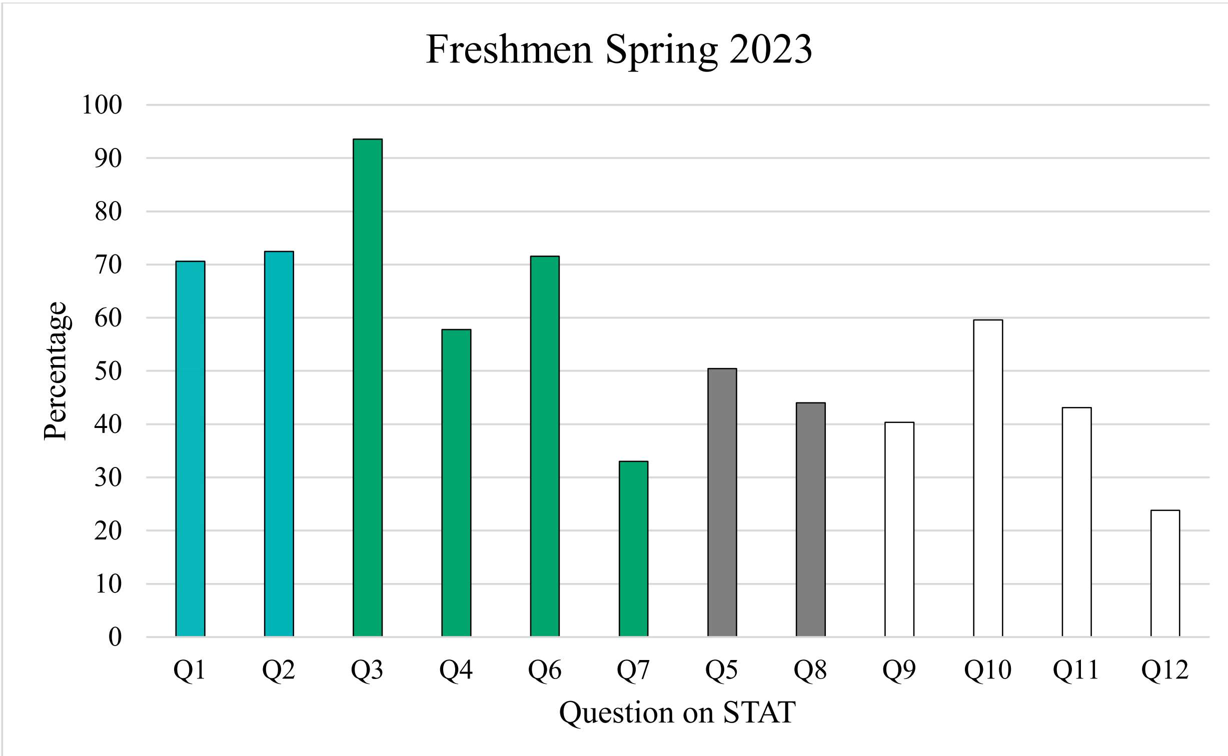


Figure 4.105: *Shows what percentage of students correctly answered each question for the pre-test for Freshmen in the Spring 2023 semester.*

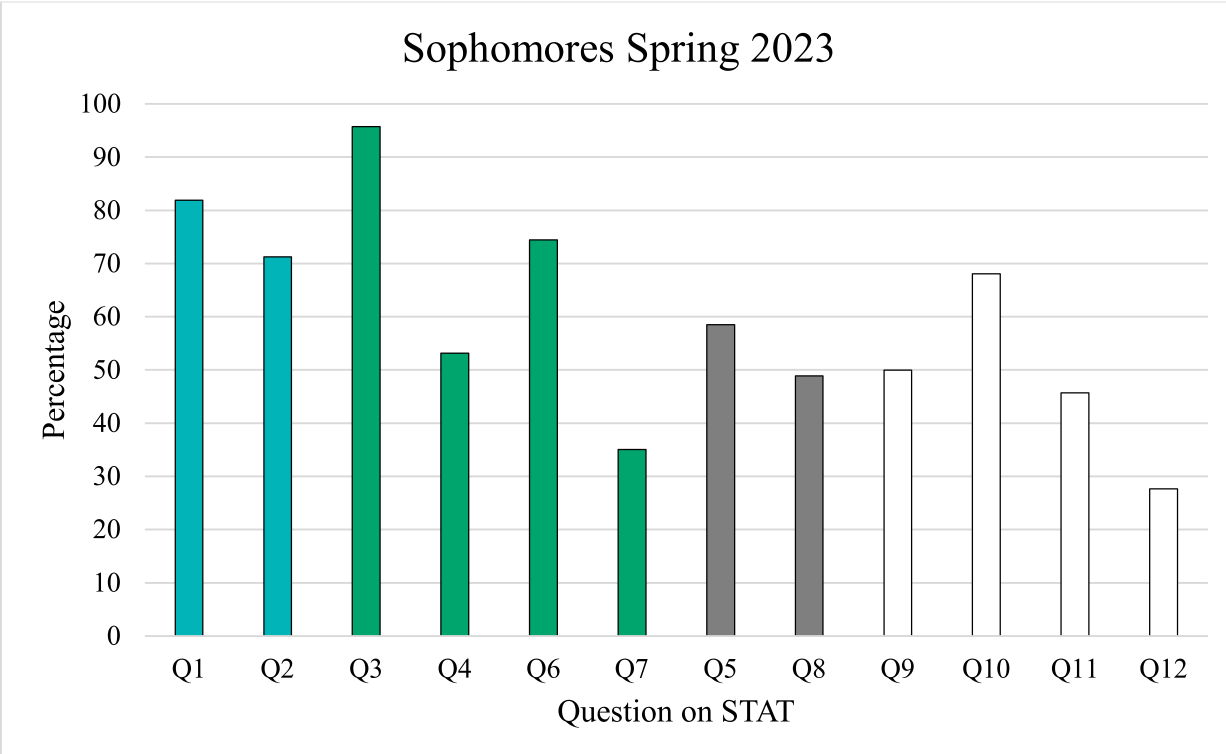


Figure 4.106: *Shows what percentage of students correctly answered each question for the pre-test for Sophomores in the Spring 2023 semester.*

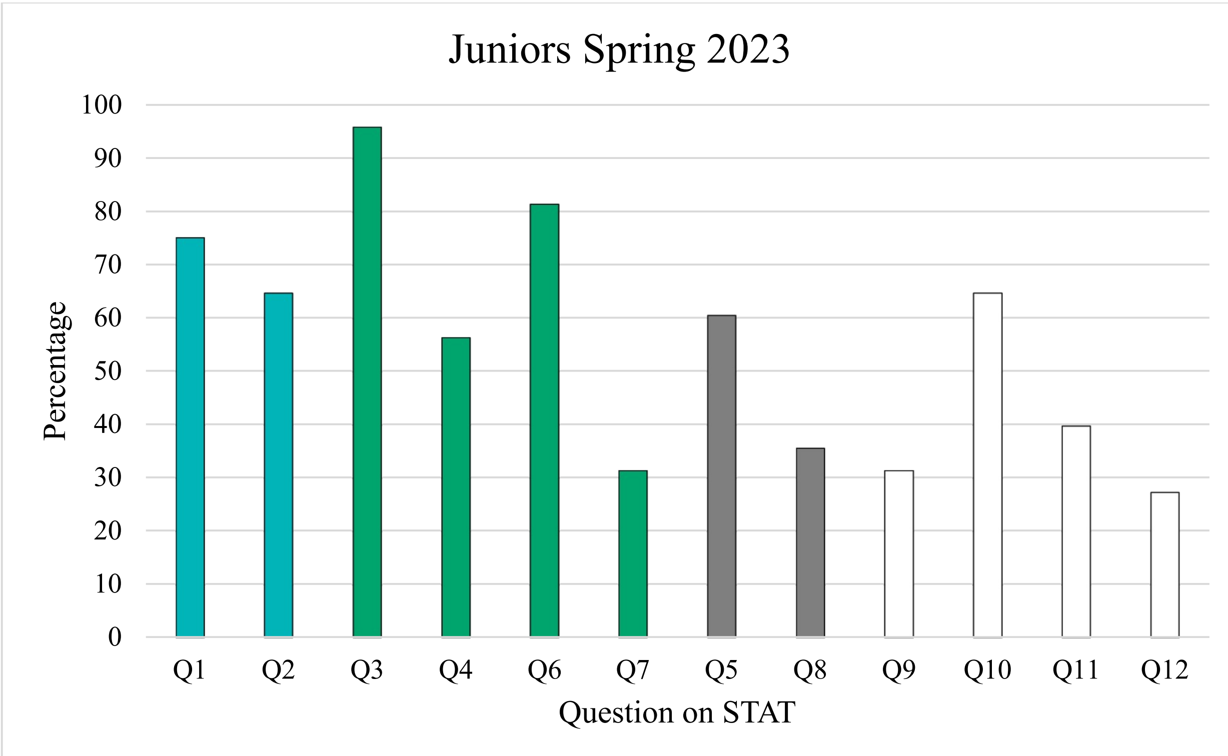


Figure 4. 107: *Shows what percentage of students correctly answered each question for the pre-test for Juniors in the Spring 2023 semester.*

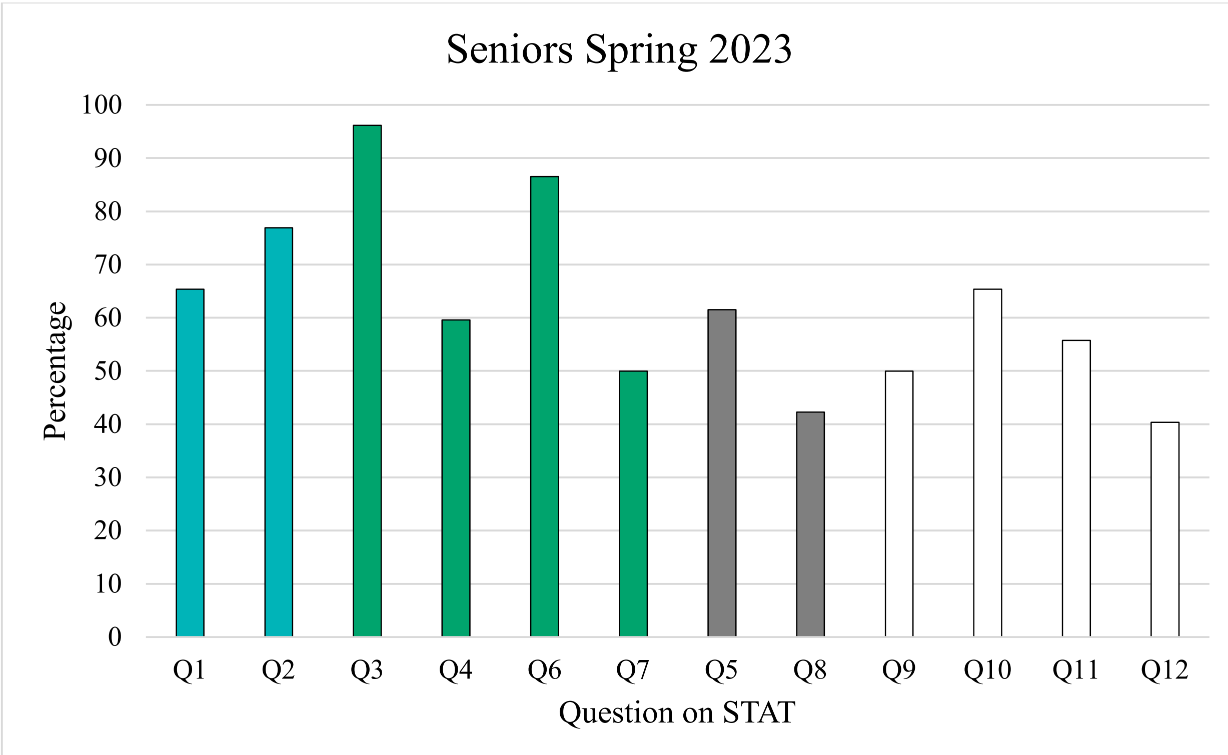


Figure 4.108: *Shows what percentage of students correctly answered each question for the pre-test for Seniors in the Spring 2023 semester.*

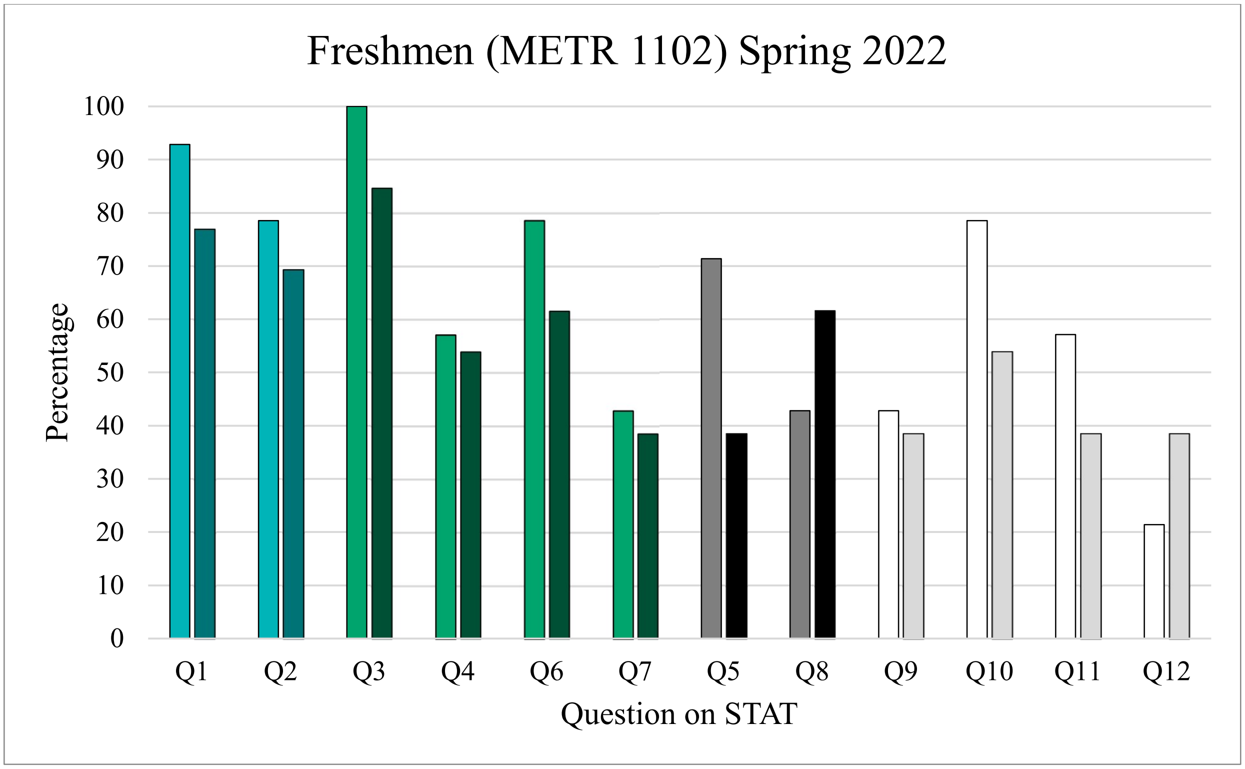


Figure 4.109: *Shows what percentage of students correctly answered each question for Freshmen (METR 1102) in the Spring 2022 semester. The lighter shades are the pre-test, while the darker shades are the post-test.*

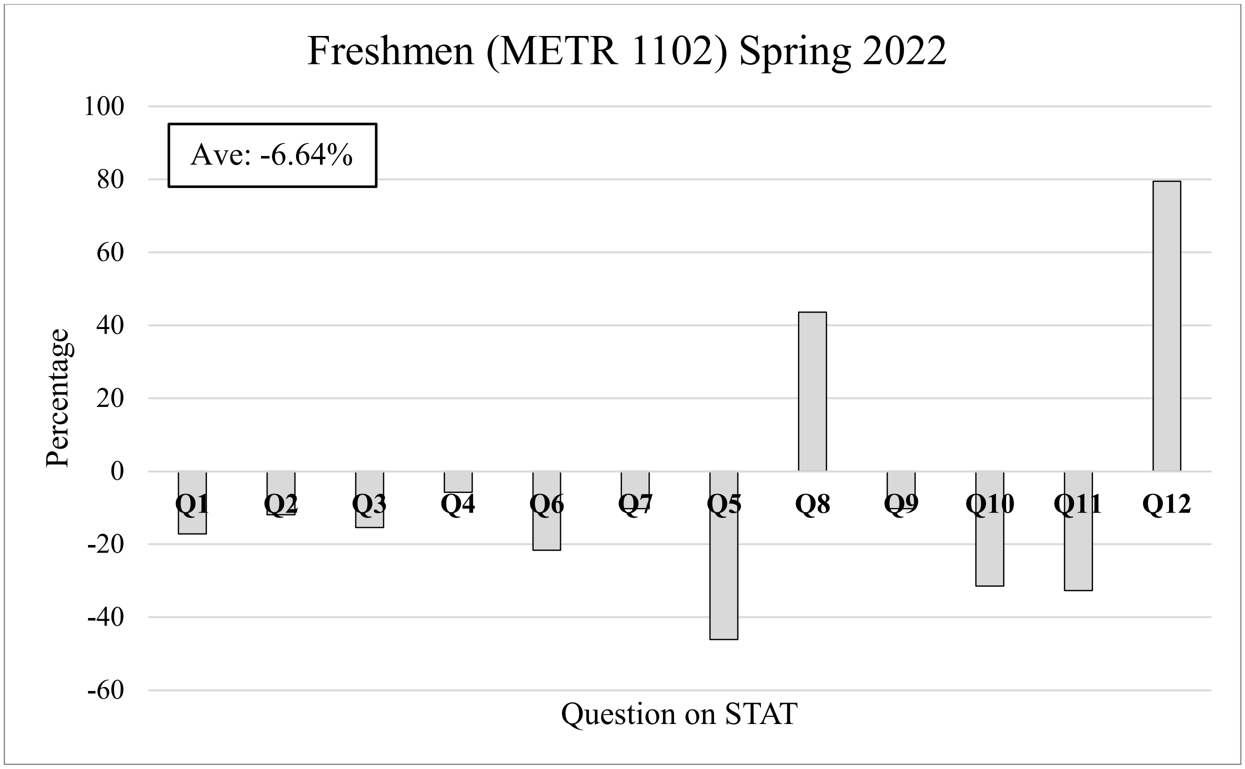


Figure 4.110: *Shows the normalized learning gains between the STAT pre-test and post-test for each question for Freshmen (METR 1102) in the Spring 2022 semester.*

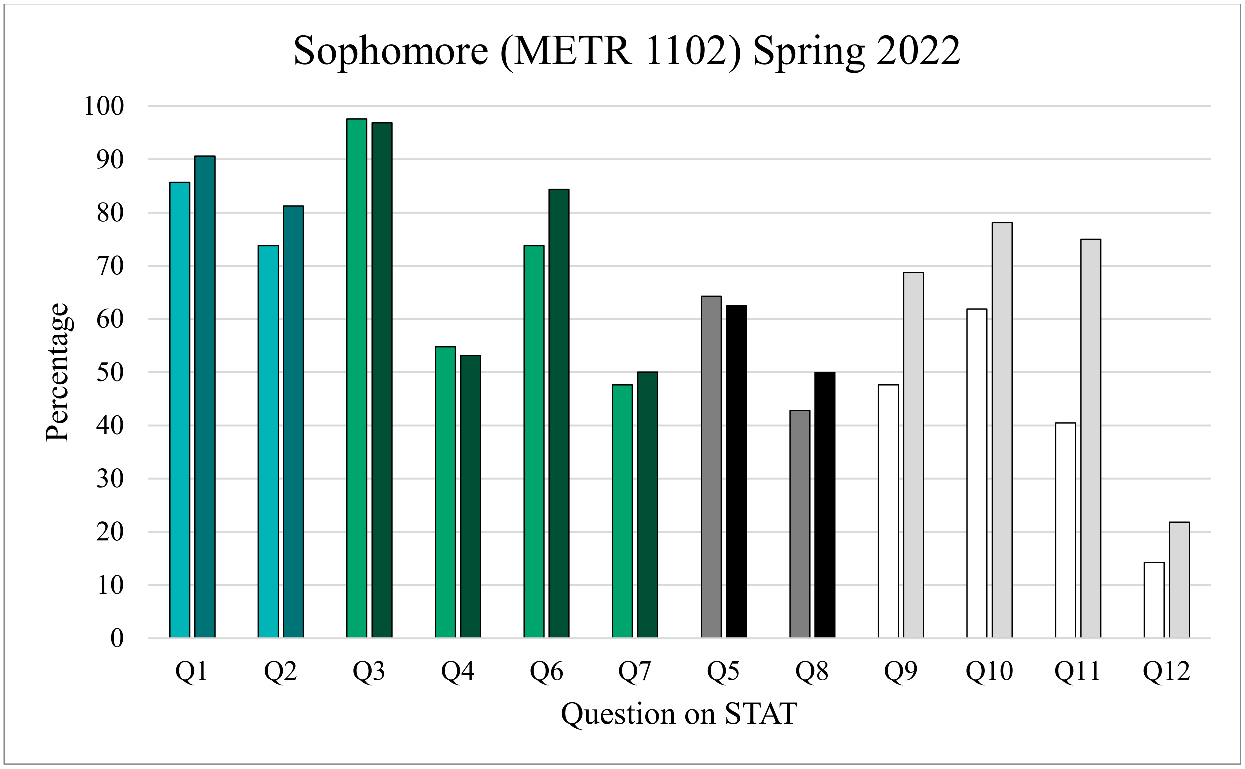


Figure 4. 111: *Shows what percentage of students correctly answered each question for Sophomores (METR 1102) in the Spring 2022 semester. The lighter shades are the pre-test, while the darker shades are the post-test.*

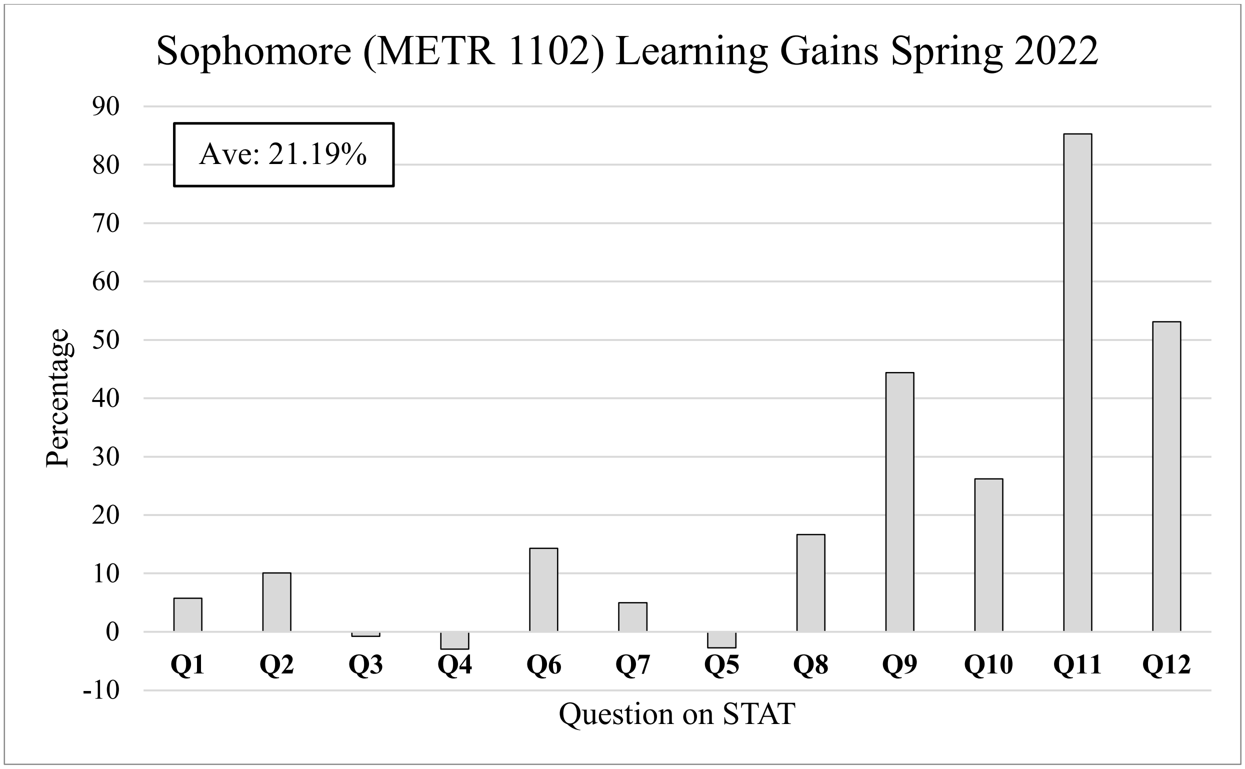


Figure 4. 112: *Shows the normalized learning gains between the STAT pre-test and post-test for each question for Sophomores (METR 1102) in the Spring 2022 semester.*

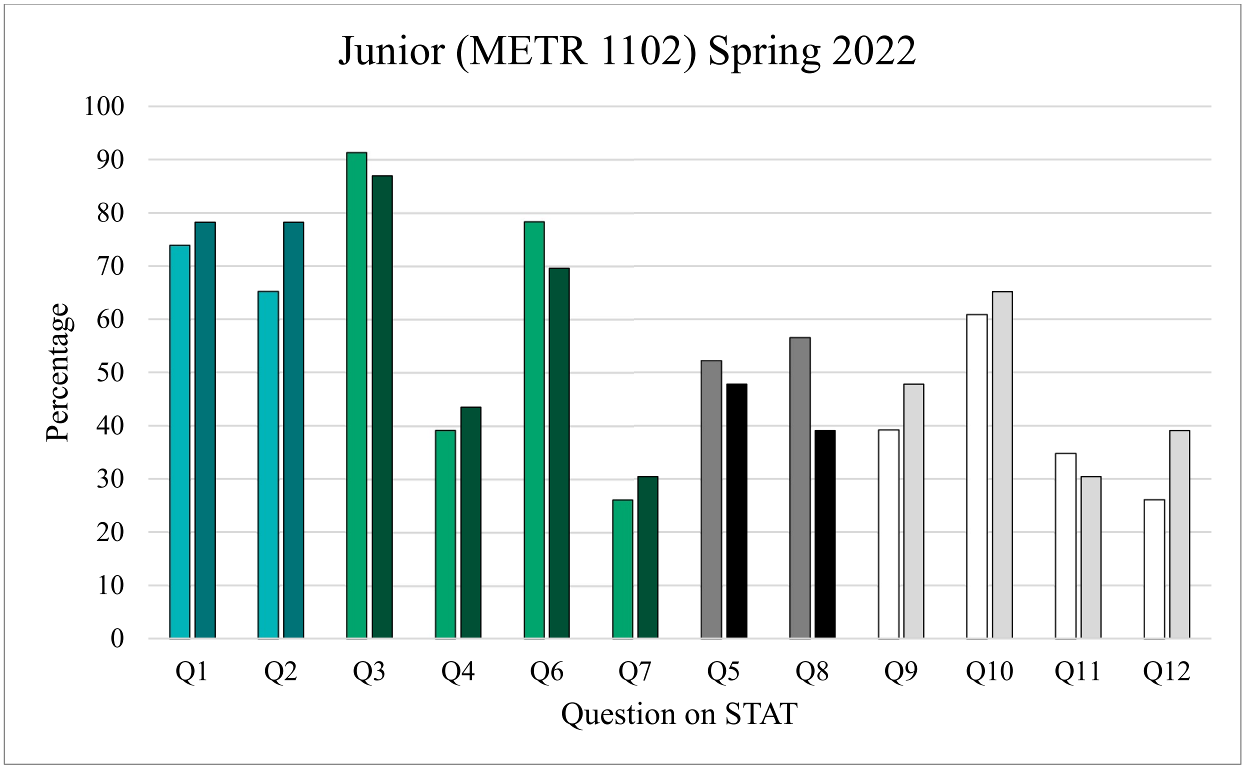


Figure 4.113: *Shows what percentage of students correctly answered each question for Juniors (METR 1102) in the Spring 2022 semester. The lighter shades are the pre-test, while the darker shades are the post-test.*

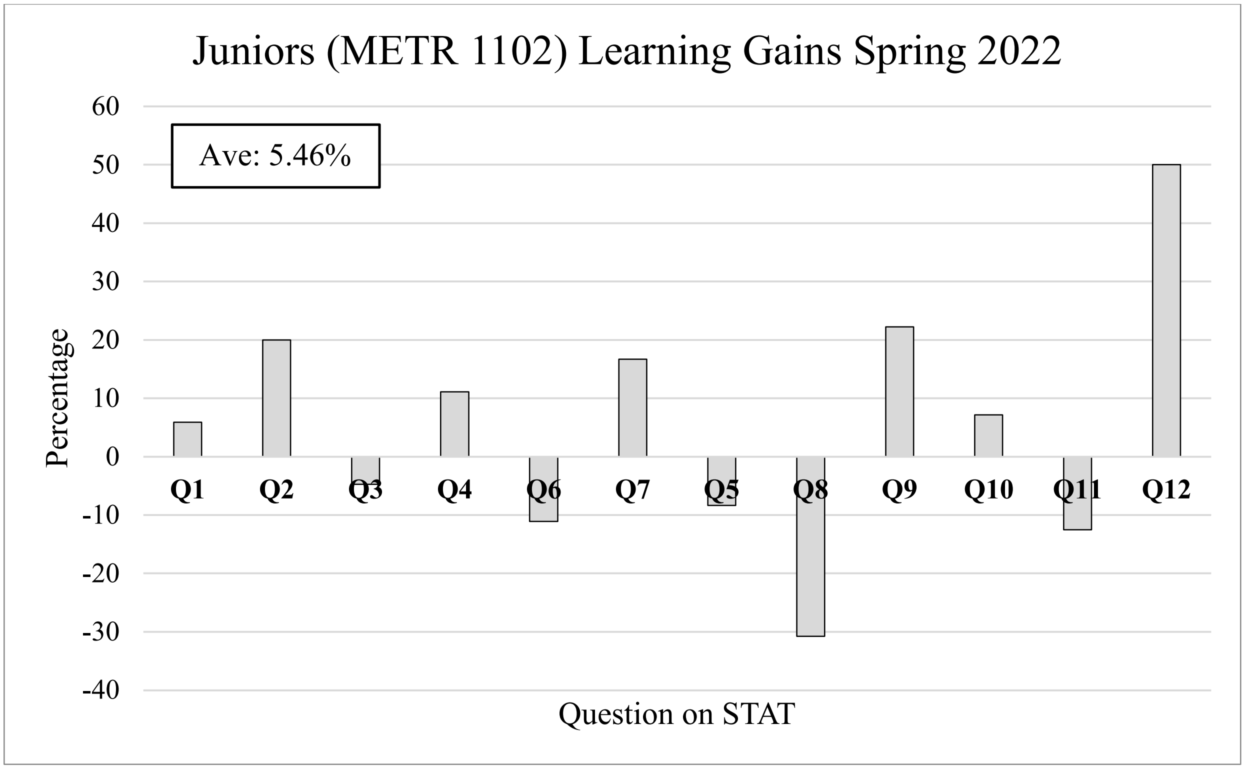


Figure 4. 114: *Shows the normalized learning gains between the STAT pre-test and post-test for each question for Juniors (METR 1102) in the Spring 2022 semester.*

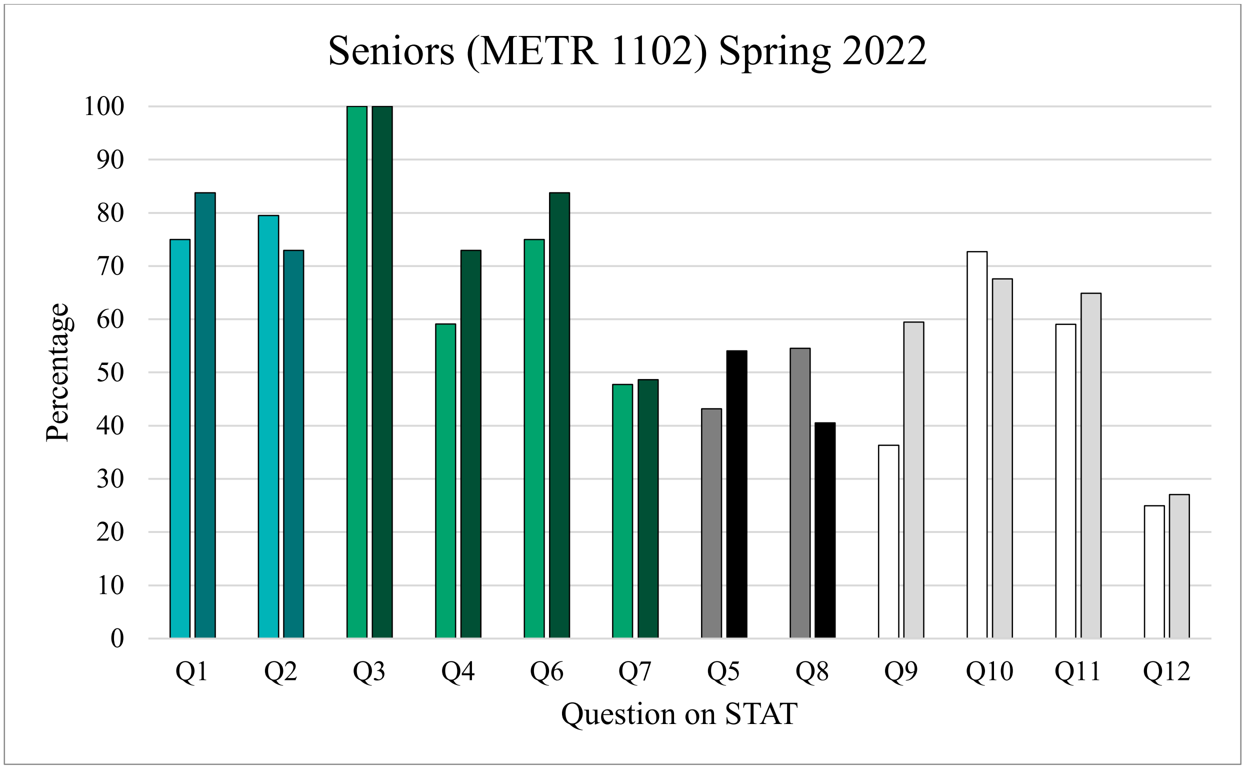


Figure 4.115: *Shows what percentage of students correctly answered each question for Seniors (METR 1102) in the Spring 2022 semester. The lighter shades are the pre-test, while the darker shades are the post-test.*

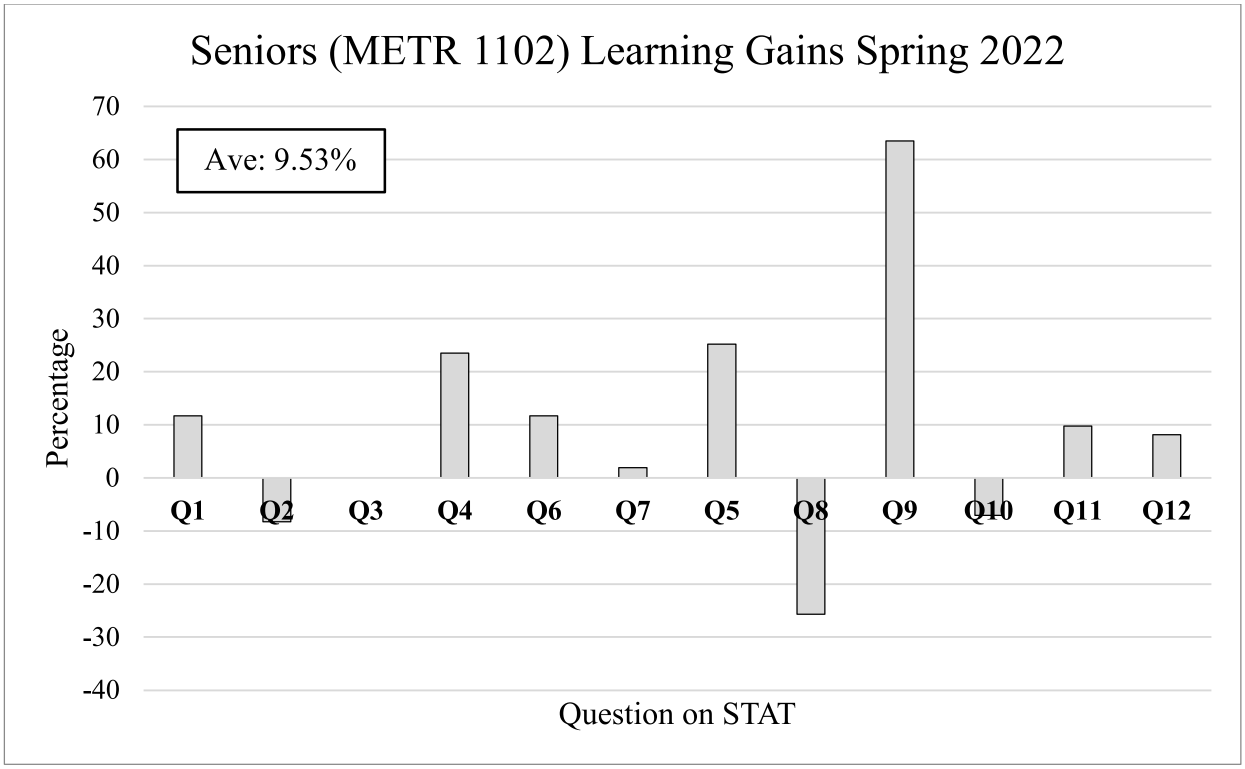


Figure 4.116: *Shows the normalized learning gains between the STAT pre-test and post-test for each question for Seniors (METR 1102) in the Spring 2022 semester.*

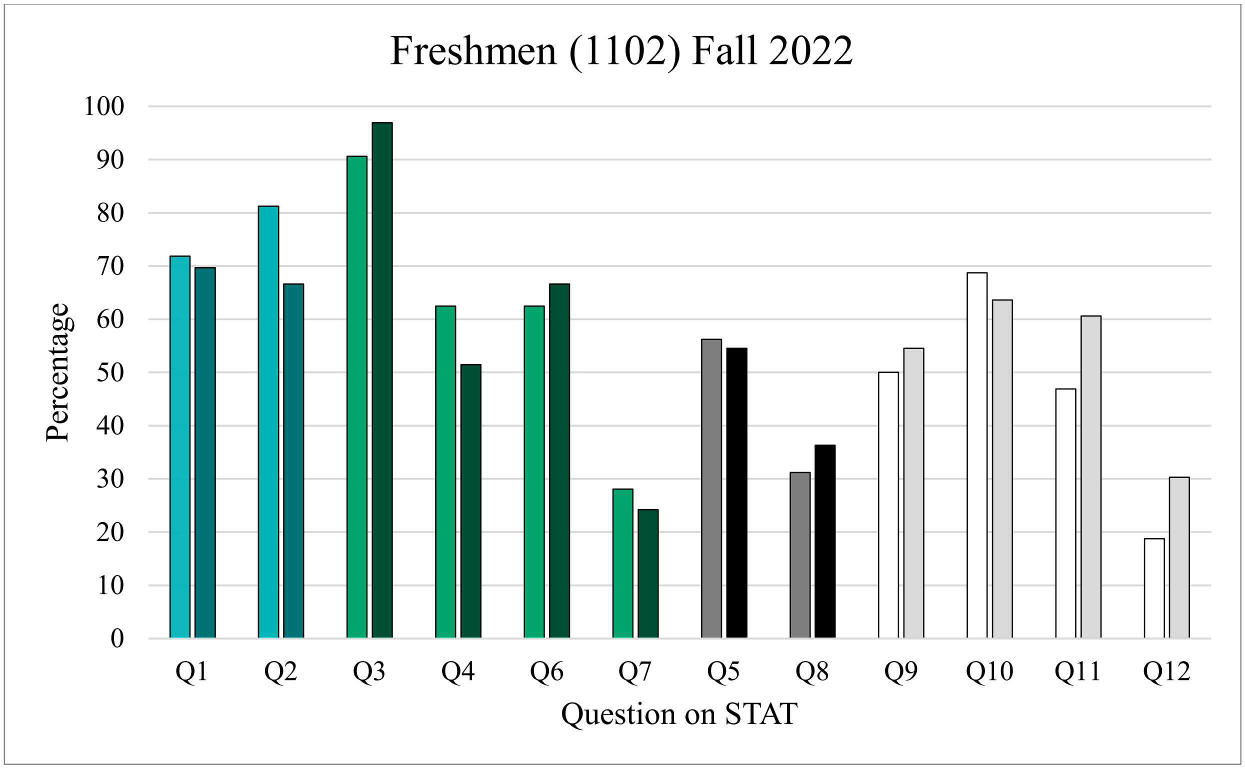


Figure 4.117: *Shows what percentage of students correctly answered each question for Freshmen (METR 1102) in the Fall 2022 semester. The lighter shades are the pre-test, while the darker shades are the post-test.*

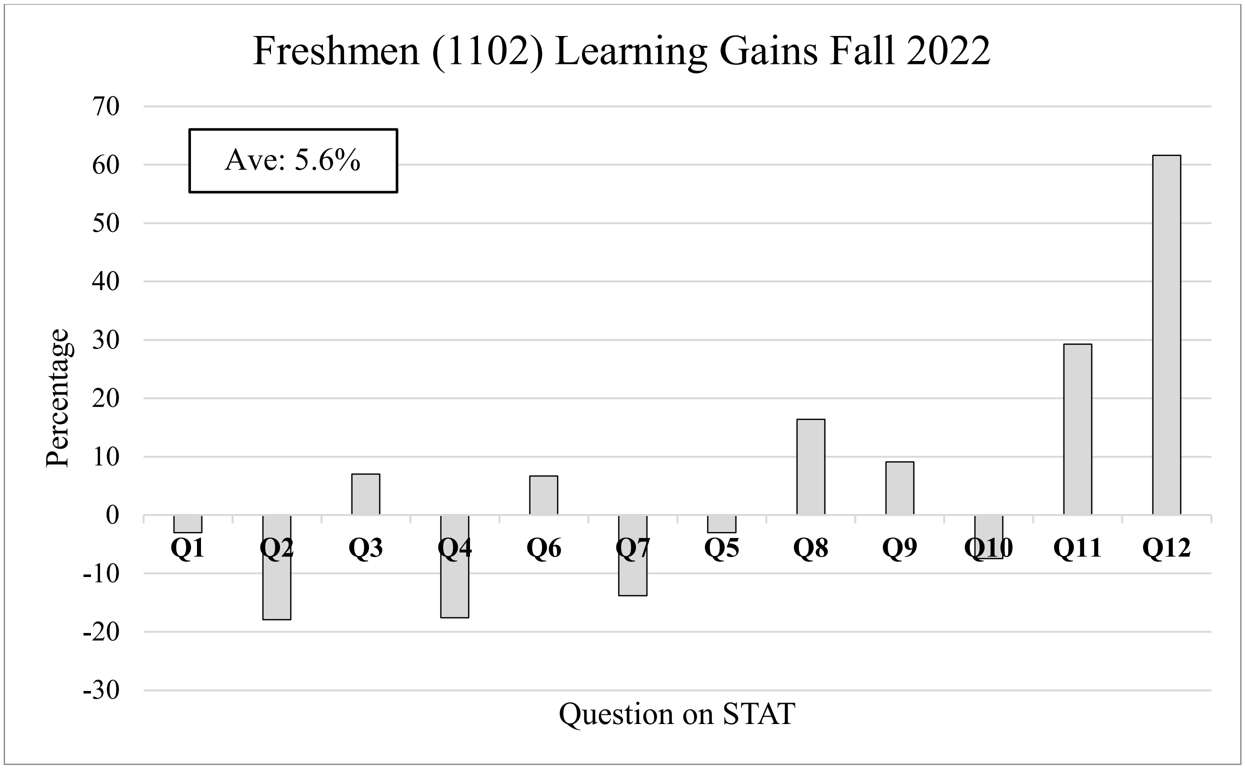


Figure 4.118: *Shows the normalized learning gains between the STAT pre-test and post-test for each question for Freshmen (METR 1102) in the Fall 2022 semester.*

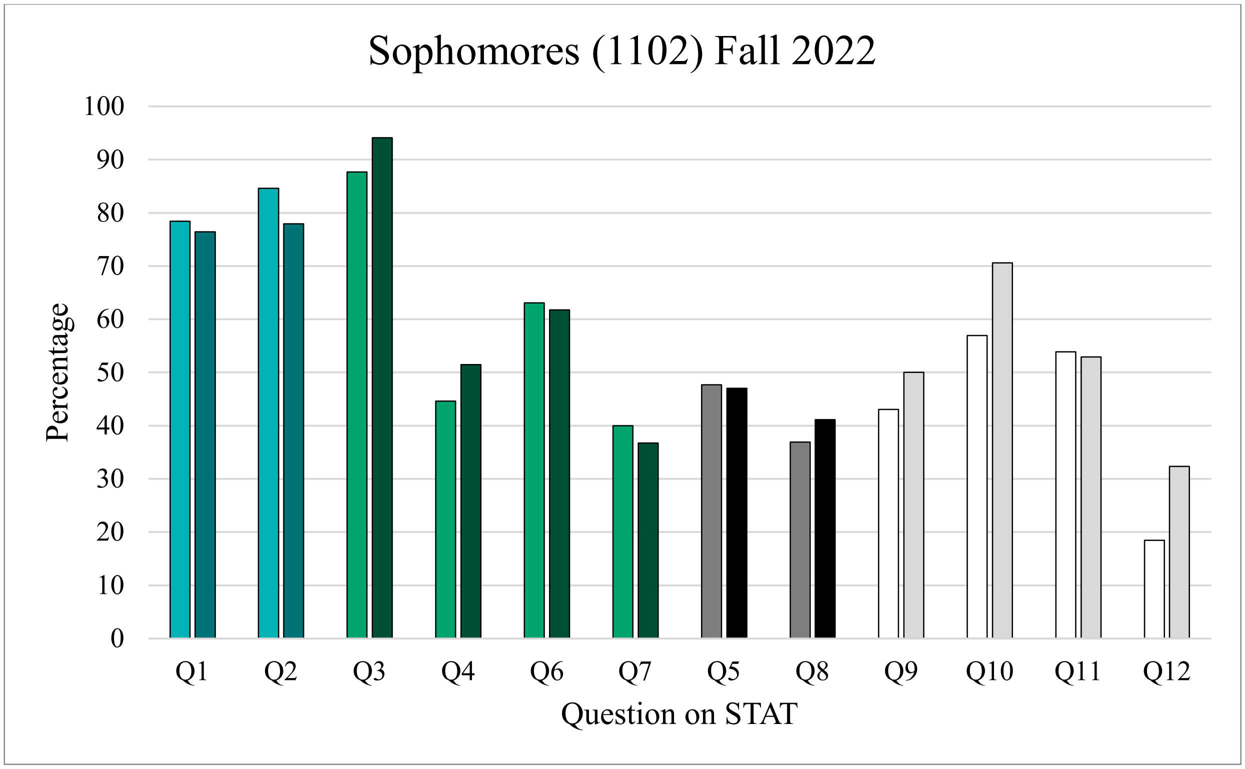


Figure 4.119: *Shows what percentage of students correctly answered each question for Sophomores (METR 1102) in the Fall 2022 semester. The lighter shades are the pre-test, while the darker shades are the post-test.*

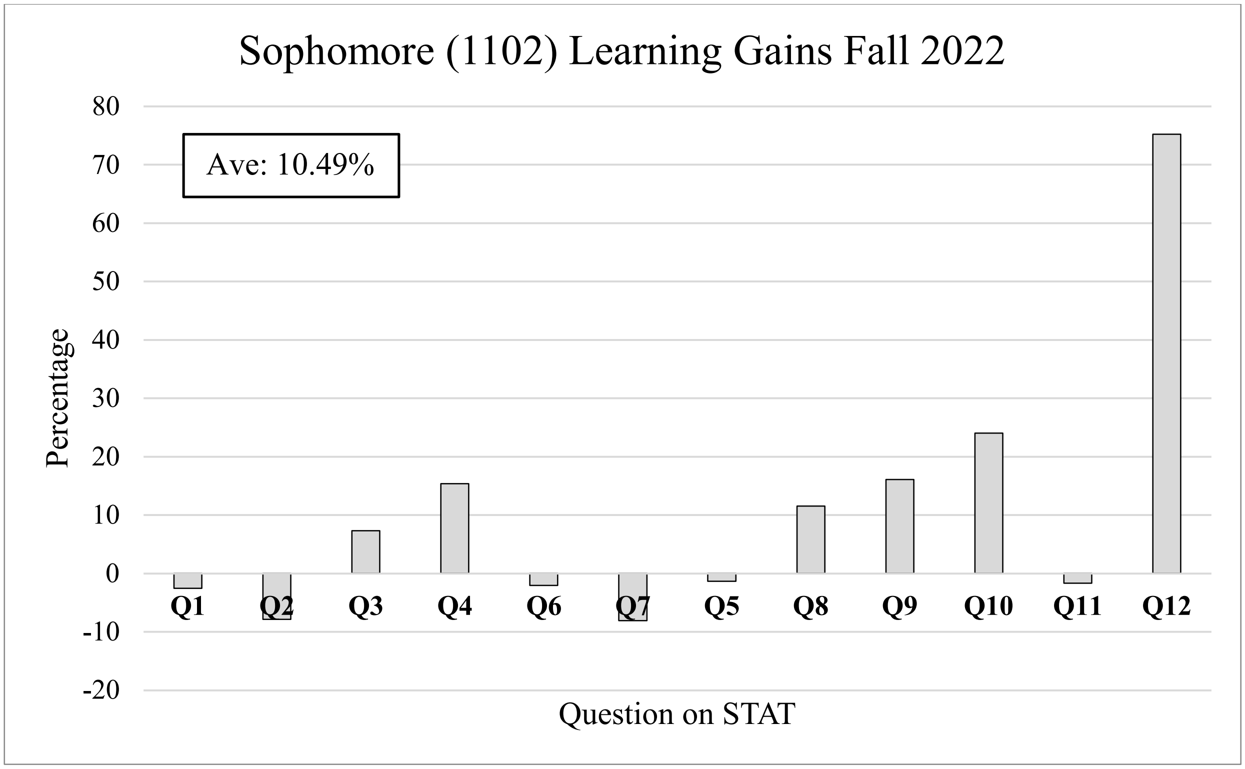


Figure 4.120: *Shows the normalized learning gains between the STAT pre-test and post-test for each question for Sophomores (METR 1102) in the Fall 2022 semester.*

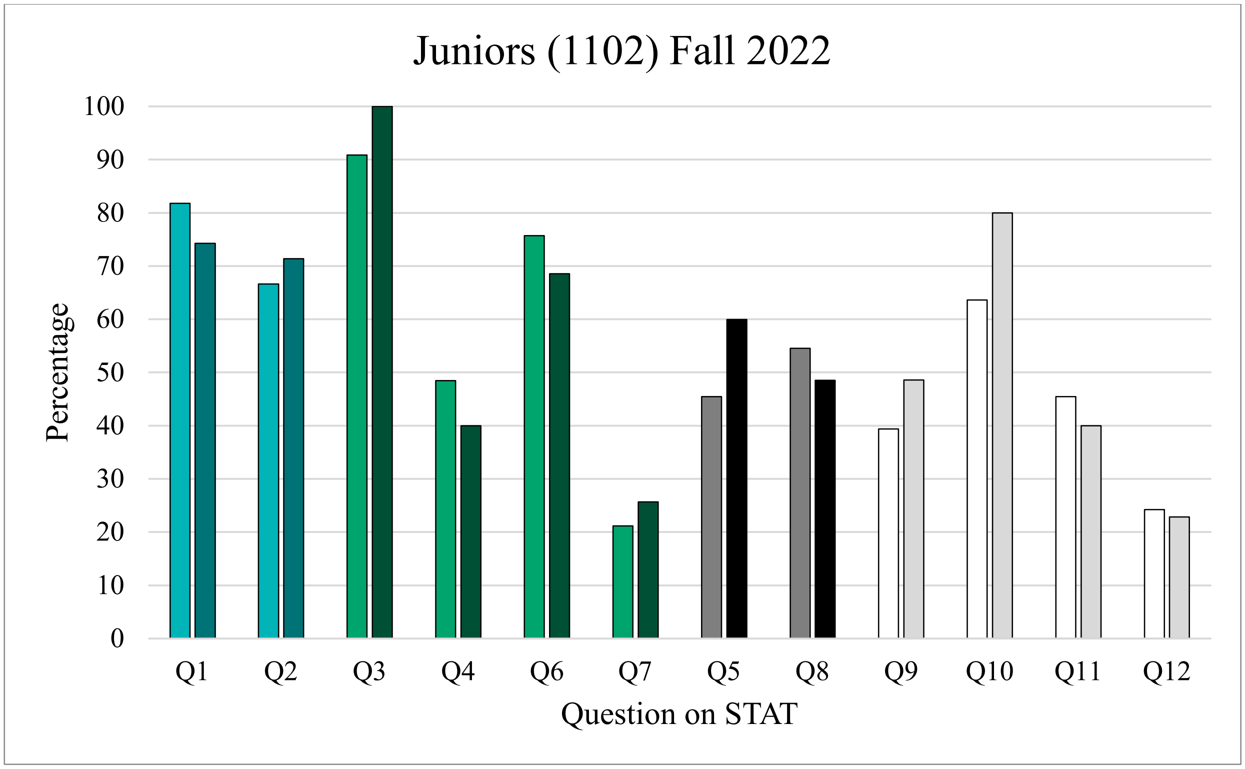


Figure 4.121: *Shows what percentage of students correctly answered each question for Juniors (METR 1102) in the Fall 2022 semester. The lighter shades are the pre-test, while the darker shades are the post-test.*

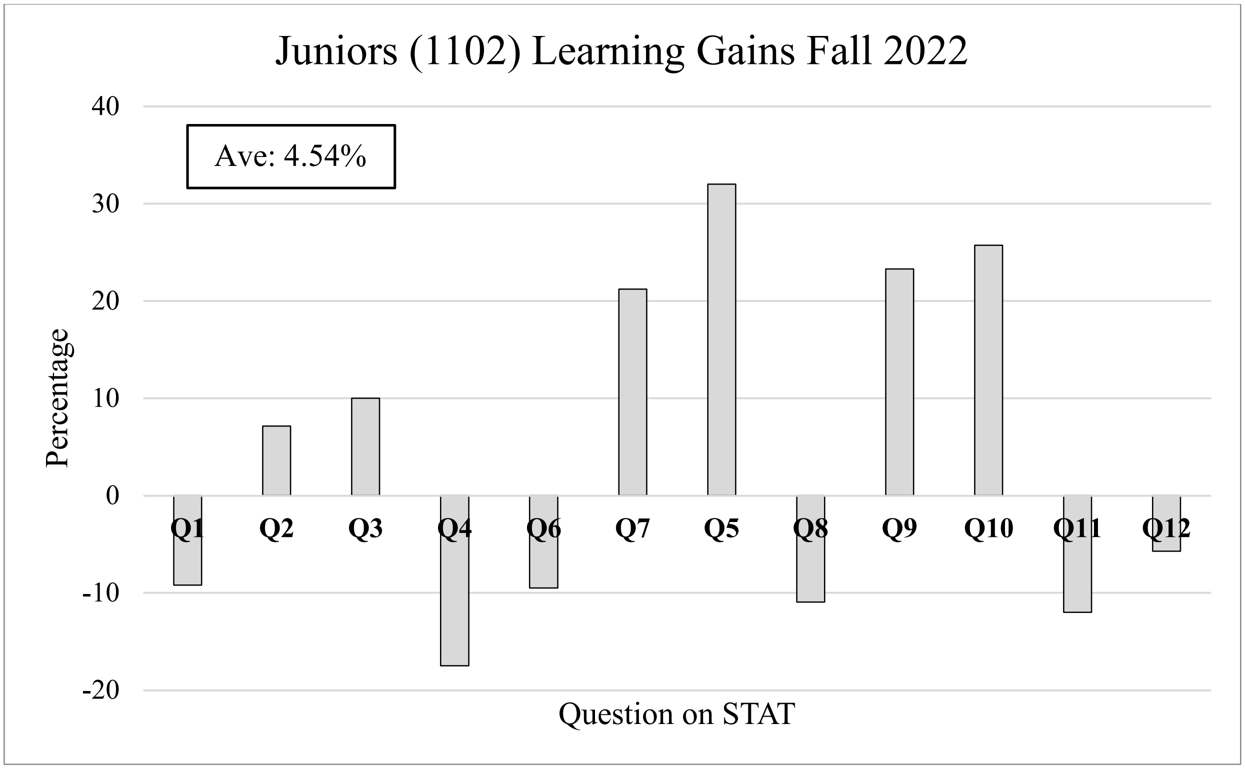


Figure 4.122: *Shows the normalized learning gains between the STAT pre-test and post-test for each question for Juniors (METR 1102) in the Fall 2022 semester.*

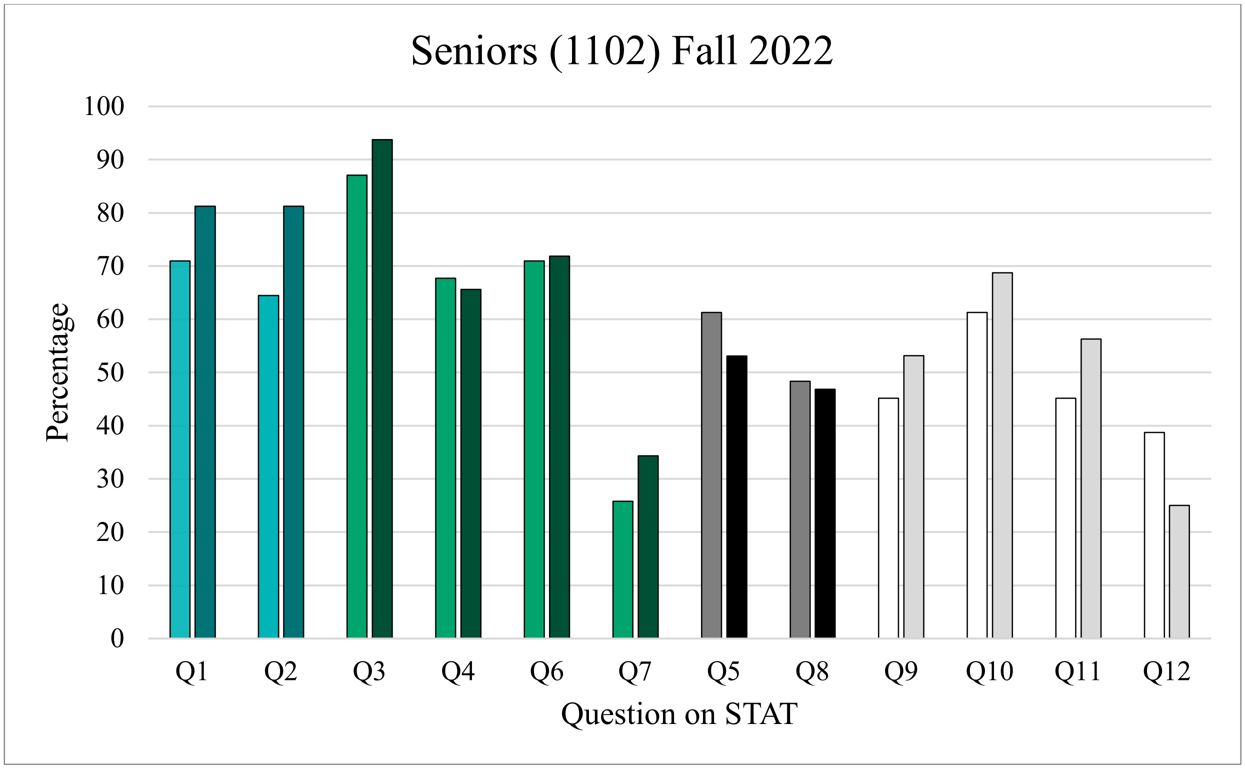


Figure 4.123: *Shows what percentage of students correctly answered each question for Seniors (METR 1102) in the Fall 2022 semester. The lighter shades are the pre-test, while the darker shades are the post-test.*

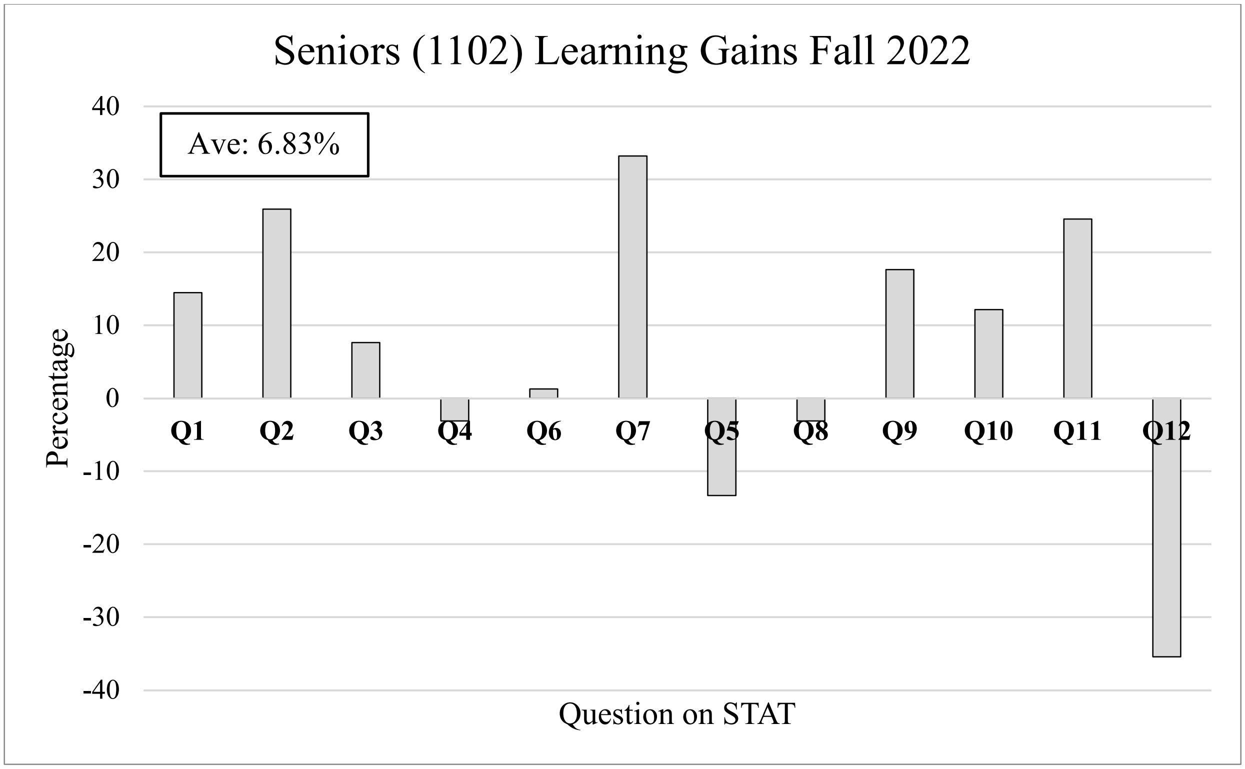


Figure 4.124: *Shows the normalized learning gains between the STAT pre-test and post-test for each question for Seniors (METR 1102) in the Fall 2022 semester.*

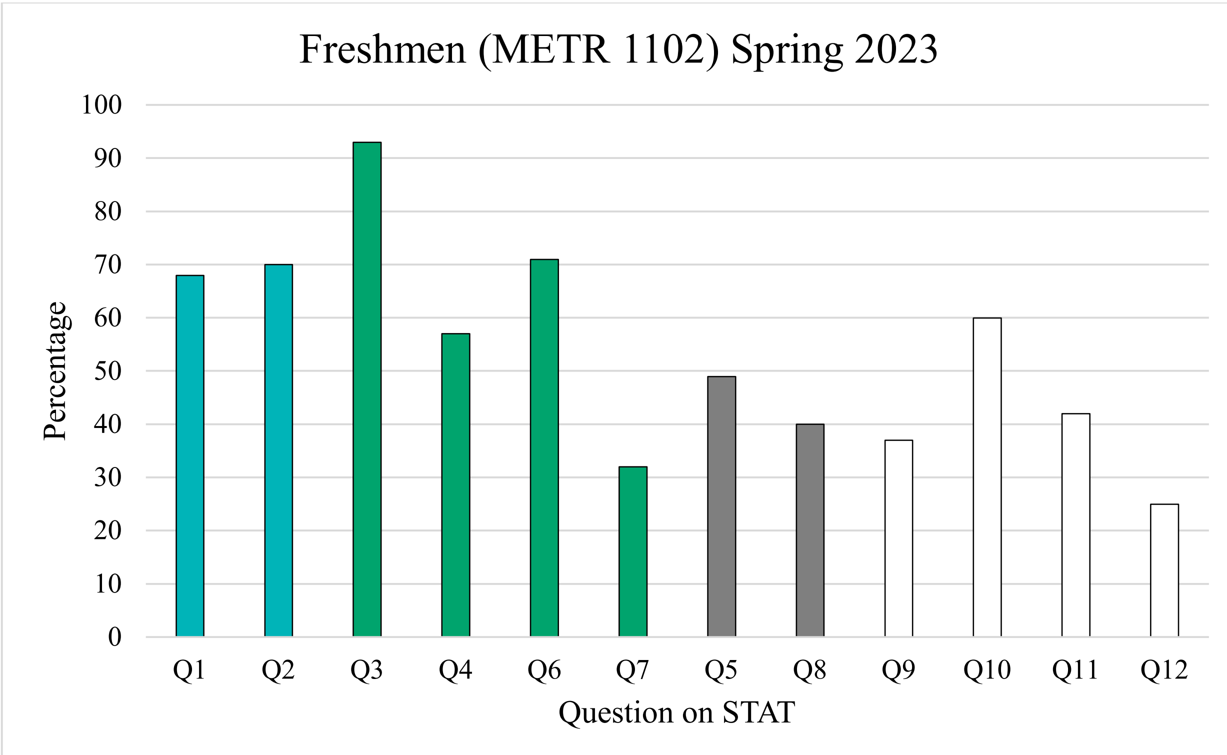


Figure 4.125: *Shows what percentage of students correctly answered each question for the pre-test for Freshmen (METR 1102) in the Spring 2023 semester.*

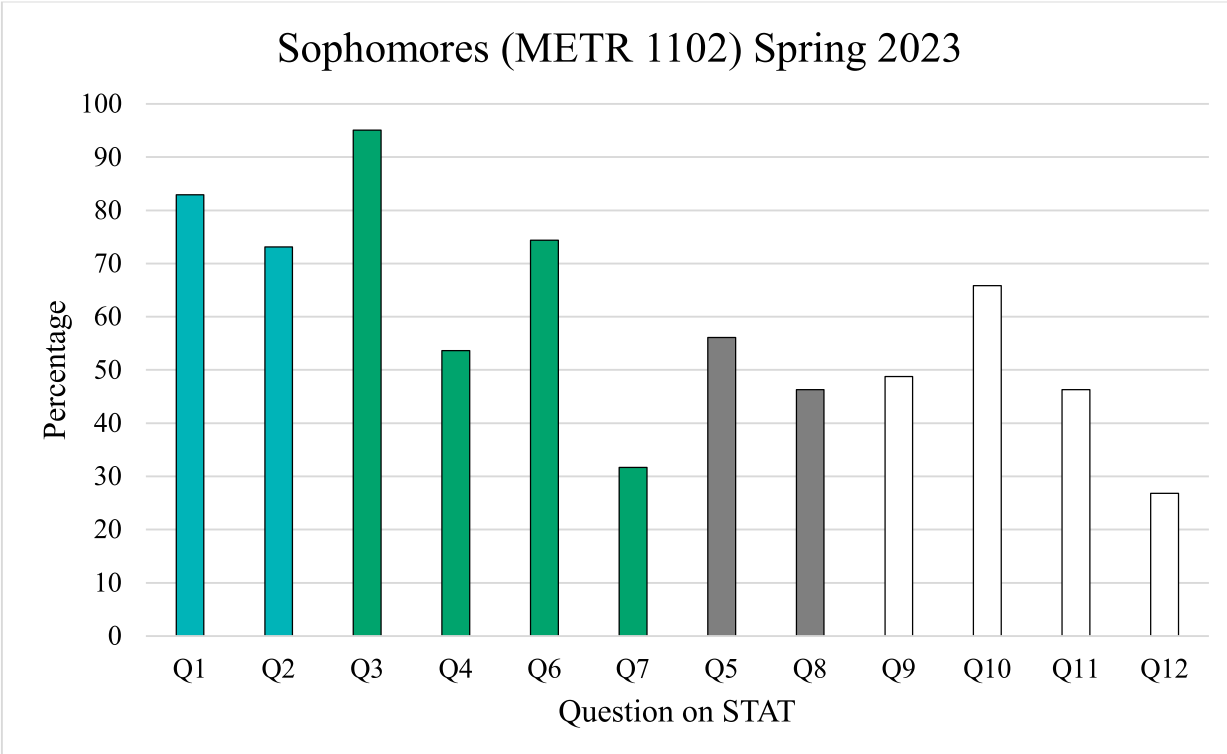


Figure 4. 126: *Shows what percentage of students correctly answered each question for the pre-test for Sophomores (METR 1102) in the Spring 2023 semester.*

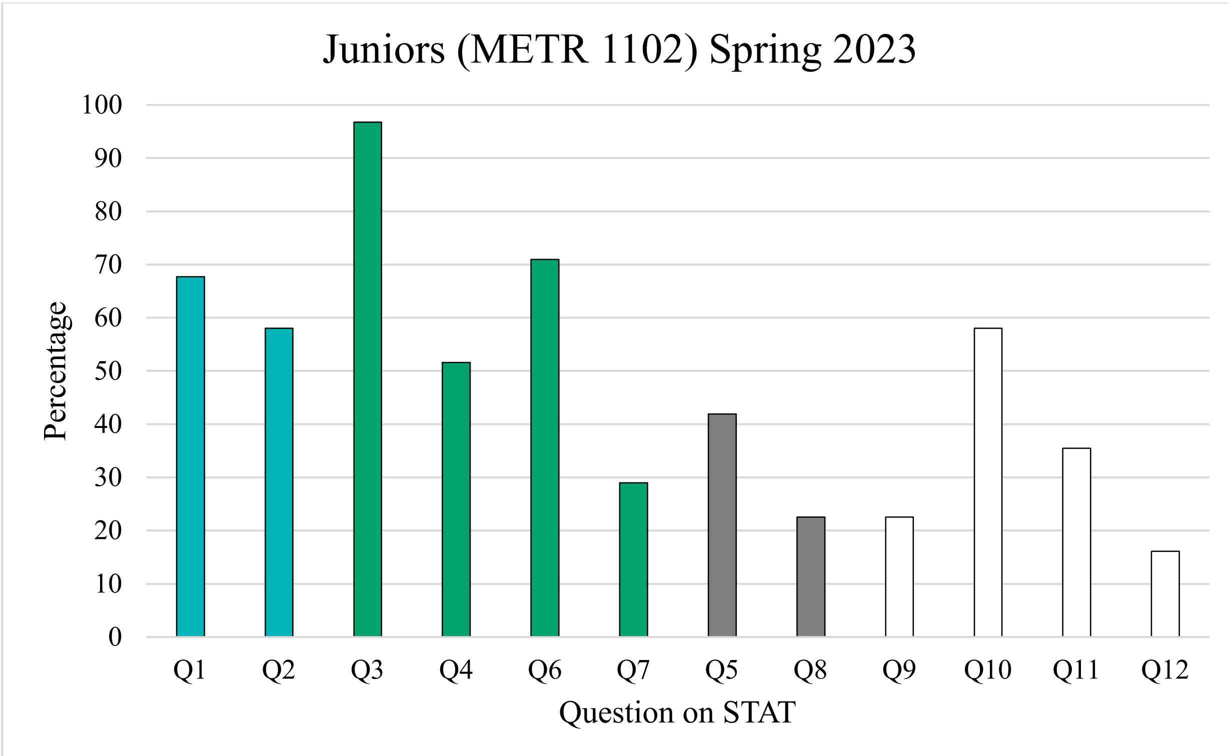


Figure 4.127: *Shows what percentage of students correctly answered each question for the pre-test for Juniors (METR 1102) in the Spring 2023 semester.*

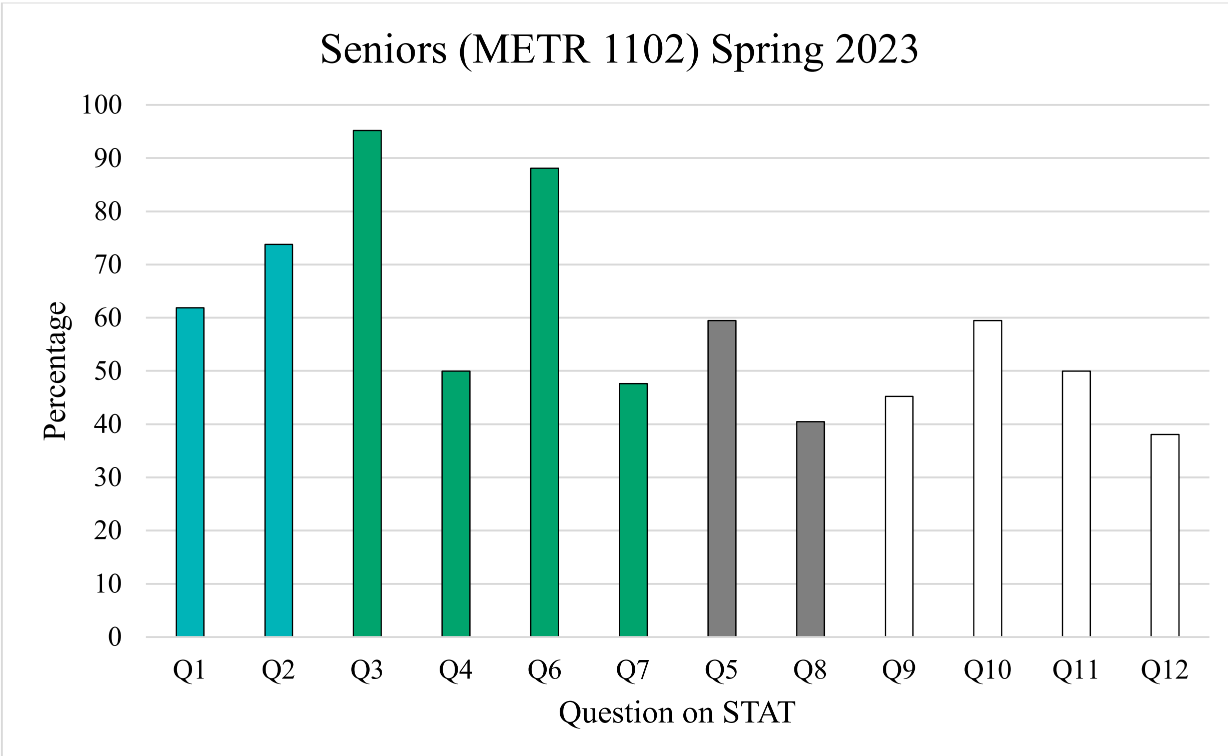


Figure 4.128: *Shows what percentage of students correctly answered each question for the pre-test for Seniors (METR 1102) in the Spring 2023 semester.*

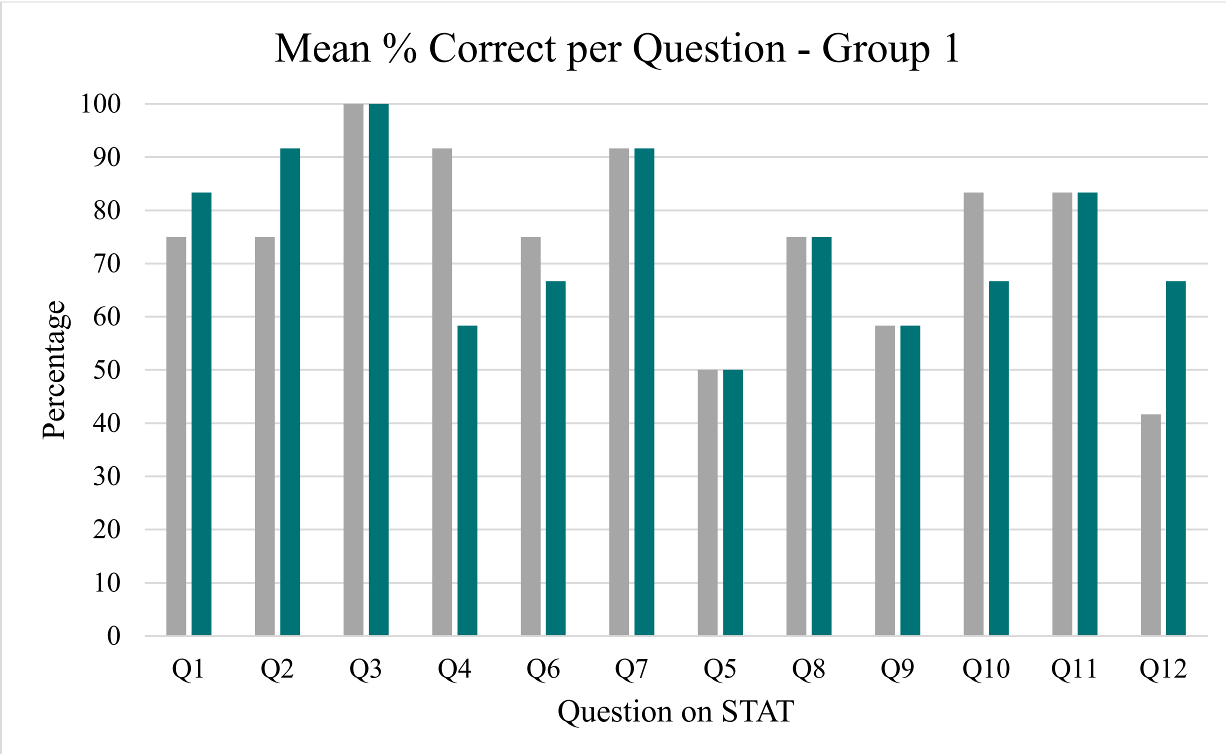


Figure 4. 129: *This graph shows the average percentage of Pathways Students that answered correctly per question on the Spatial Thinking Abilities Test. Group 1 starts in Global Environmental Change and continues to Fundamentals of Meteorology and ends in Atmospheric Thermodynamics. The grey bars represent each student's first attempt at the STAT, while the teal bars represent each student's last attempt at the STAT. The questions are in order based on the groupings for which spatial thinking skill they test.*

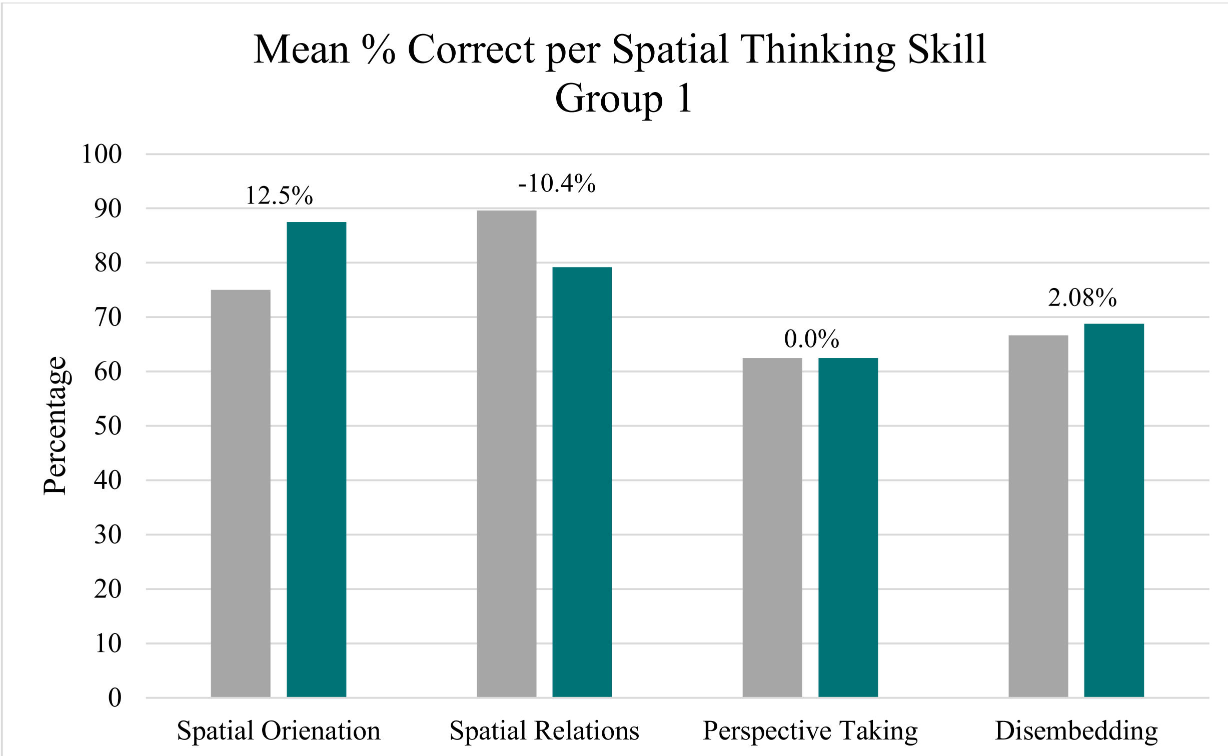


Figure 4. 130: *This graph displays the changes in the different spatial skills tested on the Spatial Thinking Abilities Test for Group 1 Pathways Students. The grey graphs represent the average percent correct per spatial thinking skill from students first attempt at the STAT, while the teal represents students' last attempt.*

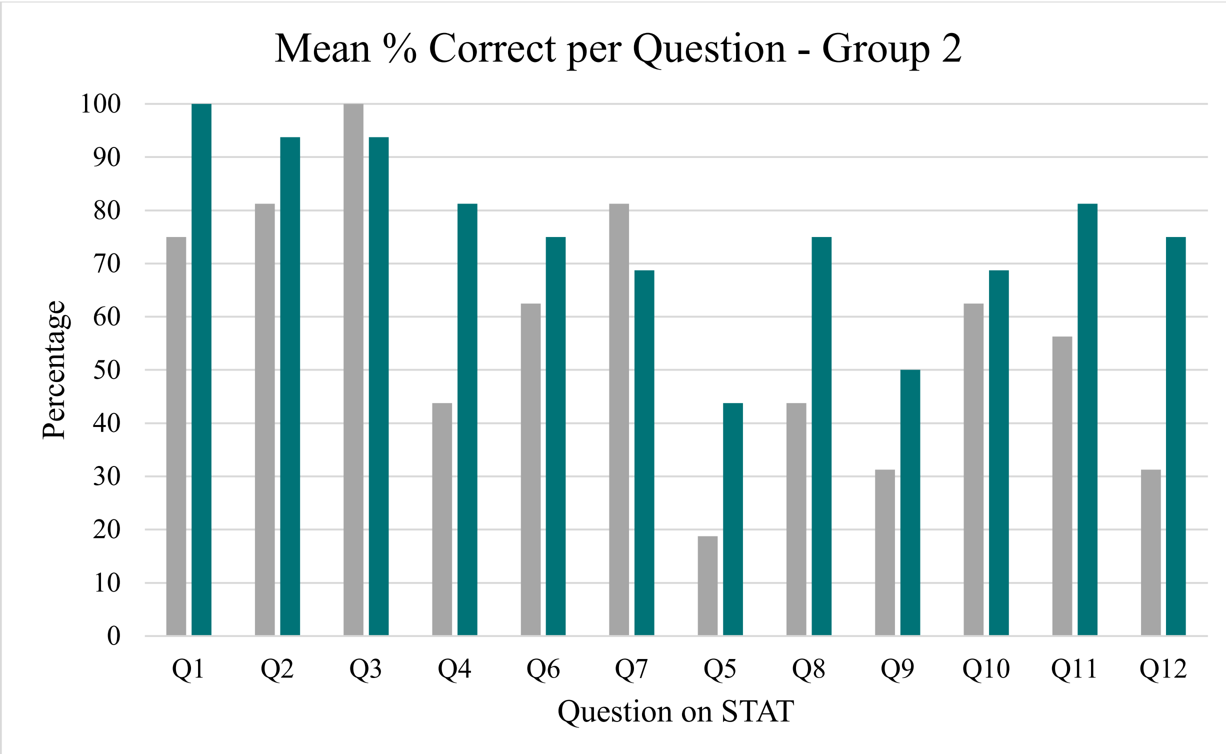


Figure 4.131: *This graph shows the average percentage of Pathways Students that answered correctly per question on the Spatial Thinking Abilities Test. Group 2 starts in Atmospheric Thermodynamics and continues to Synoptic and Physical Meteorology and ends in Atmospheric Dynamics I and Climate Dynamics. The grey bars represent each student's first attempt at the STAT, while the teal bars represent each student's last attempt at the STAT. The questions are in order based on the groupings for which spatial thinking skill they test.*

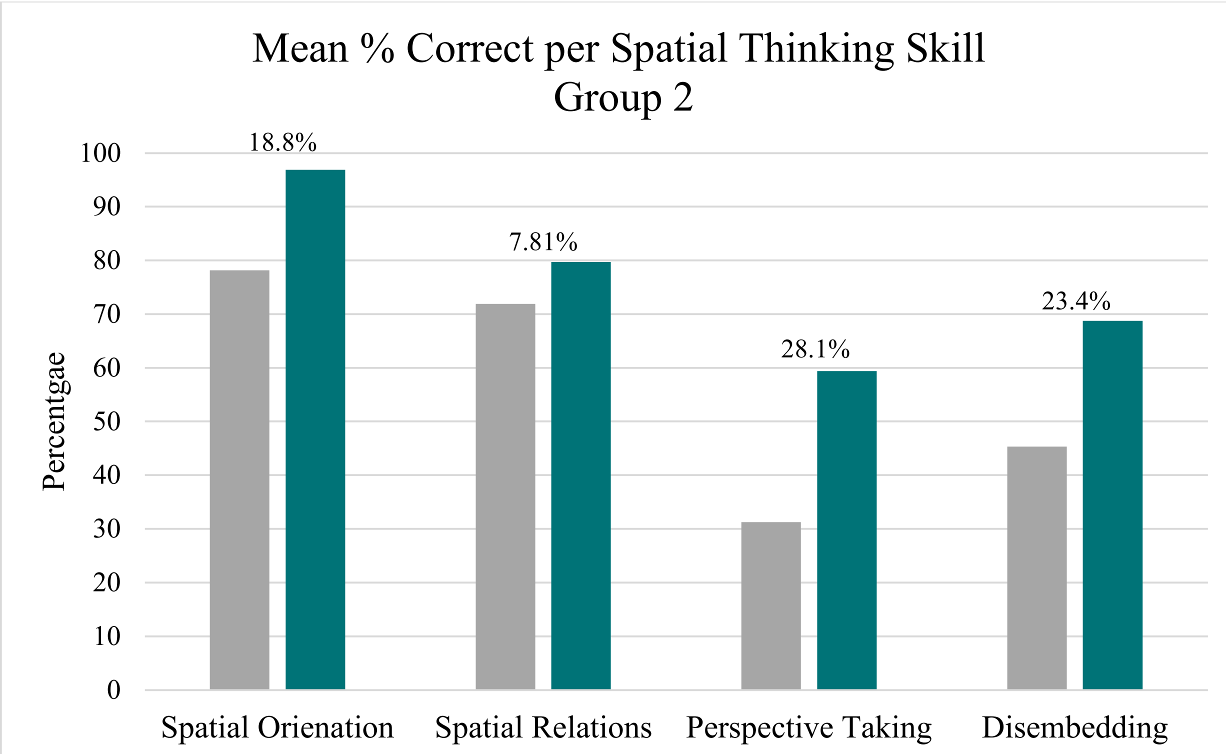


Figure 4. 132: *This graph displays the changes in the different spatial skills tested on the Spatial Thinking Abilities Test for Group 2 Pathways Students. The grey graphs represent the average percent correct per spatial thinking skill from students first attempt at the STAT, while the teal represents students' last attempt.*

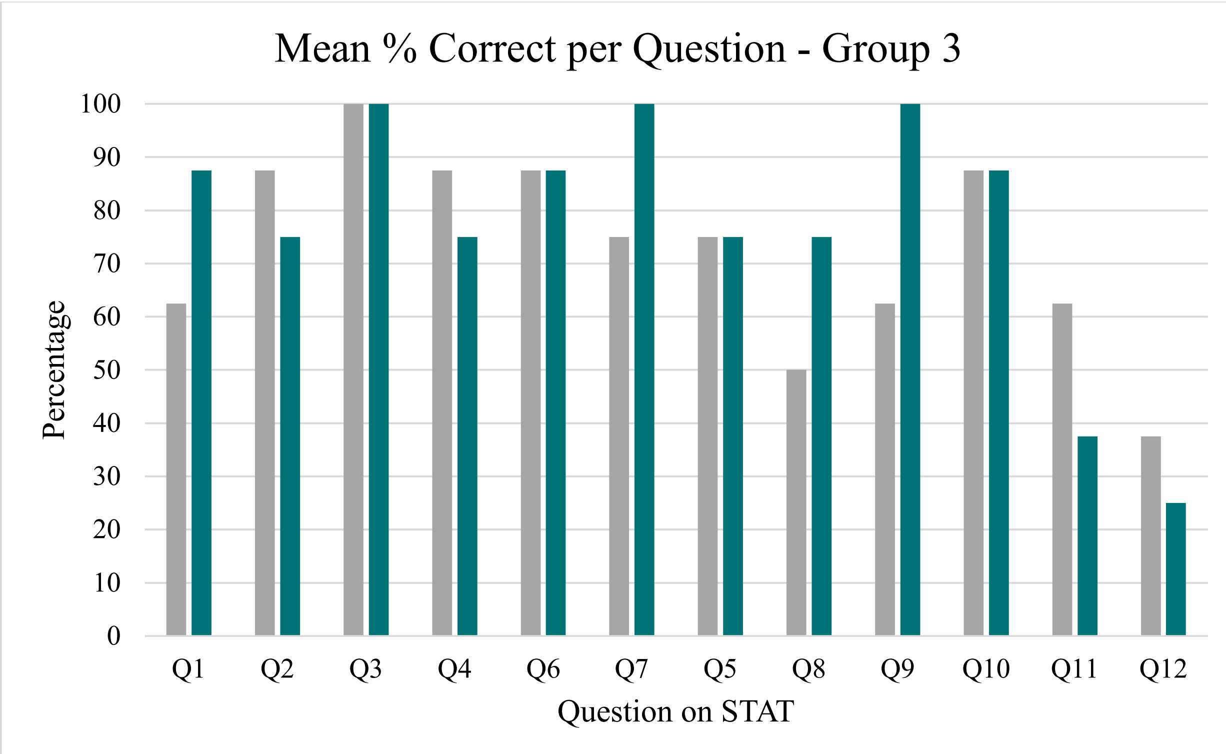


Figure 4. 133: *This graph shows the average percentage of Pathways Students that answered correctly per question on the Spatial Thinking Abilities Test. Group 3 starts in Atmospheric Dynamics I and ends in Advanced Dynamics II and Advanced Synoptic Meteorology. The grey bars represent each student's first attempt at the STAT, while the teal bars represent each student's last attempt at the STAT. The questions are in order based on the groupings for which spatial thinking skill they test.*

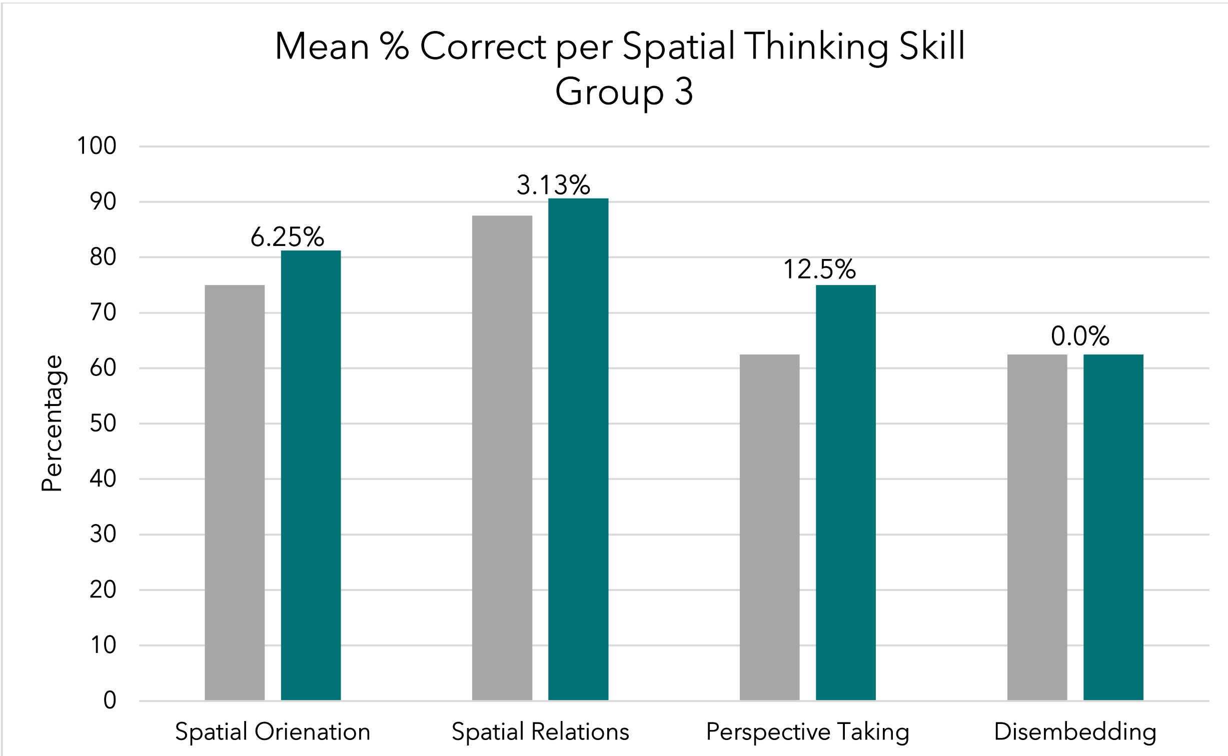


Figure 4. 134: *This graph displays the changes in the different spatial skills tested on the Spatial Thinking Abilities Test for Group 3 Pathways Students. The grey graphs represent the average percent correct per spatial thinking skill from students first attempt at the STAT, while the teal represents students' last attempt.*

5. Conclusions

Spatial thinking skills are highly correlated to success in science, technology, engineering, and math (STEM) fields (e.g., Talley 1973; Pallrand and Seeber 1984; Kozhevnikov et al. 2007; Wu and Shah 2004; Newcombe 2010; Uttal et al. 2012; Hegarty 2014; Sorby et al. 2018). How spatial thinking skills are applied and used is widely understood and represented in fields such as geology (e.g., Titus and Horsman 2009; Gold et al. 2018; Ormand et al. 2014; Petcovic et al. 2020; Bateman et al. 2022) and geography (e.g., Lee and Bednarz 2009; Lee and Bednarz 2012; Ishikawa 2013; Kim and Bednarz 2013; Metoyer et al. 2015; Bednarz and Lee 2019), but knowledge of how meteorologists use and gain spatial thinking skills is currently limited (e.g., McNeal and Petcovic 2020). What is known is that meteorologists tend to use a unique set of spatial reasoning skills, particularly mental animation, disembedding, and perspective taking (McNeal et al. 2019a, b). However, when such skills are gained is not well understood; such knowledge would be valuable to improve the undergraduate meteorology curriculum.

To document the progression in spatial reasoning, this study administered 12 questions from the Spatial Thinking Abilities Test (STAT; Lee and Bednarz 2012) exam, a holistic measure of spatial thinking skills, as a pre- and post-test in 10 required courses in the meteorology curriculum at the University of North Carolina at Charlotte. Several key findings were evident in the current data collection from Spring 2022, Fall 2022 and Spring 2023 semesters. First, on average, STEM majors outperformed Non-STEM majors (Table 4.2 and Fig. 4.4, Fig. 4.5; Table 4.3 and Fig. 4.6, Fig. 4.7; Table 4.4 and Fig. 4.8, Fig. 4.9). This is consistent with numerous prior studies (e.g., Titus and Horsman 2009). The second key finding of this study is similar to the first: Meteorology majors on average outperformed non-Meteorology majors, which was true in each semester of this study (Table 4.5 and Fig. 4.10, Fig. 4.11; Table 4.6 and Fig. 4.13, Fig. 4.14;

Table 4.7 and Fig. 4.16, Fig. 4.17). Meteorology majors had a similar performance on average as non-Meteorology majors in the Spring 2022 semester. However, in the Fall 2022 semester, Meteorology majors had a higher mean STAT score than non-Meteorology majors for both the pre- and the post-test. And keeping the same pattern, in the Spring 2023 semester, Meteorology majors outperformed non-Meteorology majors on mean STAT score (Table 4.6 and Fig. 4.15; Table 4.7 and Fig. 4.18). However, performance was similar between Meteorology Majors and Non-Meteorology (STEM) Majors in the Spring 2022 semester. Third, consistent with prior work (e.g., Linn and Petersen 1985; Howard et al. 1992; Reilly et al. 2017; Gold et al. 2018), Males generally outperformed Females (true for all three administrations of the pre-test and for the Fall 2022 post-test; (Table 4.8 and Fig. 4.19, Fig. 4.20; Table 4.9 and Fig. 4.21, Fig. 4.22; Table 4.10 and Fig 4.23, Fig. 4.24). Analyzing the different grade levels, including METR 1102 grade levels, did not provide substantial insight on how students' spatial thinking skills changed based on the student's year, as results varied each semester (e.g., Table 4.11 and Fig. 4.25 – 4.28; Table 4.12 and Fig. 4.29 – 4.32; Table 4.13 and Fig. 4.33 – 4.36; Table 4.14 and Fig. 4.37 – 4.40; Table 4.15 and Fig. 4.41 – 4.44; Table 4.16 and Fig. 4.45 – 4.48).

Normalized learning gains were useful for providing insight on improvements in spatial thinking. There are a few key findings that came from this data. First, STEM majors showed *more* improvement in spatial thinking skills in a given semester compared to Non-STEM majors based on their average normalized learning gains, though this was only evident for pre- to post-test gains for the Spring 2022 semester (Fig. 4.56 and Fig. 4.57), whereas the opposite was true for Fall 2022 (Fig. 4.58 and Fig. 4.59). Data relevant to normalized learning gains for Spring 2023 is still being collected. Based on the normalized learning gains for the Spring 2022 semester, Non-METR (STEM) Majors showed the most improvement, followed by Meteorology Majors and

Non-Meteorology Majors who showed the least amount of improvement (Fig. 4.72, Fig. 4.74, and Fig. 4.76). In the Spring 2022 semester, females showed a larger improvement between the pre- and post-test administration with a higher learning gain, however, males had a higher average learning gain in Fall 2022 (Fig. 4.52, Fig. 4.54, Fig. 4.84, and Fig. 4.86).

The Pathways students provided crucial information to help characterize the growth of spatial thinking abilities in meteorology students. Group 1, which includes students who took Global Environmental Change (ESCI 3101), Fundamentals of Meteorology (METR 3140) and Atmospheric Thermodynamics (METR 3210) consecutively, showed minimal changes or improvement in spatial thinking skills. Their overall average normalized learning gain was small (1.11%), yet it is also important to note that this group exhibited the largest increase in spatial orientation (Fig. 4.130). Group 2, which includes students in Atmospheric Thermodynamics (METR 3210), Physical and Synoptic Meteorology (METR 3220 and METR 3245), and Atmospheric Dynamics I and Climate Dynamics (METR 3250 and METR 4205), showed the largest improvement in STAT scores, and improved on all four spatial skill categories, with both perspective taking and disembedding showing an above 20% increase (Fig. 4.132). Lastly, Group 3, made up of students from Atmospheric Dynamics I and Climate Dynamics (METR 3250 and METR 4205) and Advanced Dynamics II and Advanced Synoptic (METR 3245 and METR 3250) showed a 5.47% increase in overall spatial thinking skills, with their largest increase in students answering correctly is in perspective taking (Fig. 4.134).

This study creates a useful foundation for understanding the progression of spatial thinking skills in undergraduate meteorology majors, as well as characterizing the types of that are particularly strengthened throughout the curriculum. Overall, results were consistent with past work, where males outperformed females, STEM majors better than non-STEM majors, and

Meteorology majors having stronger spatial thinking skills than non-Meteorology majors. Additionally, the pathways students helped identify which consecutive courses could be the most beneficial for strengthening students spatial thinking skills. A primary limitation of this study is the inclusion of only one institution, which may not be representative of other undergraduate meteorology curricula elsewhere. Thus, in the future, it would be beneficial to collect similar data at other schools to determine how generalizable the results are. With more data on progression in spatial thinking skills, work could then be done develop and include pedagogical interventions within courses to further enhance spatial thinking skills and support long-term student success.

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