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Research Article

An exploration of first year pre-service engineering graphics and design teachers' spatial visualisation ability at a university of technology

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Abstract

The critical shortage of engineers in South Africa is linked directly to the schooling systems' inability to develop fundamental skills required in engineering courses, such as spatial visualization ability. Not much is known on the factors that enable or constrain the development of students' spatial visualization skills. This study aimed to explore first year Engineering Graphics and Design (EGD) Pre-Service Teachers' (PSTs) spatial visualization skills and the factors that enables or constrains their spatial visualization skills. A mixed method approached was used to generate data. Data was from twenty-one first year EGD PSTs at a University of Technology, in Kwa-Zulu Natal in South Africa. The participants were purposively selected to participate in the study. The Purdue Spatial Visualization Test: Visualization of Rotations (PSVT: R) was used as a benchmark to establish participants level of spatial visualization skills. Collages and focus group interviews were used to explore the factors that enabled or constrained PSTs spatial visualization skills. The PSVT test results was analysed and categorized as per rotation. Qualitative data was subjected to content analysis. The findings of this study differ from that of other studies on student's spatial visualization skills. Other studies provide consistent evidence that male students have better developed spatial visualization skills than females. First year female participants in this study have higher scores than male participants in the PSVT:R. The factors that enhanced female students' spatial visualization ability were playing with Legos, enjoying mathematics, working with indigenous patterns while teachers and violence at schools constrained the development of spatial visualization skills.

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Introduction

South Africa has a critical shortage of engineers. The skills shortage identified in the engineering field has been linked directly to the schooling systems' inability to develop fundamental skills required in engineering courses. Consequently, fewer learners enter engineering related fields of study at tertiary institutions. The fundamental skills needed in the engineering field include among others the ability to communicate graphically, spatial visual ability as well as the ability to read and interpret graphical text in subjects like Engineering Graphics and Design (EGD) (Konadu-Yiadom, 2016). Within the South African context our education system, pays more attention to written text and tends to favor the development of verbal, written and numerical skills rather than spatial visualization ability. In EGD, leaners learn to communicate graphically and are expected to be able to read and interpret graphical text. However, a study by Singh-Pillay and Sotsaka (2017) contend that many practicing teachers of EDG lack the pedagogical content knowledge needed to develop spatial visualization ability required by learners to cope with engineering drawings such as assembly drawings. Additionally, the National Senior Certificate (NSC) EGD examiners and moderators report highlights matric learner's (in)ability to read and interpret engineering drawings for example assembly drawing (AD) (DBE, 2012-2015).

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It is well documented in literature that the fundamental skills needed to function effectively in engineering courses is spatial visual ability (Rodriguez & Rodriguez, 2016; Seery, Lynch, & Dunbar, 2010; Branoff & Dobelis, 2012; Uttal, Meadow, Tipton, Hand, Warren & Newcombe, 2013). Quantitative studies show that strong spatial visualization ability is important to create and interpret engineering drawings (Konadu-Yiadom, 2016; Makgato & Khoza, 2016). This means that spatial visualization ability is special type of intelligence or giftedness that needs to be recognised as an important part of intellectual functioning required in the STEM field. Within the South African context there is a paucity of literature on engineering graphics and design education in general and specifically on pre–service teachers' (PSTs) spatial visualization, ability as well as factors that enables or constrains first year EGD PSTs' spatial visualisation ability.

Spatial visualization ability includes the ability to visualise mental rotations of objects, the ability to understand how objects appear in different positions, the ability to conceptualize how objects relate to each other in space and the ability to understand objects in 3-D space (Cheng & Mix, 2014). This means that students with well-developed spatial visualization ability can mentally transform or rotate two- or three-dimensional (3- D) objects to whatever direction is indicated through spatial visualisation. There is widespread evidence that spatial visualization ability can be developed in all ages from early childhood to adulthood (Hawes, Tepylo & Moss, 2015). Studies have shown that training can enhance spatial visualization ability in a relatively short time. In particular, many research studies found out that spatial visualization ability of an individual can be improved by means of effective instruction in which concrete materials (Bobek & Tversky, 2016) manipulatives (Lowrie, Logan, Harris, & Hegarty 2018), digital manipulatives (Ramful, Lowrie, & Logan,2017), various toys (Batinov, 2017) and computer programs (Francis, Khan, & Davis, 2016) are employed. For instance, Bobek and Tversky, (2016) concluded that spatial visualization abilities of undergraduates majoring in architecture, mathematics education, mathematics and mechanical engineering are significantly related to their childhood experiences. In their study, Francis, Khan and Davis (2016) examined how the spatial visualization ability of the children aged 9 to 10 developed when they were learning how to program LOGO, Mindstorms and EV3 robots. During the coding process, children were imagining the robot movements in three dimensions while they were coding in two dimensions. The researchers asserted that this coding application included fluency in shifting between 2D and 3D and developed children's spatial visualization reasoning ability (Francis, Khan, & Davis, 2016).

Buckley, Seery and Canty, (2019) investigated the development of engineering students' spatial visualization ability and concluded that male and female students' spatial ability performances are different, in favor of males. Likewise, Battista (1990) reported in his cross-sectional study that, in high school, males outperformed females in most situations requiring spatial visualization due to females experiencing greater spatial anxiety than males (Ramirez, Gunderson, Levine, & Beilock, 2012). Understanding the intrinsically interconnected relationship between spatial visualization ability and factors that enable or inhibit spatial visualization may provide new ways of thinking about individual differences in spatial visualization ability and ways to reduce spatial anxiety and improve spatial visualization ability.

The Purdue Spatial Visualization Test: Visualization of rotations (PSVT: R) was used as a benchmark to establish first year EDG PSTs level of spatial visualization ability in order to scaffold their learning of EGD.

Problem of Research

South Africa has a critical shortage of engineers which has been linked to the schooling systems inability to develop fundamental spatial visualization skills in students. It is worth noting that in South African much emphasis is placed on reading of written text in schools and universities. Spatial visualization ability is special type of intelligence or giftedness that needs to be recognized as an important part of intellectual functioning required in the STEM field if we are to address the critical shortage of engineers in South Africa. Not much is known on the factors that enable or constrain the development of spatial visualization skills among students. This study intends to address the gap identified in the literature by responding to the following research questions, namely,

- What are first year EGD PSTs' level of spatial visualization ability?
- What enables or constrains first year EGD PSTs spatial visualisation ability?
- Gaming deeper insights into first year students level of spatial visualization ability and factors that enable or inhibit it may provide new ways of thinking about how to reduce spatial anxiety and improve spatial visualization ability?

Method

Research Design

This mixed method study embraced the pragmatic paradigm. The pragmatic paradigm considers the fitness of purpose when conducting a study (Creswell & Creswell, 2017). Using a mixed method methodology enabled us to combine the strengths of both qualitative and quantitative methodologies in a single study. Data was generated in two stages. In stage one quantitative data was generated and in state two qualitative data was generated. Figure 1 below is a flow diagram of the research design and data collection tools.

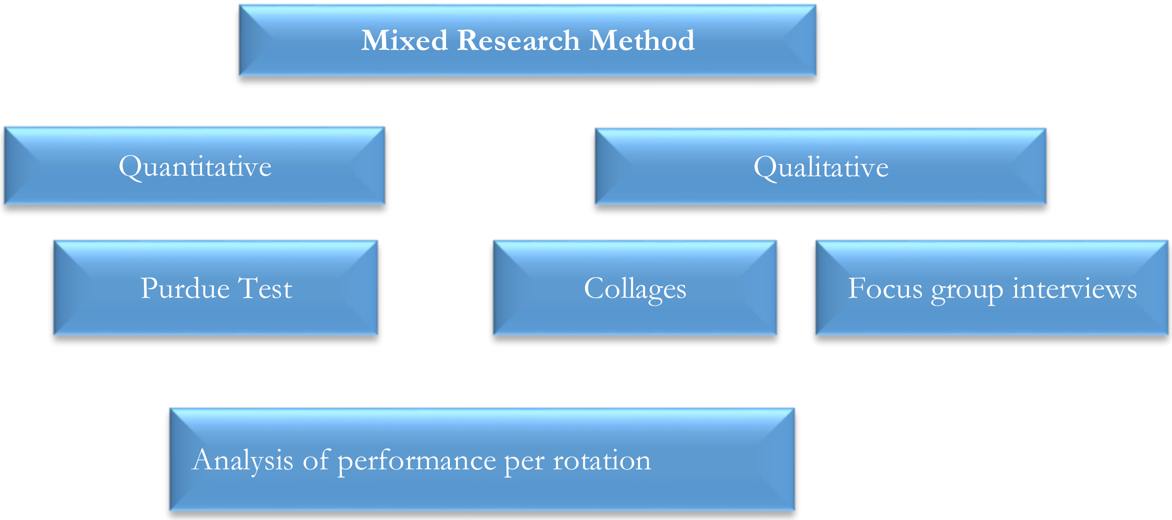

Figure 1.
Flow Diagram of Research Design and Data Collection Tools

Participants

Twenty-one first year EGD PSTs (9 females and 12 males) who had enrolled for the B Ed EGD module were purposively selected to participate in the study. Purposive sampling is described by Rule and John (2011) as the "sampling where the people selected as research participants, are deliberately chosen because of their suitability in advancing the purpose of the research" (p. 64). The criteria for the selection of participants is they were enrolled for the EGD module at a particular university of technology and could provide information in response to the research questions posed.

Ethics

Permission to conduct the research was granted by the university ethics committee. Informed consent was sought from the first year EGD PSTs, they were also assured of confidentiality and anonymity. Data was generated during the first week of semester one in 2018 at a University of Technology, in the Midlands region of Kwa-Zulu Natal in South Africa. In other words, data was generated before the commencement of the lectures for Bachelor of Education (B. Ed) EGD curriculum in order to establish first year EGD PSTs spatial visualization ability.

Data Collection Tools

For state one of data generation, the Purdue Spatial Visualization Test: Visualization of rotations (PSVT: R) was used as a benchmark to establish first year EDG PSTs level of spatial visualization ability and to respond to research question one. The test is used in engineering graphics to measure spatial visualization ability to mentally rotate objects. The PSVT:R is unique in that it includes a variety of 3-D objects (including objects with inclined, oblique, and/or curved surfaces), and it requires a higher level of spatial visualization ability.

The PSVT: R has 30 items consisting of 13 symmetrical and 17 non-symmetrical figures of 3-D objects, which are drawn in a two-dimensional (2-D) isometric format. The duration of the test is twenty minutes. In each item, the respondents' task is to mentally rotate a figure in the same direction visually indicated in the instructions and identify the most appropriate choice among the five options provided. In this, study a pencil and paper, PSVT: R was used. The PSVT: R comprised of three sections, in the first section (questions 1-6) the three-dimensional object was rotated once, in the second section (questions 7-22) the object was rotated twice and in the third section (questions 23-30) the object was rotated thrice. An example problem is shown in Figure 2.

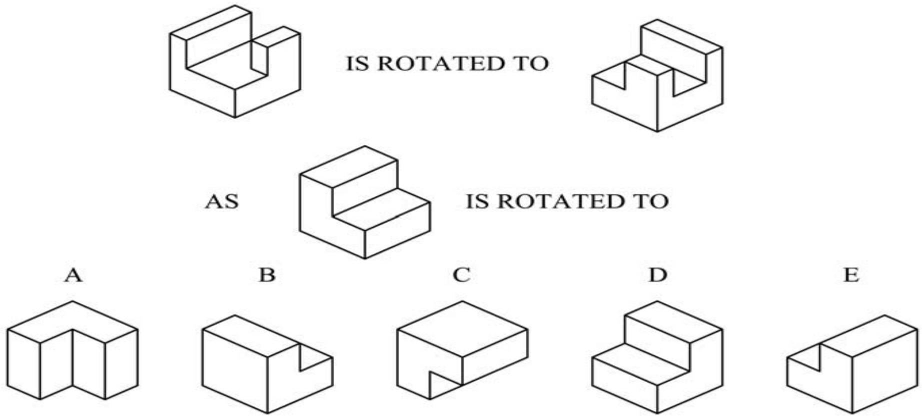

Figure 2.
PSVT: R Example Problem

For stage two of data generation, qualitative data was generated via collages and focus group interviews in order to answer research question two.

A collage is a piece of art, made by sticking various pictures and other materials on a poster or similar backing, it represents feelings and experiences about the situation depicted (Khanare & de Lange, 2017) (in this instance what enables or constrains first year female EGD PSTs spatial visualization ability). Using art as a research method provides researchers with a window into the lived experiences of the participant and a means to understand how they make meaning of these experiences pertaining to what enables or constrains their spatial visualization ability; their enculturation, stereotypes, etc. The first year EGD PST were provided with a wide variety of magazines from which to source picture for their collages. The brief provided to first year EGD PSTs was that they had to position themselves, their encounters, experiences with regard to what enables or constrains their spatial visualization ability in the collage. Each chosen picture/s or word/s will tell a story about their experiences /challenges pertaining to their spatial visualization ability. To create the collages the EGD PSTs sat in groups (3 groups were formed, each group had 7 members). Each group collectively looked through magazines provided to them for pictures and words that captured what enabled or constrained their spatial visualization ability. They also cut out words and sentences that added to what they aimed to articulate through their collages. The collage making session was audio recorded. Upon completion of the collages, they were invited to a focus group interview. The purpose of the focus group interview was to present their collages and for the researcher to probe their responses. The focus group interviews were audio recorded. The recoding was transcribed verbatim. Transcripts were printed and returned to the participants for member checking in order to ensure participants had an opportunity to review what they had said, add more information if they wanted to, and to edit what they said. Member checking contributes to the trustworthiness and credibility of the data generated (Cohen et al., 2018)

Data Analysis

The PSVT:R test results was analysed and categorized as per rotations they appear in the test itself. The number of correct responses for each type f rotation was noted. This enabled us to establish the PSTs' level of spatial visualization ability. A comparison was made of male and female PSTs' level of spatial visualization ability.

For the qualitative analysis the transcribed transcripts that were checked by the participants were read and re-read while bearing in mind the term/s associated with each picture in order to note patterns, convergences and divergences between the data from the collages and focus group interviews. Figure 3 below reflects how data was analyzed for each data generation method.

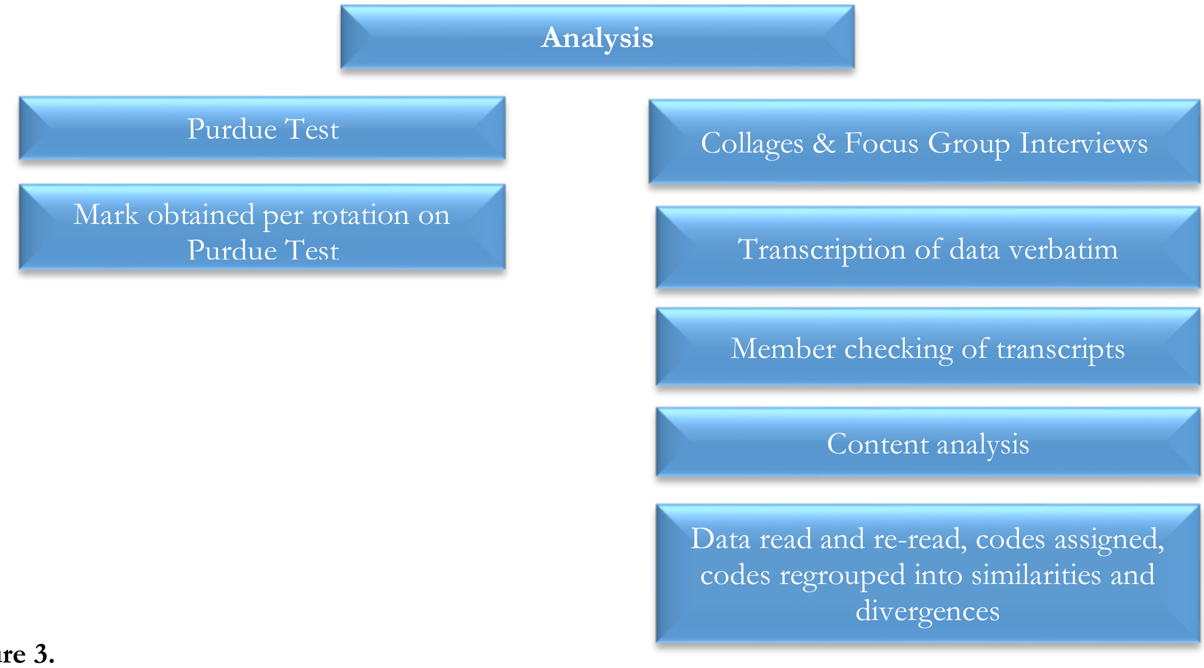

Figure 3.
Flow Diagram of Data Analysis Process

Results

In this section data from the PSVT: R, collages and focus group interview are presented.

Data from the **PSVT: R** is presented first as mentioned earlier the PSVT:R was used to measure PSTs spatial visualization ability to mentally rotate objects.
Table one below reflects the performance of first year EGD PSTs on the three components of the PSVT: R.

Table 1.
PSTs' Performance on Three Components of PSVT

Participant (P)	Gender	One rotation: question 1-6: out of 6 marks	Two rotations: question 7-22:out of 16 marks	Three rotations: question 23-30:out of 8 marks	Total marks out of 30
1	**F**	4	8	5	17
2	**M**	2	2	1	5
3	**M**	3	8	4	15
4	**F**	3	7	3	13
5	**M**	2	4	2	8
6	**M**	5	9	4	18
7	**M**	4	7	5	16
8	**M**	3	4	1	8
9	**F**	4	10	4	18
10	**M**	3	5	2	10
11	**M**	4	6	2	12
12	**F**	4	9	6	19
13	**M**	3	7	2	12
14	**M**	3	5	2	9
15	**F**	4	12	4	20
16	**F**	3	9	5	17
17	**M**	1	4	4	9
18	**M**	4	3	2	9
19	**F**	4	8	3	15
20	**F**	4	8	4	16
21	**F**	3	8	4	15
Total pass		18	10	11	11
Percentage		**86%**	**48%**	**52%**	**52%**
Total fail		3	11	10	10
Percentage		**14%**	**52%**	**48%**	**48%**

It is visible from table 1 above that 18 (86%) first year EGD PSTs obtained above 50% for the first part of the test (one rotation). Three EGD PSTs got more than 3 incorrect answers for questions 1-6 of the test. The implications are that these 3 PSTs are lacking or rather have not nurtured foundational spatial visualization ability (as yet) even though they studied EGD at high school from grades 10-12 (for a period of 3 years).

Questions 7-22 of the PSVT-R entailed mentally rotating the object twice. Only 10 PSTs (48%) managed to obtain a score of above50% (i.e. 8 correct responses for section two of the test). 11 PSTs (52%) were unable to mentally rotate the object twice, once again revealing these first year EGD PSTs have poorly developed spatial visualization ability.

Eleven first year EGD PSTs (52%) obtained more than 4 (50%) correct responses to questions 23-30 which entailed mentally rotating the object thrice. 10 PST (48%) were unable to mentally rotate the object thrice.

A closer examination of table 1 illuminates, first that the majority of PSTs (86%) can visualize 3D objects if they rotated once. Second, that as the number of rotations increased first year EGD PSTs found it more difficult to visualize the rotations. In other words, they display a decrease in spatial visualization ability as the number of rotations increase. The findings of this study are aligned with the findings of Maeda, Yoon, Kim-Kang & Imbrie, (2013) study which highlighted that more than 50% of first year engineering students were able to answer most of the PSVT: R items correctly.

Thirdly table one reveals, that female EGD PSTs performed better or are more gifted that male EGD PSTs in terms of spatial visualization ability on the PSVT: R. Table 2 reflects the performance of first year EGD PSTs in PSVT:R according to gender for each section of the test.

Table 2.
Performance of Male and Female EGD PSTs in the PSVT: R

Gender	Number passed one rotation (Q1-6)	Number passed two rotations (Q7-22)	Number passed three rotations (Q 23-30)	Mean	Median
Male = 12	9	2	3	10.91(36%)	9(30%)
Female = 9	9	8	8	16,6 (55%)	17 (56%)

It is explicit from table two above that the performance of male and female PSTs changed drastically once they had to mentally rotate the 3D objects twice and thrice.

Only two first year male EGD PSTs were able to mentally, rotate the 3D object twice while only 3 were able to mentally rotate the 3D object trice as compared to 8 first year female EGD PSTs who were able to mentally rotate the 3D object twice and trice. A comparison of the mean and median scores indicates first year female EGD PSTs are better able to mentally rotate an object twice and trice as compared to male EDG PSTs. The mean score for first year female EGD PSTs in the test is 16.6 as compared to 10.9 for male EGD PSTs. Hence, it can be inferred that female first year EGD PSTs have more enhanced spatial visualization ability than their male counterparts. This particular finding differs from that of other studies on mental rotation ability, which focus on students in engineering field and provides consistent evidence for gender differences that favor males (Wang & Degol, 2017; Buckley, Seery, & Canty, 2019; Ramirez, Gunderson, Levine, & Beilock, 2012).

This study provides evidence that first year female EGD PSTs performed better in the PSVT: R test than first year male EGD PSTs. Data from the collages and focus group interviews elucidate the factors that enable or constrains first year EGD PSTs spatial visualisation ability.

Collages/Focus Group Discussion

Data from the collages and focus group interviews were used to respond to research question two, namely, what enables or constrains first year EGD PSTs spatial visualisation ability?

Enablers of PSTs spatial visualisation skills included playing with Legos/block, enjoying mathematics, working with indigenous patterns while teachers and violence at schools constrained first year female EGD PSTs' spatial visualization skills.

Figure 4.
Collage Showing Factors that Enable and Constrain the Development of Spatial Visualization

Enablers of PSTs Spatial Visualization Skills

Playing with Legos/blocks

Nine first year female EGD PSTs indicated that they had played with Legos /blocks when they were in pre and primary school as is evident in the focus group interview:

> *"I have always played with Legos- as a child – it helps me to think about which block are needed and how the blocks would fit together to form the model."* P9 focus group interview
>
> *"Playing with Legos and blocks let me manipulate shapes- and get them to fit together- I learnt to image the shapes mentally and how they will fit and work together"* P12 Focus group interview

From the above excerpts, it is evident that playing with Legos and blocks enabled "seeing" of the parts that make up the whole model as well as figuring out how the parts relate to each other. The above findings show that playing with certain types of toys can enhance spatial visualization ability. This finding resonates with other research studies which established that spatial visualization ability of an individual can be improved by means of various toys (Batinov, 2017), concrete materials that can be manipulated (Bobek & Tversky, 2016) and digital manipulatives. The above finding accounts for first year female EGD PSTs have adept spatial visualization ability.

Enjoying mathematics as a child

Many first year EGD PSTs explicated that they enjoyed learning mathematics in primary school as is conspicuous in the excerpts below:

> *"I used to get full marks when we had to calculate the surface area or find the volume of an object – I could image what needed to be done*" P20 focus group interview.
>
> *"I enjoyed learning about shapes, congruency and graphs it allowed me to image, mentally flip the shape in my mind and draw to scale- I still use these skills in EGD*" P6 focus group interview

The excerpts above illustrate that engaging with mathematics enabled these first year EGD PSTs to visualize, mentally rotate objects, estimate and draw to scale. In other words, mathematics developed these PSTs spatial reasoning which use in EGD. Links between spatial visualization ability and mathematics reasoning has been established by a study conducted by Mix, Levine, Cheng, Young, Hambrick and Konstantopoulos (2017). These scholars found that mental rotation was significantly related to the mathematical factor among kindergarteners, whereas in sixth graders spatial visual working memory and form copying were significantly related to the mathematical factor.

Working with indigenous patterns

First year EGD PSTs elaborated that being involved with drawing/painting indigenous patterns in their early years helped them in EGD as reflected in the excerpts below

"*I used to help my gogo (granny) to draw free hand indigenous patterns on the walls of our home-by repeating the pattern in a particular sequence , I had to help her all the time, doing bead work , making patterns on clothing, I learnt to sketch different patterns and shapes and visualise the next sequence of patterns. I use these skills in EGD*" P9 Focus group interview

"*When decorating the walls at home I learnt to copy and distinguish shapes from other shapes, including symbols, I learnt about repeating and alternating patterns- this helps me to image and transform patterns and shapes mentally*". *P7, focus group interview*

Working with repeating indigenous patterns provides early opportunities to sketch freehand, visualise, rotate patterns, identify and describe predictable sequences. Engaging in these skills allowed first year EGD PSTs to develop and enhance their spatial visualization ability. This particular finding indicates that indigenous art forms can be used to develop learners' spatial visualisation ability.

Constraints of PSTs spatial visualization skills

Teachers

Many first year EGD PSTs (14) indicated that EGD teachers who lack content knowledge and knowledge of how to teach EGD contributed to their poor performance in EGD as is visible in the excerpts below:

"*My EGD teacher at school just could not teach, he would get angry if we asked questions or asked him to explain something*" P2, focus group interview

"I was always lost in class as a result I just scraped a passed in EGD, my teacher could not explain what we were expected to learn in EGD" P11, focus group interview.

Teachers' lack of content knowledge and the inappropriate teaching strategies they use sculpts PSTs performance in EGD and their spatial visualizations skills. Our findings reveal that first year EGD PSTs' lack of spatial visualization skills is attributed to teachers' lack of content knowledge, self-efficacy of STEM teaching (Tortop & Akyildiz, 2018) and inability to explain concepts. The above findings concur with Singh-Pillay and Sotsaka, (2017) and Sotsaka (2015) studies which emphasizes that traditional teaching methods and approaches do not scaffold the students' visualization skills and that EGD students encountered the problem of visualization in learning of EGD because current teaching and learning of EGD is via static drawing.

Discussion and Conclusion

The finding of this study illuminate that first year female EGD PSTs performed better than first year male EGD PSTs in the PSVT:R. This means female participated were better able to visualise and mentally rotate objects for two and three rotations as compared to male participants. It can thus be inferred that female participants in this study had better spatial visualization ability than first year male EGD PSTs. This particular finding is significant, as it differs from the findings of studies by Wang and Degol, (2017); Buckley, Seery, & Canty, (2019); Ramirez et al., (2012) which assert that male students perform better as spatial visualization tasks and hence have better developed spatial visualization skills than female students.

The findings of this study bring to the fore experiential factors that enable and constrain first year EGD PSTs' spatial visualization skills. Factors that enable fist year EGD PSTs spatial visualization skills include playing with Legos/building blocks, enjoying mathematics as a child and working with indigenous patterns. The aforementioned first two factors are consistent with those identified in Young et al., (2018) study, which reveal that playing with certain types of toys improves learner's spatial visualization ability. It is worth noting that this study illuminates that working with indigenous patterns (whilst painting their homes or doing bead work) fosters the development of spatial visualization skills such as free hand sketching, ability to rotate patterns, ability to imagine and predict sequences. Our finding also brings to the fore the potential role of indigenous art (painting and bead work) in enabling the development of spatial visualization skills and ability among students studying EDG. South African has a rich heritage of indigenous art and design patterns This finding has implications for further research, first in terms of the use of indigenous design patterns as a teaching and learning tool to develop learners' spatial visualization skills. Second in terms of gender and spatial visualization ability. Third in terms of addressing the critical shortage of engineers in South Africa.

Moreover, the findings of this study illuminate factors that constrain first year EGD PSTs' spatial visualization ability includes teachers and violence. Our finding pertaining to teachers resonates with Singh-Pillay and Sotsaka (2017); Sotsaka, (2015), which highlight that teachers' lack of content knowledge, traditional teaching methods and approaches (Huda, Munifah & Umam, 2020) do not scaffold the development of students' spatial visualization skills. Furthermore, Singh-Pillay and Sotsaka (2017) asserts that EGD students encountered the problem of visualization in learning of EGD because current teaching and learning of EGD is via static drawing.

Limitations of Study

The sample size was small, and sampling was confined to one institution. To overcome this limitation qualitative data was generated via focus group interviews and collages.

Recommendations

The finding of this study highlight first the need for further research on the potential role of indigenous art in the promotion of spatial visualization skills such as free hand sketching, ability to rotate patterns, ability to imagine and predict sequences.

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