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Spatial ability of transitioning 2D to 3D designs in virtual environment: understanding spatial ability in apparel design education

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Abstract

As the apparel industry has been transforming through digital-driven technologies in the apparel design process, the need for students to learn spatial visualization skills specified within a three-dimensional virtual environment is critical. By applying an apparel spatial visualization test into a virtual environment (ASVT-V), the purpose of this study is to examine the three-dimensional visualization skills in a virtual prototype environment of students who are majoring in apparel design and product development at the college level. The dataset was collected from 70 college students and analyzed by adopting correlation and variance analysis (ANOVA). Results from an online survey indicate that their ASVT-V scores were positively related to their general spatial visualization skills measured by a paper folding test. The results also indicate that students who received higher scores on the ASVT-V performed better in apparel design-related courses, while there was no influence on their perceived performance from the number of apparel design-related courses taken. This study provides practical implications for professionals in apparel design and product development education in that they can consider ASVT-V scores to understand and enhance domain-specific spatial visualization skills.

Keywords: Apparel spatial visualization test (ASVT), Spatial ability, Virtual environment, Paper-folding test, Perceived performance

Introduction

Spatial ability refers to an ability in understanding and reasoning the spatial relations among objects (Kyllonen et al., 1984), which can be conceptualized with individual capabilities to mentally represent spatial relations in the transformation process of objects (i.e., spatial visualization) and analyze three-dimensional (3D) objects in a mental rotation process (i.e., mental imagery). Spatial ability has been recognized as requisite for apparel design related education as the design process consists of many stages that require a great level of visual processing and spatial ability, such as sketching, draping, sewing, and evaluating fit (Ahn & Workman, 2012). For example, from beginning stages of the process, students use their spatial abilities to mentally imagine the drape of a garment on the body before they actually sketch a 2D garment illustration. Once a sketch is created, the students translate it into a 2D flat pattern or begin the process of translating the 2D sketch using a 2D-to-3D draping process to create a garment prototype. Finally, when the prototype is constructed, the garment is then analyzed for fit on a body form, which can be done through mental visualization transitioning 2D to 3D garment and mental rotation of the garment. Because the ability of transition from 2 to 3D objects is applied to various phases of garment making process, it is a significant ability for students in the apparel design education. With a holistic spatial understanding toward 2D flat pattern and 3D objects over multiple stages of apparel production, apparel design education can be done effectively and successfully.

As translation of 2D to 3D objects is critical in the design process, adopting 3D computer-aided design (CAD) software programs have become an important part of the design education (Papahristou & Bilalis, 2017). Through the use of 3D prototyping software, students can create and visualize their ideas through 3D simulation, which provides practical and realistic ways of understanding the garment making process. Indeed, previous researchers discussed that adopting 3D virtual technology is positively related with students' spatial ability for applying 2D patterns into 3D garment fitting (e.g., Park et al., 2011; Suh & Cho, 2020). Because the spatial ability requires the use of mental imagery and spatial ability from a design concept to virtual fitting, the capability to mentally visualize the process plays a critical role within computer-aided design environment (János & Gyula, 2019; Papahristou & Bilalis, 2017). Further, the apparel industry's design and product development process continue to transition into a highly automated and computer-aided industry (Papahristou & Bilalis, 2017). Therefore, the need to examine students' spatial ability and its relation to domain-specific understanding toward 2D patterns and 3D objects within virtual environment is critical in apparel design education. Currently, there is only one developed test to measure spatial abilities transiting 2D patterns to 3D garments that is specific to apparel product development—the Apparel Spatial Visualization Test (ASVT). ASVT was developed by Workman et al. (1999) and measures the spatial visualization abilities specific to apparel design within a 2D environment format (i.e., paper test). Although ASVT is specific to the ability to mentally rotate apparel design and follow the product development process, it does not examine these spatial visualization or mental imagery skills in a 3D virtual environment. In fact, very few studies have examined 3D prototyping software as an effective instructional tool in apparel design and product development education. Park et al., (2011) investigated the effectiveness of 3D prototyping technology as an instructional tool (i.e., OptiTex™) and developed 3D simulation instruments for design education. While previous researchers identified 3D simulation as an effective training method, the role of the students' special ability in transitioning from 2 to 3D apparel designs within a virtual environment in explaining the students' perceived performance has not been identified.

As the embeddedness of 3D virtual prototyping software increases in the apparel fashion industry (Papahristou & Bilalis, 2017), the implementation and development of a 3D CAD simulation in a spatial visualization test specific to apparel product (i.e., ASVT) would be beneficial in understanding what factors can improve the students' virtual prototyping abilities and how instructors can better prepare students to increase their performance. Therefore, through the ASVT applied into a virtual environment (ASVT-V), this study is to examine the college students' domain-specific spatial ability through its relation to general spatial abilities–spatial visualization and spatial mental imagery. Another important purpose is to identify the role of domain-specific spatial ability (i.e., ASVT-V) in apparel design education through its effects on enhancing their performance in domain-specific courses. Findings from this study contributes to the enhancement of spatial ability related to 3D virtual prototyping in apparel design education. By adopting 3D simulation technology into apparel design courses that requires domain-specific spatial ability (e.g., apparel design and production, or technical design), professionals in the field of education can provide enhanced learning opportunities to students majoring in apparel design and product development.

Literature review

Spatial ability

Spatial ability is a complex, multifaceted concept that many researchers have worked to decode (Kyllonen et al., 1984). Previous researchers have identified the factors that constitute spatial ability (Kyllonen et al., 1984; Sorby, 1999). For example, early researchers characterized spatial ability as a human's cognitive ability to visually perceive shapes, positions, and forms when mentally rotated or manipulated (Kyllonen et al., 1984). Researchers have also described it as an innate ability to visualize that is partially linked to general intelligence (Sorby, 1999). More recently, spatial ability has been identified as an individual ability, comprised of multiple skills used to navigate the visual field by transforming or manipulating 2D or 3D objects (Suh & Cho, 2020).

With its convoluted nature, spatial ability is thought to be a fundamental cognitive skill for the creative process and execution of design (Williams & Sutton, 2011). Moreover, researchers suggest the importance of cognitive spatial abilities in Science, Technology, Engineering, Arts, and Mathematics (STEAM)-related professions because of the need to form nonvisible concepts into visible ideas (Suh & Cho, 2020). STEAM-related fields specific to product design and creativity use different spatial components—e.g., spatial visualization and mental rotation—that are integral to design performance (Suh & Cho, 2020). Through the improvement of spatial ability skills, important design performance skills such as creativity can be improved in education (Cho, 2017). In a similar vein, researchers suggested that the lack of spatial ability can result in poor spatial design performance (Liao, 2017). This indicates that those who lack the ability or experience in spatial activities or abilities may encounter difficulties in learning or performing spatial ability-centered tasks.

Spatial ability is a key factor in creative design performance in 2D and 3D design applications (Gitimu & Workman, 2007; Suh & Cho, 2020). Thus, researchers have found a relationship between spatial abilities and design ability (Suh & Cho, 2020). Numerous researchers suggest that through training, spatial abilities can be enhanced using assessment tools that challenge spatial activities (Linn & Petersen, 1985). Linn and Petersen (1985) compared spatial abilities in participants who completed spatial training and participants who had no formal training. Results from this study confirmed the notion that prior training can enhance spatial abilities (Linn & Petersen, 1985). Another study found that the level of spatial abilities differs among individuals (Gitimu & Workman, 2007). These individual differences are integral in understanding spatial ability and its complexity. Differences in abilities consist of how a person evaluates, perceives, understands, and solves problems in the spatial environment (Gitimu & Workman, 2007). Moreover, spatial experiences influence an individual's ability to process and create during spatial activities (Khoza & Workman, 2008). Researchers have also identified various spatial ability tools that can be used to measure the sub-dimensions of spatial ability such as spatial visualization and mental rotation (Dere & Kalelioglu, 2020; Hoffler, 2010; Lin & Chen, 2016; Lohman, 1979) .

Sub-dimensions of spatial ability

Spatial ability encompasses numerous subconstructs that vary in skills and components. According to Suh and Cho (2020), the concept of spatial ability and its sub-constructs varies in definition. Other researchers have mainly identified two sub-dimensions that are closely associated with assessment tools related to 3D objects. These two are an individual's ability to mentally visualize the object (i.e., spatial visualization) and rotate it (i.e., spatial mental imagery) (Dere & Kalelioglu, 2020; Hoffler, 2010; Lin & Chen, 2016; Linn & Petersen, 1985; Lohman, 1979).

Spatial visualization

This skill is considered one of the most important sub-dimensions of spatial abilities. Possessing this skill is critical to a wide range of design-centered professions and STEAM education (Williams & Sutton, 2011; Suh & Cho, 2020). This is because spatial visualization skills have an impact on STEAM education achievement and performance (Buckley et al., 2018). Spatial visualization was identified as a process of imaging movement and transformation of the object, and its visuals according to changes in the objects (i.e., twisting or folding the object) (McGee, 1979). During the process of spatial visualization, people process complex spatial information about objects including whether they are folded and/or transposed (French et al., 1963). Researchers have identified spatial visualization as a multifaceted ability to mentally manipulate a spatial configuration and create a representation of the configuration from a new perspective (Suh & Cho, 2020). Furthermore, researchers have uncovered a relationship between spatial visualization and obtaining information to understand the development of 3D images (Gobert, 1999). Pervious researchers suggest spatial visualization acts as a bridge from the conceptualization stage of design to the transformation of design concepts into sketches (Linn & Petersen, 1985). Spatial visualization abilities have been examined using the Paper Folding Test (PFT) (French et al., 1963; Olkun, 2003). French et al. (1963) applied the paper folding process to examine how people imagine the spatial visualization process involved with folding and unfolding of a piece of paper. Later, the PFT was created by Ekstrom et al. (1976), where it consists of mentally visualizing the outcome of folding and unfolding a configuration after a hole has been punched. Researchers created this test to measure participants' varying aptitudes of spatial visualization skills. Previous researchers showed the PFT identifies how people solve problems when presented with visual information (Burte et al., 2019), where they determined that the PFT does not assess individual differences in spatial abilities (Burte et al., 2019). Although limitation of PFT lies on that the measurement is based on the mental process of 2D objects (i.e., punching and folding a piece of paper) (e.g., Lin and Chen, 2016), lots of previous studies focusing on apparel design education adopted the PFT to measure students' spatial visualization ability (Ahn and Workman, 2012; Workman and Caldwell, 2007; Workman and Lee, 2004). This shows that the spatial visualization ability to transpose 2D patterns into different formation is particularly important for a garment making process (Ahn and Workman, 2012; Workman and Caldwell, 2007; Workman and Lee, 2004).

Spatial mental imagery

This imagery is the ability to "see with the mind's eye" when seeing an object or scene mentally rotated (Wimmer et al., 2015). Compared to spatial visualization focusing on complex information related to changes of objects' form (i.e., folding), spatial mental imagery is identified as an ability to engage rapidly and accurately in analyzing a pair of stimuli in a mental rotation process (Ekstrom et al., 1976). Lin and Chen (2016) identified the difference between special visualization and spatial mental imagery, and they mentioned that the focus of the mental imagery is on the individual ability to rotate objects to manipulate its position and angle within 3D environment. Other researchers found that this skill involves mental manipulation of an object and its relationship to other parts of the object (Compos, 2009; Pellegrino et al., 1984; Peters et al., 1995). To measure spatial mental imagery, Campos (2009) developed a test based on the visualization aspect of mental imagery—the Measure of the Ability to Form Spatial Mental Imagery (MASMI). This test involves the unfolding a cube with different signs on each side and the participant has to mentally rotate the cube and visualize it together (Campos, 2009). Spatial mental imagery is said to be one of the most often measured with another sub-dimension of spatial ability—spatial visualization (Hoffler, 2010). In a study attempting to identify commonalities and differences among sub-dimensions of spatial ability, Miyake et al. (2001) established a correlation between spatial visualization and spatial mental imagery. Both require a certain level of spatial memory such as the ability to imagine an object and store the information temporarily for its new arrangement (Hoffler, 2010; Miyake et al., 2001).

Apparel design spatial ability (ASVT) and applications in a virtual environment (ASVT-V)

The ASVT developed by Workman et al. (1999) measures spatial visualization ability in transforming 2D garments into a 3D format. The spatial visualization measured by ASVT is a domain-specific ability for students majoring in apparel design and product development (Workman et al., 1999). Previous researchers have analyzed the effects of educational training on the ASVT scores and identified the relationships of domain-specific spatial ability and general spatial ability (Table 1). Through the development of the test specific to measuring apparel design spatial abilities, Workman et al., (1999) found that this test can be implemented as a method of training participants in improving their spatial abilities. Workman and Lee (2004) examined how culture and training effects an individual's spatial performance of tasks by using two different measurements: ASVT and the PFT. They found that individuals are influenced by the environmental factors that surround them (e.g., educational training) (Workman & Lee, 2004). They discovered that when students received training in classes, their scores improved on both tests (Workman & Lee, 2004). Based on this discovery, Khoza & Workman (2008) examined the effect of an individual's environmental factors in relation to learning style and spatial performance. For this study, the ASVT was used to examine the relation among

Table 1 Previous studies: domain-specific spatial ability in apparel design education

Author	Purpose	Measures	Key results
Workman et al. (1999)	Develop a test that measures spatial skills relative to product development and apparel design	Apparel Spatial visualization test (ASVT) Differential aptitude test – space relations	The ASVT measures spatial skills specific to apparel design and product development – not significantly correlate with the differential aptitude test
Workman & Zhang (1999)	Determine if ASVT is correlated with general spatial visualization ability and the level of training	ASVT Surface development test	Spatial visualization abilities are related to level of training and the ASVT scores
Workman & Lee (2004)	Examine the effects of culture and training on performance of spatial tasks by using ASVT and PFT to students from two cultures	ASVT Paper folding test (PFT)	Students improve significantly on both the PFT and ASVT as a result of training received in their classes
Gitimu et al. (2005)	Provide understanding of individual differences in processing of spatial information	ASVT Strategical information processing style	There is a significant difference in performance on the ASVT between students with more training and those with less training in apparel design
Gitimu & Workman (2007)	Provide understanding of individual differences in processing of spatial information	ASVT	Individuals use multiple strategies to accomplish most cognitive tasks
Workman & Caldwell (2007)	Examine the effects of indirect training provided by apparel design and product development courses on spatial visualization skills	ASVT PFT	Results support the viability of indirect training provided in courses to improve spatial visualization skills
Gitimu & Workman (2008)	Identify, categorize, and verify strategies that students use to solve items on the ASVT	ASVT Use of strategy questionnaire	Different individuals use different strategies to solve the same spatial cognitive task
Khoza & Workman (2008)	Examine the effects of culture and training on preferred perceptual learning style and performance of spatial tasks in apparel design	ASVT Perceptual modality preference survey	Preferred perceptual learning style is affected by culture, training, and culture of participants
Ahn & Workman (2012)	Examine spatial visualization skills and leisure activities of apparel industry professionals	PFT ASVT	Professionals use spatial visualization skills for 47% of the time at work and considered these skills very important to their jobs
Ahn & Workman (2010)	Develop and critically evaluate instruments to assess estimation and measurement skills for students in apparel design education	Estimate of linear measurements of full-scale lines	Training provided in apparel design classes improve students' spatial skills
Park et al. (2011)	Evaluate the 3D simulation technology as an innovative instructional tool in apparel design education	3D simulation developed	3D simulation technology has a potential as an efficient instructional tool for improving student's visualization skills
Kamis et al. (2015)	Identify the spatial visualization ability among apparel design students	ASVT Use of strategy questionnaire	Various combinations of strategies are effective to answer each question in ASVT

participants' spatial tasks and learning styles (e.g., visual, auditory, or reading/writing modes). They found that students in upper-level apparel design courses showed higher scores on ASVT, and there was a cultural difference on their learning styles (i.e., United States vs. Swazi students).

When examining training, Workman and Caldwell (2007) found that there was a significant improvement in spatial visualization abilities among students who received training. This study used a student-led learning process whereby the students were actively engaged in the learning process of using critical thinking and problem solving (i.e., indirect training). By investigating information processing on apparel-related spatial performance using the measures of ASVT and the strategical information processing style, Gitimu et al. (2005) found that students' performance was influenced by hands-on educational training and not the strategic information process style. Gitimu and Workman (2007) also indicated that the students' strategy choices determined their performance on the ASVT. They found that individual students used difference strategies to solve problems related to spatial tasks (ASVT). Later, Ahn and Workman (2012) developed a spatial skill measurement (i.e., Estimate of Linear Measurements of Full-Scale Lines) to examine whether full-scale garments developed from students can be improved through educational training and estimated through the measurement. They found that training provided in apparel design classes contributed to spatial skills necessary for them to make full-size garments.

Further, a few researchers identified the role of spatial ability in apparel studies. For example, Park et al. (2011) conducted an analysis to explore 3D simulation technology as an effective tool for enhancing participants' spatial visualization skills. This study examined apparel design and product development college majors with various experience levels and spatial abilities. Using three different instructional methods (i.e., 3D simulation, conventional lectures, and patternmaking practices), the results showed that students' abilities to mentally visualize the flat pattern on a body were greatly improved (Park et al., 2011). Results also indicated the effectiveness of 3D technology as a tool for improving students' spatial abilities when combined with traditional lecture and patterning-making practices. They suggest that students' spatial ability in visualizing flat patterns into rendering processes over virtual body models can be improved by adopting 3D simulation technology. Even though this study did not measure ASVT scores, the results suggest that apparel-specific spatial ability can be applied to a virtual environment. In addition, 3D simulation technology has been identified as an effective tool for college students majoring in design programs (Park et al., 2011; Suh & Cho, 2020); however, previously adopted ASVT scores were measured within a 2D format (i.e., a paper form). As students majoring in apparel design and product development have attended courses incorporating 3D visualization and/or simulation technologies, the ASVT might not fully uncover the domain-specific spatial ability for these students. Thus, this study applies the ASVT in a virtual environment (i.e., ASVT–V) and examines how it performs in measuring domain-specific spatial ability for the discipline of apparel design and product development.

As discussed above, previous literature in the field of apparel design education reported a positive relationship between ASVT scores and general senses of special ability (Workman et al., 1999; Workman & Lee, 2004; Park et al., 2011). Regarding a special ability in transforming 2D to 3D, previous scholars have suggested that domain-specific spatial ability, such as spatial visualization from 2 to 3D interior design, is positively correlated with general spatial ability that consists of mental rotation and spatial visualization (Suh & Cho, 2020). Therefore, we hypothesized that domain-specific ASVT-V scores for apparel design and product development will be positively related with students' spatial visualization and mental imagery scores.

H1: General spatial ability—the spatial visualization and mental imagery scores—will be positively related with ASVT-V scores.

Influence of education on domain-specific special ability (ASVT-V) and performance

In this study, we suggest that education in apparel design courses that require spatial ability positively influences domain-specific spatial ability (i.e., ASVT-V scores), which eventually increases students' performance in their courses. Domain-specific spatial skills are integral in the ability to mentally picture 3D shapes (Martin-Gutiérrez et al., 2010). These skills are examined in various fields of education, such as interior design, product design, engineering, and apparel design (Chang, 2014; Martin-Dorta et al., 2008).

Overall, previous literature indicates that spatial skills are a key factor in creative performance and conceptual design, and they can be developed through education (Chang, 2014; János & Gyula, 2019; Onyancha et al., 2009). For example, Chang (2014) discovered a positive effect on creativity and spatial comprehension when using CAD software in a product design course (i.e., designing a chair). Results from this study indicated that courses utilizing CAD are effective not only for greatly increasing spatial skills but also for students' performance in these courses (Chang, 2014). Martín-Dorta et al. (2008) examined spatial ability specific to the field of engineering where the development of spatial skills is directly linked to the success of professional work and academic performance (e.g., Martin-Gutiérrez et al., 2010). The researchers developed a remedial course to improve engineering students' spatial abilities using 3D CAD modeling (Martín-Dorta et al., 2008). Results indicated that a remedial course proved effective in students improving and gaining spatial ability skills, which consequently improved their performance in the course. Continuing to measure engineering students' spatial skills, János and Gyula (2019) examined students' learning and understandings of 3D technology and their spatial capability. The researchers developed a 3D CAD course measuring students' abilities at the beginning of the semester and again at the end (János & Gyula, 2019). Similar to previous studies, results suggested that 3D CAD courses improve the spatial skills of students. Results also suggest that CAD modeling activities bridge a gap for students who have poor spatial ability skills (Dere & Kalelioglu, 2020; János & Gyula, 2019). In addition, adopting a Conceive Design Implement and Operate (CDIO) teaching strategy, Haung and Lin (2017) explored how 3D modeling courses impact the spatial ability skills of college students in non-design related departments. CDIO integrated with 3D modeling technologies combines both thinking and practice. This study investigated differences among learners and the improvement of various spatial ability subdimensions by combining both CDIO and 3D modeling technology and materials (Haung & Lin, 2017). In this study, students were tasked with the challenge of developing a product concept, completing a 3D modeling, and producing a final product (Haung & Lin, 2017). Results indicated that 3D modeling technologies integrated with CDIO resulted in students developing and improving their sub-dimensional skills of spatial ability and performance in the class (i.e., learning outcomes; Haung & Lin, 2017). Moreover, spatial ability is a necessary cognitive ability for apparel design and product development (Workman & Lee, 2004). Previous scholars supported that taking domain-specific education (e.g., Design CAD classes) is efficient in improving students' visualization skills and overall class performance (Park et al., 2011). Those scholarly efforts indicate that domain-specific education can improve specific spatial ability required in the field, and consequently increase students' performance in the course. In the apparel design and product development education, previous research indicated that training led to improvements in spatial visualization ability (Khoza & Workman, 2008; Workman & Lee, 2004). As ASVT has contributed to the understanding of how to improve spatial availability and class performance for students majoring apparel design and product development programs (Gitimu et al., 2005; Linn & Petersen, 1985; Toomey & Heo, 2019), we suggest that taking domain-specific courses (i.e., major-related courses) would improve scores from ASVT-V and students' overall performance in those courses. Therefore, following hypotheses were suggested.

H2: When students take more apparel design and product development courses, their ASVT-V scores will increase.

H3: When students have higher ASVT-V scores, they will perceive a greater performance in apparel design and product development courses.

Effect of domain-specific special ability on student performance

Lastly, we suggest that when apparel design major students take more domain-specific courses, they can increase their performance in those courses. Onyancha et al. (2009) suggest that targeted training can be an effective way for improving spatial abilities. For example, mechanical engineering students who enrolled in an entry-level CAD course were divided into three groups based on their spatial ability level (e.g., Low group, Intermediate group, and High group) (Onyancha et al., 2009). Students in the low group received target training, students in the intermediate group (experimental group) were offered training but did not have to opt in, and students in the high group (control group) did not receive any training (Onyancha et al., 2009). Results from this study indicated that students who received targeted training enhanced their performance in the class with their improved spatial ability skills, while students with non-training did not improve their performance (Onyancha et al., 2009).

Similar to apparel design and product development, interior design is another field where spatial ability skills are essential. Interior design involves the use of 2D and 3D drawing formats, including planning, elevation, and physical models (Suh & Cho, 2020). Adopting general spatial ability tests and the domain-specific measurement (i.e., Architecture and Interior design domain-specific Spatial Ability Test), they examined student proficiency in 2D-to-3D visualization. Importantly, they found that the domain-specific education consequently improved students' performance in design courses (Suh & Cho, 2020). Therefore, we suggest that when apparel design major students take more major-related courses, they will perceive a greater performance in the courses they took. Thus, the following hypothesis is suggested. All hypotheses are presented in Fig. 1.

H4: When students take more apparel design and product development courses, they will perceive a greater performance in those courses.

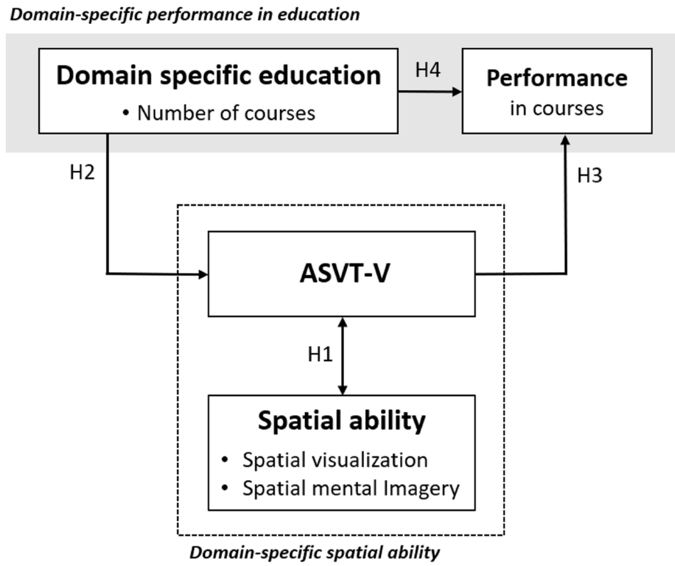

Fig. 1 Conceptual model (ASVT-V: Apparel Spatial Visualization Test applied to Virtual environment)

Methodology

Stimulus development: applying ASVT into virtual environment (ASVT-V)

To develop ASVT-V, we adopted the original ASVT and transformed it into virtual environment. The ASVT developed by Workman et al., (1999) measures spatial abilities specific to apparel design and product development. It consists of 20 sets of flat pattern pieces that may be constructed into a garment (Workman et al., 1999, Fig. 2). Each question consists of one flat pattern piece and five garment sketches. The test requires a participant to determine the correct garment outcome made from a flat pattern piece (Workman et al., 1999). In the current study, by utilizing CLO 3D, a 3D fashion design software, we created virtual garment visualizations, and all sets of ASVT questions were applied to the virtual environment (Fig. 3). ASVT-V questions maintained same patterns and garments that the original ASVT has. In the ASVT–V format, for each question, participants can see five videos of 3D garment outcomes, where they can manipulate the video, by pausing, going forward, or backwards in order to see how the garment appears in all areas of the body (i.e., front, side, and back) within the virtual environment (Fig. 3). The inter-rater reliability coefficient (Olson et al., 2003) was conducted by two experienced professionals, and the developed measurement was confirmed its reliability and consistent when comparing the original ASVT questions ($W = 0.90$; Kendall's coefficient of concordance).

Measurements

To test the participants' general spatial ability, we adopted PFT (Fig. 4; Ekstrom et al., 1976; Burton & Fogarty, 2003; Cronbach's $\alpha = 0.85$) and MASMI test (Fig. 5; Campos, 2009). The PFT, created by Ekstrom et al. (1976), measures capability of visualizing outcomes of an unfolded configuration after punching holes on folded layouts (i.e., spatial visualization). We adopted the PFT because previous scholars in the field of

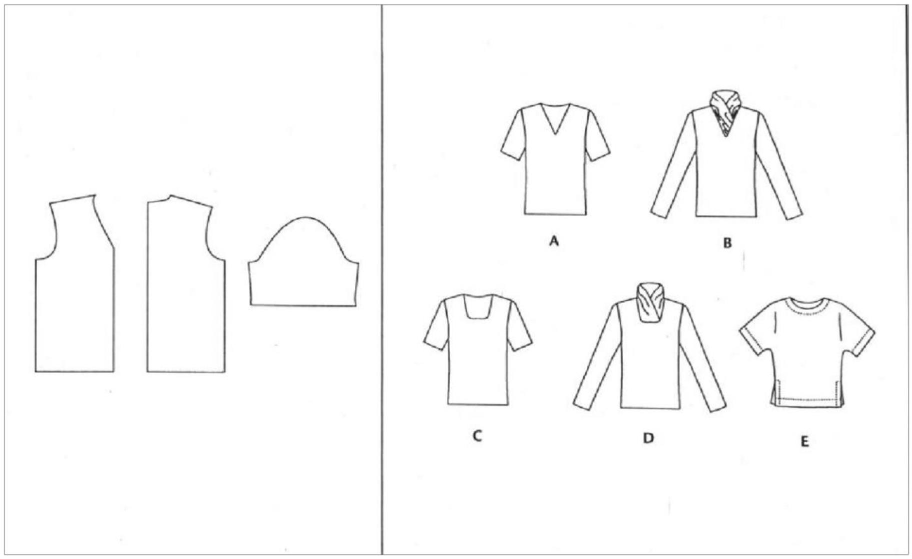

Fig. 2 Example of Apparel Spatial Visualization Test (ASVT). This is one of questions of ASVT. Participants are required to choose a garment image from multiple options (from **A** to **E**) that correspond the pattern pieces in the left side

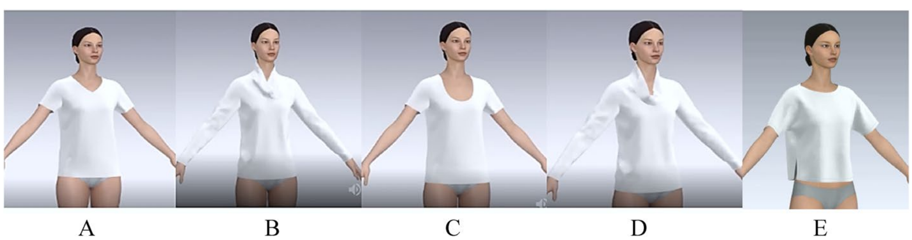

Fig. 3 Example of Apparel Spatial Visualization Test applied to Virtual environment (ASVT-V). This is one of questions of ASVT-V. Participants are required to choose a 3D garment from multiple options (from **A** to **E**) that correspond the same pattern pieces presented in Fig. 2

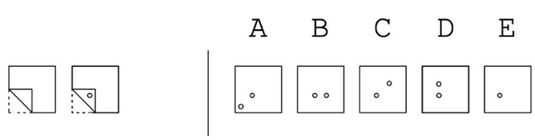

Fig. 4 Example of spatial visualization test: Paper Folding Test (PFT). This is one of questions of PFT. Participants are required to choose an image from multiple options (from **A** to **E**) that correspond to the folding pieces in the left side

apparel design education identified its effectiveness as an assessment for complex spatial maneuvers performed mentally among students (Ahn & Workman, 2012; Workman & Caldwell, 2007; Workman & Lee, 2004). In addition, the MASMI test is based on the visualization aspect of mental imagery (i.e., spatial mental imagery). This test requires participants to mentally visualize a cube (3D object) being folded together while by looking at an unfolded cube with different signs on each side (Cronbach's

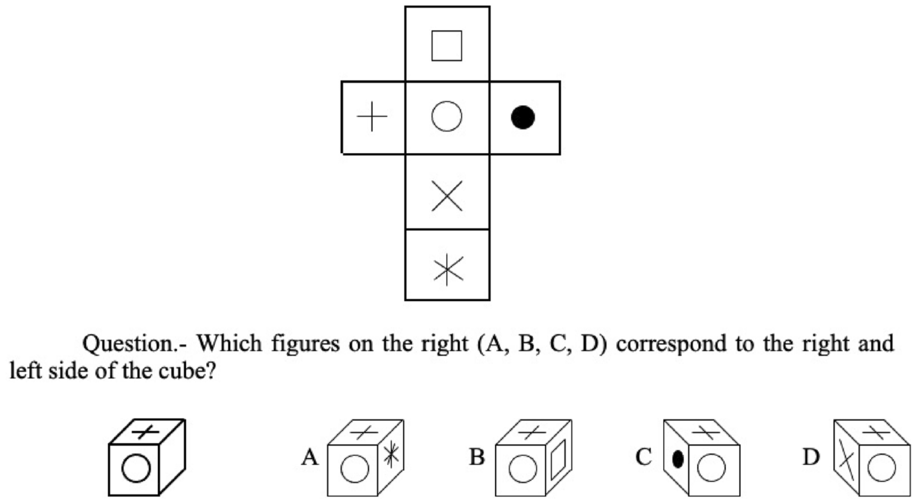

Fig. 5 Example of spatial mental imagery test: Measure of the Ability to form Spatial Mental Imagery (MASMI). This is one of questions of MASMI. Participants are required to choose a cube image from multiple options (from **A** to **D**) that correspond to the right and left side of the cube

α = 0.93; Campos, 2009). Previous scholars suggested that the MASMI can be an effective tool to measure virtual visualization processes in the domain-specific field related to designing and creating 3D objects (Kozhevnikov et al., 2013; Pérez-Fabello et al., 2018). Further, the survey also included questions about apparel design courses taken and perceived performance on those courses. Demographics questions were asked (i.e., current grade level, overall grade, gender, and age).

Data collection procedure

This research utilized the online survey developed from Qualtrics. Data collection was conducted at the university located in the Midwest region of the United States. Target participants are college students majoring the apparel design and product development program in the university. After approval from the Institutional Review Board (i.e., IRB ID: 260270), participants were recruited online (i.e., email and social media site) and participated in the study from May 3 to May 17, 2021. They were all college students in the apparel design and product development discipline at the university. Freshmen students identified that they are interested in majoring the discipline. After deleting incomplete data, responses were collected from a total of 70 participants (Table 2). About 43 participants (61.4%) were female, while 27 (38.6%) identified as male. The ages of the students ranged from 19 to 29 with the majority reporting that they are 19 (n = 31) and 20 (n = 12) years of age. Approximately 44.3% of the participants were first-year students, 15.7% were second-year, 7.1% were third-year, and 32.9% were fourth-year. With regards to academic backgrounds of participants, approximately 54% of the students' GPA ranged from 3.4 to 3.8 on a 4.0 scale. They all took courses related to the major of fashion design and product development. Courses are ranged from lower-level classes (i.e., providing background knowledge about apparel production and industry) to mid-level or upper-level classes that incorporated visualization and 3D stylization technologies (i.e.,

Table 2 Demographic and academic background

Variables	Frequency	Percentage
Gender		
Male	27	38.6
Female	43	61.4
Birth year		
1995	1	1.4
1998	11	15.7
1999	13	18.6
2000	2	2.9
2001	12	17.1
2002	31	44.3
Grade level		
Freshman	31	44.3
Sophomore	11	15.7
Junior	5	7.1
Senior	23	32.9
Number of courses taken		
1*	13	18.6
1,2*	5	7.1
1,2,3*	6	8.6
1,2,3,4*	18	25.7
1,2,3,4,5*,6*	1	1.4
1,2,3,4,5,6,7*	13	18.6
1,2,3,4,5,6,7,8*	2	2.8
Experience		
Apparel industry experience	28	40.0
Other	42	60.0

* 1 = CN (Course Number) 1200, Apparel Design and Production; 2 = CN 2280 Apparel Production; 3 = CN 2380 Integrated Apparel Design and Production I; 4 = CN 2480 Apparel and Textile Presentation; 5 = CN 2580 Digital Textile and Apparel Applications; 6 = CN 3380 Integrated Apparel Design and Production II; 7 = CN 3400 Technical Design; 8 = CN 4480 Creativity and Problem Solving; 9 = CN 4980 Apparel Production Management. CN 1000–2000 refers to lower-division courses while CN 3000–4000 refers to upper division courses providing in-depth study related to the major

Photoshop, Illustrator, CAD, 3D simulation video, 3D patterns making, OptiTex, CLO 3D). About 60% of participants mentioned that they took at least one to four courses, with 40% indicated that they took at least six or more courses.

Results

Correlation results: H1

To test H1, we used Pearson's r to test for the correlation among the variables (Table 3). Alpha at 0.01 was used to determine the significance for all statistical analyses. We found a positive correlation between the scores of the PFT and MASMI test: r (68) = 0.348, $p < 0.01$. We also found that there was a positive relationship between the paper folding test and ASVT-V scores: r (68) = 0.735, $p < 0.01$. However, there was no significant correlation between the MASTI and ASVT-V scores. Consequently, H1 was partially accepted.

Table 3 Correlation among scores of general spatial ability tests and VSTV-V (H1)

	1.PFT	2.MASMI	3.VSVT-V
1. Paper Folding Test (PFT)	–		
2. Measure of the Ability to Form Spatial Mental Imagery (MASMI)	.35**	–	
3. Apparel spatial visualization test applied to virtual environment (ASVT-V)	.74**	.19	–
M	7.33	6.51	13.59
SD	2.30	1.92	4.37

PFT scores are out of 10 points ($M = 7.33$, $SD = 2.30$); MASMI scores are out of 10 points ($M = 6.51$ $SD = 2.53$); ASVT-V scores are out of 20 points ($M = 13.59$, $SD = 4.03$); $p^{**} < .01$

Table 4 Number of apparel design and product development courses taken: three groups

Variable	Frequency	Percent	SD	Std. error
1–2 classes (lower-level)	18	25.7	4.26	1.00
3–6 classes (mid-level)	25	35.7	2.45	.490
7–9 classes (upper-level)	27	38.6	5.02	.967

Low-level classes includes CN 1200 Apparel Design and Production and CN 2280 Apparel Production; Mid-level classes additionally includes CN 2380 Integrated Apparel Integrated Apparel Design and Production I, CN 2480 Apparel and Textile Presentation, CN 2580 Digital Textile and Apparel Applications, CN 3380 Integrated Apparel Design and Production II; High-level courses additionally include CN 3400 Technical Design, CN 4480 Creativity and Problem Solving, and CN 4980 Apparel Production Management

Effects of the number of courses taken on ASVT–V scores: H2

To test H2, we created three groups according to the different numbers of courses taken by adopting the median split method (Table 4). A median split is used to turn a continuous variable into a categorical one by splitting the variables into equal groups (DeCoster et al., 2011). Participants in the first group (25.7%) have taken one or two courses. The second group (35.7%) have taken three to six courses. Participants in the third group (38.6%) have taken seven to nine courses. Students in the first group (i.e., 1–2 classes) took courses that have a course number (CN) of 1200 and 2280, which indicates that students in this group only took lower-level courses that provide fundamental knowledge about apparel design and production. Students in the second group (i.e., 3–6 classes) took courses that have a course number ranged from 1200 to 3380, which shows that participants in the second group took up to mid-level courses. Lastly, student in the third group (i.e., 7–9 classes) took all courses that have a course number ranged from 1200 to 4980, which indicates that students in this group took all ranges of classes to upper-level courses about apparel design and production. Course number information is presented in Table 4.

Further, ANOVA analysis was conducted. Results showed the effect of the number of apparel design and product development course taken on ASVT–V scores was significant: F (2, 69) 6.091, $p = 0.004$ (Table 5). Further, to test differences in mean score of ASVT–V scores across three groups, a multiple comparison was conducted (Table 6). Results show that students who took seven to nine courses perceived significantly greater ASVT-V scores compared to students who only took lower-level courses (i.e., one to two classes) and those who took classes up to the mid-level courses (i.e., three to six classes). This means that the more courses a participant has taken (i.e., 7–9 courses),

Table 5 ANOVA results (H2)

Variable	Sum of squares	df	Mean square	F	Sig
Between groups	201.43	2	100.72	6.091**	.004
Within groups	1107.94	67	16.54		
Total	1309.38	69			

$p^{**} < .01$

Table 6 Mean difference of ASVT-V scores across three groups (H2)

Three groups		Mean difference (I-J)	Std. error	Sig	95% CI	
(I) Group	(J) Group				Lower	Upper
1–2 classes (Lower-level)	3–6 classes (Mid-level)	− .55	1.26	.900	− 3.56	2.46
	7–9 classes (Upper-level)	− 3.78**	1.24	.009	− 6.74	− .81
3–6 classes (Mid-level)	1–2 classes (Lower-level)	.55	1.26	.900	− 2.46	3.56
	7–9 classes (Upper-level)	− 3.23*	1.13	.015	− 5.93	− .52
7–9 classes (Upper-level)	1–2 classes (Lower-level)	3.78**	1.24	.009	.81	6.74
	3–6 classes (Mid-level)	3.23*	1.13	.015	.52	5.93

$p^{*} < .05$, $p^{**} < .01$

the higher ASVT–V results the student achieved compared to students who took one or two course (β = 3.778, $p < 0.01$, 95% CI [0.81 6.74]) or three to six courses (β = 3.227, $p < 0.05$, 95% CI [0.52 5.93]). Therefore, H2 was accepted.

Table 7 ASVT-V scores: three groups

Variable	Frequency	Percent	Valid percent	Cumulative percent
Low ASVT-V	24	34.3	34.3	34.3
Mid ASVT-V	19	27.1	27.1	61.4
High ASVT-V	27	38.6	28.6	100.0

Effects of ASVT–V scores on performance in courses: H3

Using a median split, the scores of the ASVT–V were split into three separate groups (Table 7). The first group (n = 24, 34.3%) scored low on ASVT–V. Participants in the second group (n = 19, 27.1%) had scores in the mid-range. The third group (n = 27, 38.6%) had high scores on the ASVT–V.

To test H3, an ANOVA analysis was conducted. The results indicated that there was a significant difference in perceived performance across three groups of ASVT-V scores: F (2, 36) = 10.411, $p = 0.000$ (Table 8). To test differences in mean scores of those three groups, multiple comparison was conducted (Table 9). The results indicate that there is a

Table 8 ANOVA results (H3)

Variable	Sum of squares	df	Mean square	F	Sig
Between groups	94.40	2	47.20	10.41***	.000
Within groups	163.20	36	4.50		
Total	257.69	38			

$p^{***} < .001$

Table 9 Mean difference of ASVT-V Scores and performance in product development courses (H3)

Three groups		Mean difference (I-J)	Std. error	Sig	95% CI	
(I) Group	(J) Group				Lower	Upper
Low ASVT-V	Mid ASVT-V	.89	1.08	.690	− 1.75	3.54
	High ASVT-V	− 2.88**	.73	.001	− 4.67	− 1.10
Mid ASVT-V	Low ASVT-V	− 8.94	1.08	.690	− 3.45	1.75
	High ASVT-V	− 3.77**	1.08	.004	− 6.42	− 1.13
High ASVT-V	Low ASVT-V	2.88**	.73	.001	1.10	4.67
	Mid ASVT-V	3.78**	1.08	.004	1.13	6.42

$p^{**} < .01$

Table 10 ANOVA results (H4)

Variable	Sum of Squares	df	Mean square	F	Sig
Between groups	28.30	2	14.15	2.22	.123
Within groups	229.29	36	6.37		
Total	257.69	38			

significant difference in the performance across three groups according to their ASVT-V scores. This indicates that the group with high ASVT scores indicated greater performance in apparel design related courses than the group that had low ($\beta = 2.882$, $p < 0.01$, 95% CI [1.10 4.67]) and mid ($\beta = 3.776$, $p < 0.01$, 95% CI [1.13 6.42]) ASVT scores. Thus, H3 was accepted.

Effects of the number of courses taken on performance in courses: H4

Similar to H2, to test H4, an ANOVA analysis was conducted. Results showed there were no significant differences in perceived performance in courses according to the numbers of courses taken: F (2, 36) = 2.222, $p = 0.123$ (Table 10). Multiple comparisons revealed that there was not a significant difference along with the ANOVA result (Table 11). Thus, H4 was rejected.

Discussion

The future of apparel design education continues to change as technology rapidly reshapes the fashion and apparel industry. As technology continues to infiltrate the design atmosphere, understanding how spatial ability plays a role in design visualization is important. By applying the ASVT–V using the design software CLO 3D, the

Table 11 Mean difference of number of courses taken and perceived performance (H4)

Three groups		Mean difference (I-J)	Std. error	Sig	95% CI	
(I) Group	(J) Group				Lower	Upper
1–2 classes (Lower-level)	3–6 classes (Mid-level)	− 2.03	1.89	.535	− 6.64	2.58
	7–9 classes (Upper-level)	1.68	.89	.123	− 3.71	.36
3–6 classes (Mid-level)	1–2 classes (Lower-level)	2.03	1.89	.535	− 2.58	6.64
	7–9 classes (Upper-level)	.350	1.87	.981	− 4.22	4.92
7–9 classes (Upper-level)	1–2 classes (Lower-level)	1.68	.83	.123	− .36	3.71
	3–6 classes (Mid-level)	− .35	1.87	.981	− 4.92	4.22

purpose of this study is to understand the spatial ability of current college students. By examining the visualization skills and mental imagery in a virtual prototyping, this research sought to understand the importance of improving domain-specific spatial ability skills that can be measured by ASVT-V. It also sought to examine how the spatial ability could influence students' performances in apparel design and product development courses.

In this study, results show that the more courses the students took, the higher their ASVT–V scores. This indicates that students with more knowledge and experience about creating and developing garments were able to transform 2D patterns (i.e., pattern blocks) into correct 3D garment outcomes within virtual environment. We found that when students took more than six courses (i.e., up to upper-level classes), their ASVT-V scores were greater than those of students who took less courses (i.e., lower-level or mid-level classes). Lower-level courses include Apparel Design Production (CN 1200) and Apparel Production (CN 2280) that are introductory courses about design techniques, garment assembly operation, and swan products industry technologies. Mid-level courses include Integrated Apparel Design and Production I/II (CN 2380, CN 3380), Apparel and Textile Presentation (CN 2480), and Digital Textile and Apparel Application (CN 2580). Students who took those mid-level classes were introduced 2D-to-3D design software such as Optitex and CLO 3D, where they learned those software programs but, did not utilize the program for making a garment. Also, another course (CN 2480) is incorporated with image creating and editing software such as Photoshop and Illustrator. Upper-level courses additionally include Technical Design (CN 3400), Creative and Problem Solving (CN 4980), and Apparel Production Management (CN 4980). Importantly, students in the Technical Design were involved in project-based learning by adopting various 3D simulation software such as Optitex, CLO 3D, and Sketch. Other two classes also provide lab-based experiential learning through projects and exhibitions by creating apparel objects. This shows that when students have more experience in apparel design and product development and 3D simulation technologies (i.e., upper-level courses), they have more spatial ability than those students who do have less experience. Although the relationship between domain-specific courses and visualization ability was identified by earlier researchers (i.e., Workman & Lee, 2004), by applying

ASVT to virtual environment (i.e., ASVT-V), our results expand the earlier findings into the current and upcoming fashion industry transformation into digital areas. In addition, we found that ASVT–V scores are significantly related to scores achieved from the paper folding test (i.e., PFT), while there was no relationship with the mental rotation test (i.e., MASMI). To be specific, even though paper folding test scores were associated with spatial metal imagery scores, the spatial mental imagery scores were not related to the ASVT-V scores. As there was a relationship between ASVT-V and general visualization scores (i.e., PFT scroes), the validation of ASVT-V was maintained. Also, no correlation between ASVT-V and MASMI might be because that, in our assessment of ASVT-V, the 3D models were automatically rotated within each video clip. Although participants could pause the video and adjust the speed of the rotation, this might not fully explain participants' mental rotation process that is defined as a core part of mental imagery ability (Ekstrom et al., 1976). This can result a weak relation between ASVT-V scores and mental imagery scores in our study's context.

Lastly, we suggest that the use of 3D simulation technology will become increasingly important in apparel design and product development education and industry. The successful adoption of 3D simulation technology and students' performances can be assessed from ASVT-V. Importantly, we found that the number of apparel design and product development courses taken did not explain perceived performance, while ASVT–V scores could explain their performance. Given the finding that ASVT–V scores can be positively enhanced from apparel design and product development courses taken, this shows the critical role of ASVT–V scores between the domain-specific education and student performance. So, when the courses help students to enhance their domain-specific or major-related spatial ability, this eventually increases students' performance in their courses. This finding is in line with the previous studies results. Dere and Kalelioglu (2020) investigated the spatial abilities of students using a web-based 3D design environment. They tried to understand what contributions could increase students' creative ability of 3D design (Dere & Kalelioglu, 2020). Their results indicated that education (e.g., related courses taken) improved both the students' ability to mentally visualize and manipulate spatial objects. Although our findings' direction is similar with the previous study, our results are meaningful as we apply a domain-specific spatial ability for students who majored in apparel design and product development, which ultimately suggests the importance of education within 3D virtual environment in increasing spatial ability and students' performance in courses.

Conclusion and limitations

We have several implications. First, the study provides critical implications on the future development of curricula for apparel design and product development courses. When courses can increase students' 3D spatial ability related to multi-dimensions of apparel products by actively adopting 3D simulation tools, students' performance will be enhanced. Second, results of this study provide theoretical implication as it is the first study to apply ASVT into 3D virtual environment (ASVT–V) for examining the role of domain-specific spatial ability in apparel design education research. While previous researchers examined spatial ability in apparel research using a developed 2D format test (Ahn & Workman, 2012; Gitimu & Caldwell, 2007; Workman et al., 1999), there was little research on spatial ability within a virtual environment in apparel research (e.g., Park et al., 2011). While the ASVT test measures apparel spatial visualization abilities of individuals in a 2D formatting, it is lacking the ability to measure apparel spatial ability within a 3D environment. By applying the ASVT to virtual environment, this study contributes to the current literature focusing on ASVT. Finally, our results indicate the importance of understanding spatial ability incorporated with the virtual environment especially for the specific education discipline of apparel design and product development. This will become increasingly important as the industry seeks individuals with 3D visualization and simulation experiences.

Although this study developed a research model and designed the survey carefully, the study has limitation. One of the limitations of this study is its sample size. This may likely be due to the fact that the survey was sent only to students majoring in apparel design and product development within one university. Thus, researchers should continue to aim to reach a larger sample size in the future. For example, future studies could expand their recruitment to multiple universities to capture a larger number of apparel design and product development students and broaden the findings of the current study. Further, it is possible that there are other factors influencing the domain-specific spatial ability and performance of classes. For example, previous scholars suggested spatial ability can be improved through pattern making courses (Workman & Caldwell, 2007; Workman et al., 1999). Also, gender and cultural difference can be related with students' achievement in domain specific spatial ability (Gitimu & Workman, 2007; Workman & Lee, 2004). Thus, in future studies, the potential relationship needs to be examined by adopting ASVT-V. Importantly, this research compares the ASVT–V to both the paper folding and mental imagery measurements (i.e., PFT and MASMI). However, we did not compare it to the scores achieved from the original ASVT. Even though we maintained the same questions from the original ASVT questions, future research can compare the original ASVT with the ASVT–V for increasing the validity and reliability of ASVT–V scores. Lastly, as this study applied an apparel spatial visualization test to the virtual environment, for future studies, the test can be used to further understand apparel-related spatial ability in various educational settings. For example, future scholars can dive deeper into understanding the different levels of spatial ability to identify the benefits of utilizing the ASVT–V training tools in a course curriculum.

Abbreviations

ASVT	Apparel spatial visualization test:
ASVT-V	Apparel spatial visualization test applied to virtual environment
PFT	Paper folding test
MASMI	Measure of the ability to form spatial mental imagery
3D	Three dimensional
2D	Two dimensional
CAD	Computer-aided design
CDIO	Conceive design implement and operate
STEAM	Science, technology, engineering, arts, and mathematics
ANOVA	Analysis of variance
CN	Course number

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Authors' contributions
Dr. Youn advised a direction of the study for building a research framework. Anna as a graduate student researcher developed stimuli for the study. She collected and analyzed a dataset and worked on the first draft. Dr. Youn revised and rebuild the manuscript. All authors read and approved the final manuscript.

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