AGE DIFFERENCES IN SPATIAL VISUALIZATION ABILITY: TRACKING ITS’ DEVELOPMENT ACROSS PREADOLESCENT AND ADOLESCENT YEARS

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Abstract
Spatial visualization is the ability to visualize complex spatial relations among the constituent parts of an object and manipulate them to predict how the whole will look when constructed from its parts. The literature review indicated that the development of this ability across preadolescent and adolescent years is less explored. The present research, therefore, purported to study the development of Spatial Visualization ability across the preadolescent and adolescent years. In Study I, a new test was developed and administered to 150 preadolescents and adolescents. It was validated using a 2-Parametric Logistic Item Response Theory model. In Study II, the Developmental Trajectory of the ability across the preadolescent and adolescent years was explored by administering the newly developed test to 760 participants (Mean age=11.54 years; SD=2.84). A one-way Analysis of Variance model indicated significant age differences. Further, Trajectory Analysis revealed a linear trajectory across the developmental period. Findings were discussed in light of Piagetian and Neo-Piagetian theories.

Keywords: spatial visualization; test development; preadolescence; adolescence; trajectory analysis

Introduction
Spatial visualization (SV) is the ability to deal with complex, multistep manipulations of spatially presented information (Linn & Peterson, 1985). According to Lohman (1979), it is the "ability in manipulating visual patterns, as indicated by the level of difficulty and complexity in visual stimulus material that can be handled successfully, without regard to the speed of task solution". It is thereby considered to be the most extensively studied ability in cognitive psychology (Carpenter & Just, 1986). As described by Carroll (1993), spatial visualization requires certain processes for apprehension, encoding, and mental manipulation of spatial forms. Perhaps, this explains the fact that this ability loads highest on tests like the Spatial Relations subtest of the Differential Aptitude Test

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(Bennet, Seashore, & Wesman, 1972). Items of the Spatial Relation subtest require subjects to "hold a visual array of information, comprehend the relations among the information units, apply mental operations to perform transformations of the spatial relations to predict an inference and evaluation of predicted outcome" (Datta & Dutta Roy, 2015).

Hegarty (2010) proposed two components for spatial intelligence. The first is the ability to make a flexible choice between mentally representing or simulating objects and choosing a more analytic form of thinking that involves rule-based reasoning. And the second component is the "meta-representational competence" (diSessa, 2004) which involves the ability to choose between the optimal external representation for a task, use it productively, and improvise as required. While the first one is about choosing the optimal internal representation, the second one is about choosing the optimal external representation. The second component of spatial reasoning as identified is beyond the scope of the present study since the aim of the present study is to explore the internal aspects of the visuospatial reasoning processes. Here our concern is, therefore, the internal representation or the imagery processes that are involved in spatial reasoning.

The spatial reasoning processes involve the ability to "visualize", which is, to imagine the spatial relations among the objects and use imaginal (analog) codes to describe the same. Research suggests that both the spatial visualization ability and mental rotation ability involve this ability "visualize" and therefore mental imagery. Hegarty (2010) suggested that the choice of strategy for internal representation of spatial relations involves mental imagery. In their study, Hegarty, De Leeuw, and Bonura (2008) administered the Paper Folding test and the Vandenberg Mental Rotation test to students and asked them to think aloud about the strategies they used to solve the problems. Based on the strategies identified, they developed a "strategy choice" questionnaire and administered it to the second group of students, and asked them to report which form of strategy they used the most while solving the computerized versions of the same tests. Their findings revealed that the majority of the students used an Imagery strategy to solve the Paper Folding test. That is, they imagined/visualized folding the paper and then punching it to form the hole. While the imagery strategies were the most used ones, the students also made use of other analytic strategies. The researchers categorized these as spatial analytic strategies (noting the location of the punched hole and then checking the answer options to select the correct one) and pure analytic strategies (counting the number of folds and then inferring the number of holes that will result). While the imagery strategy was purely based on visualizing the spatial relations and imagining the transformation mentally, the spatial analytic strategy takes into consideration the spatial information but makes judgments analytically. The pure analytic strategy, on the other hand, is completely based on a rule-based algorithm. The researchers noticed similar findings for the mental rotation test as well. While most students reported using an imagery-based rotation strategy, a considerable number of students also reported the spatial analytic strategy (examining the relative directions of the
different segments of the object) and the pure analytic strategy (counting the number of blocks in an object). Interestingly, in both cases, the researchers found that students who reported using analytic strategies scored significantly more than those who reported using imagery for solving the problems. The researchers concluded that even though imagery forms a central part of spatial reasoning skills, analytic rule-based strategies also form an important part of these skills. These rule-based strategies include decomposing the whole into parts and visualizing a lesser amount of information at a time, or the abstraction of non-spatial information and using rules to eliminate options to choose the correct answer. Hegarty (2010) suggested that the most successful spatial reasoner possesses the ability to flexibly choose between imagery-based visualization and rule-based inference drawing and this argument is supported by the research relating spatial reasoning abilities with working memory components (Kane et al., 2004; Miyake et al., 2001).

Research studies distinguish between object representation and spatial representation abilities. Different forms of mental imagery elicit different forms of activation in different areas of the brain (Kosslyn, Ganis, & Thompson, 2001). While the dorsal visual pathway leading from the occipital lobe to the posterior parietal lobe has been identified to be the spatial information processing pathway, the ventral visual pathway leading from the occipital lobe to the inferior temporal lobe has been identified to be the object information processing pathway. Damage to the dorsal pathway disrupts the ability to recognize location while damage to the ventral pathway leads to an inability to visualize shapes (Courtney, Ungerleider, Keil, & Haxby, 1996; Levine, Warach, & Farah, 1985). O’Craven and Kanwisher (2000) further corroborates this finding through their functional MRI reports. They found activation in the fusiform face area (FFA) when subjects visualize faces while activation occurs in the Para hippocampal place area (PPA) when subjects visualize indoor or outdoor spatial layouts. Additionally, a high amount of spatial visualization correlates highly with the dorsal pathway, particularly in the right parietal cortex (Lamm, Bauer, Vitouch, & Gstättner, 1999) while a high amount of object visualization correlates with the ventral pathways chiefly the lateral occipital complex (Motes, Malach, & Kozhevnikov, 2008). Kozhevnikov, Kosslyn, and Shepard (2005) noted that individuals having high spatial visualization ability excelled in spatial tasks but performed poorly in object visualization tasks, while the opposite trend was observed for individuals with high object visualization ability. Moreover, previous research suggests a negative trend of association between the ability to perform spatial tasks and the ability to form and maintain pictorial images (Kosslyn, Brunn, Cave, & Wallach, 1984). These findings suggest that there exists a distinction between object visualization and spatial visualization abilities.

Kozhevnikov, Blazhenkova, and Becker (2010) argued that not only these two processes are independent, but also there is a “trade-off” between these two processes in terms of attentional capacity. The researchers administered tests of object visualization and spatial visualization to children, college students, and
professionals in an attempt to explore their "trade-off" hypothesis concerning age. Their findings completely supported the hypothesis of a "trade-off" between the object and spatial visualization abilities. Artists scored high in object visualization tasks but the opposite trend was noted for individuals in the area of science. The researchers concluded that even though individual scores high on a specific type of visualization task, the total amount of total visualization ability is finite and is distributed "differentially to object or spatial visualization ability or a combination of both" (p. 34).

Spatial Visualization ability is very closely associated with Abstract Reasoning ability. Abstraction is innate in the categorization of objects. Categorization refers to the process in which concepts, following some rules, determine if a new object/entity is representative of a particular category or not (Rips, Smith, & Medin, 2012). Once the concept of an event is achieved, the individual can categorize the concept based on the rules of the category. But for this categorization, the individual needs the ability to visualize and understand the spatial relations among the objects. Thus, spatial visualization is inherent and indispensable for the process of abstract reasoning.

Applications of spatial abilities are huge in different disciplines, although it depends upon the specific abilities required for the discipline (Porter & Glick, 2020). Spatial visualization ability includes several multistep manipulations of the visual stimulus, capacity of visual imagery, understanding of part-whole relationships, and the ability to transform three-dimensional objects in space (Maeda et al., 2013; Porter & Glick, 2020). Spatial visualization ability plays a significant role in mathematics achievement (Baki, Kösa, & Güven, 2009; Battista, Frazee, & Winer, 2018; Hawes, Moss, Caswell, Seo, & Ansari, 2019; Kurtuluş & Uygan, 2010). Hawes and colleagues (2019) undertook a latent variable approach to study the relationships among spatial visualization skills, numerical skills, executive functions, and mathematics achievement in a sample of 4- to 11-year-old children. They found that spatial visualization skills and numerical skills predict mathematics achievement when controlled for age. Moreover, numerical skills mediate the relationship between spatial skills and mathematics achievement. Apart from mathematics, spatial visualization also plays important role in engineering (Branoff & Dobelis, 2012; Porter & Glick, 2020; Segil, Sullivan, Tsai, Reamon, & Forbes, 2017; Sorby, 2007; Strong & Smith, 2001; Williamson & Andrew, 2018). For instance, Maeda et al. (2013) found that performance in spatial ability tests predicts success in engineering education. Carnevale et al. (2011) suggested that spatial ability scores are higher among STEM-related disciplines involving engineering and construction. Spatial visualization ability is also associated with success in mathematics and geometry (Panaoura et al., 2007; Turgut & Yilmaz, 2012). Yenilmez and Kakmeci (2015) pointed out that spatial visualization skills play a very important role in the formation of geometrical shapes and the ability to visualize two-dimensional or three-dimensional objects from different perspectives.
Development of Spatial Visualization ability

Although the spatial skills are reported to be identified in spatial literature only a few decades ago (Linn & Peterson, 1985; Shepard & Metzler, 1973), seminal research on the development of these abilities was done way back in the late ‘40s by none other than Jean Piaget and Barbel Inhelder through series of experiments with children using different tasks. Findings from their research resulted in the development of the theory of cognitive development and paved the way for several thousands of later research.

Research concerning the development of visuospatial reasoning abilities has studied mostly the amount of development that takes place at a certain age level. Evidence suggests that several visuospatial abilities first emerge during early childhood and develop throughout the middle childhood period. For instance, different components of spatial orientation ability, namely perspective-taking and landmark knowledge emerge during the early years of life (Reiser, 1979) and continue to develop throughout the adolescence period. Nevertheless, the pattern of change in each of the abilities is largely unexplored.

Piaget proposed that spatial skills develop through three different stages. In the first stage, children acquire topological skills during the age of 3-5 years. The topological skills are chiefly two-dimensional and help the child to identify proximity to another object, its sequence in an array, or its position in an environment. In the second stage, children acquire projective spatial ability. This stage involves visualization of three-dimensional objects and the ability to perceive how they will look from a different perspective, or transform it mentally. This stage is acquired typically by adolescence for objects that are familiar in our everyday life. For unfamiliar objects, however, even young adults might find it difficult to visualize. In the third stage, the ability to visualize the area, volume, distance translation, rotation, and transformation develops. Thus this stage enables the individual to combine measurement concepts with projective skills. Subsequent research has explored how the concept of a part-whole relationship develops in the early childhood years (Bishop, 1978; Sorby & Baartmans, 2000). However, despite all this research evidence on the development of part-whole relationships and organization among children, literature on spatial visualization ability still lacks the understanding of its’ developmental pattern, specifically during the pre-adolescent and adolescent years. According to the Piagetian theory of spatial skill development, by adolescence projective skills should be developed (Piaget & Inhelder, 1956). This should enable the adolescent to visualize and transform three-dimensional objects. Empirical support for this hypothesis is however lacking and still needs to be investigated.

The present research, therefore, purported to study the development of spatial visualization ability across the preadolescent and adolescent years. For the same, a new test measuring spatial visualization skills was needed to be developed since all the existing tests of spatial visualization ability are intended for children aged 13 years or more. Further, the developmental trajectory of the
spatial visualization ability was tracked across the preadolescent and adolescent periods.

These two separate studies were undertaken: In Study I, a new test was developed and validated using a 2-Parameter Logistic Item Response Theory model. In Study II, the developmental trajectory of the spatial visualization ability was explored across the preadolescent and adolescent periods.

Study I

Assessing Spatial Visualization ability

By far the most popular measure of spatial visualization ability is the Spatial Relations subtest from the Differential Aptitude Test Battery (Bennett, Seashore, & Wesman, 1947). Over the past few decades, the Spatial Relations subtest has been widely used in several kinds of research (Dorval & Pepin, 1986; Sorby, 1999). It consists of 50 items where the subject has to choose the correct alternative from four 3-dimensional options that can be formed by folding a 2-dimensional plane. Medina et al. (1998) reported that the Spatial Relation test best predicts success in engineering graphics courses when compared to other measures of spatial visualization ability. Van Garderen (2006) tested the association between mathematics achievement and spatial visualization ability of sixth-grade students using the Block Design subtest from the Wechsler Intelligence Scale for Children (WISC-III; Wechsler, 1991) and the Middle Grades Mathematics Project Spatial Visualization Test (MGMP-SVT; Lappan, 1981). The Block Design test requires the subjects to form two-dimensional patterns using 3D blocks. The MGMP-SVT, on the other hand, consists of 32 multiple choice items comprising one-, two- and three-dimensional figures presented in line drawing, and the subjects need to identify a rotated view of the figure different from the dimension it is presented. Battista (1990) administered the Purdue Spatial Visualization Test- Rotation (PSVT-R; Guay, 1977) as a measure of spatial visualization ability for exploring the relationship between spatial skills and high school geometry. Nonetheless, how far the PSVT-R is efficient enough to assess the visualization factor is a question that needs further explanation since mental rotation and spatial visualization factors although share variances have been identified to be separate spatial factors (Linn & Peterson, 1985; Maier, 1994). While mental rotation skills involve the rotational transformation of an object’s visual mental image (Takano & Okubo, 2003; Zacks, 2008), spatial visualization skills are concerned with the ability to deal with complex, multistep manipulations of spatially presented information (Linn & Peterson, 1985).

More recently, Quaiser-Pohl (2003) developed the Mental Cutting Test “Schnitte” (Fay & Quaisar-Pohl, 1999; Quaisar-Pohl & Fay, 2000) in which subjects need to cut three-dimensional hollow geometrical figures. The test consists of 17 multiple-choice items and is suitable for high school students (10th-11th & 13th-grade students), college students, and adults. The test has been found
to have sufficient reliability and validity indices and correlated positively with other measures of spatial skills. The authors suggested that the test can be used also as a vocational aptitude test for professions involving visualization (e.g., pilots, designers, architects, etc.). More recently, Campos (2009) developed a new measure of spatial visualization that is Measure of the Ability to form Spatial Mental Imagery (MASMI) for the adult population. The test consists of 23 multiple-choice items with four alternatives, two correct and two incorrect. The total score can be obtained by adding the correct options and subtracting the incorrect ones. The test has high internal consistency (Campos, 2009, 2012) and correlates moderately with a measure of mental rotation ability (MARMI; Campos, 2012). However, the test exhibited very low or negative association (range: -.15 to .14) with various measures of visual imagery (Campos, 2012).

The above review reveals that to date quite some measures do exist for assessing the spatial visualization factor. Nonetheless, quite regrettably, none of these measures can be administered to children. For instance, both the DAT-SR and PSVT-R are applicable for children above 13 years of age. The rest of the tests as reported are applicable either for adolescents or for young adults and so on. This is rather an intriguing fact that leads us to believe that spatial visualization is not measurable or is not sufficiently developed to be measured among young children. But the theories of spatial reasoning speak otherwise. Hence, there is a serious lack in the literature on the assessment of the visualization factor concerning its assessment among children.

**Objective**

To construct and validate a new test of Spatial Visualization ability for preadolescent and adolescent age groups.

**Method**

*Conceptualizing items for the Spatial Visualization test*

As theorized by Piaget & Inhelder (1956), the 7-8 years-old child is capable of carrying out concrete operations. During the concrete operational stage, the visible and tangible becomes organized through general operations which are reversible and enable the child to combine relations. By this age, the child gains a mastery of the operations of seriation and subdivision which becomes functionally reversible at this age. Thus the child is now able to perform a series of bisections of a line or a surface and develops the understanding that any object can be subdivided into smaller components until it can be seen or felt.

As advocated by the researchers, the biggest achievement of this stage is the ability to synthesize the whole from its constituent parts and this occurs between the ages of 7-8 and 10-11 years. That is, the knowledge of Synthesis-Analysis develops during this age. With the attainment of formal operations, the subject becomes able to integrate different spatial relations meaningfully. Thus, complex shape synthesis becomes easier (Inhelder & Piaget, 1956). This forms the
fundamental basis of the ability to transform mentally the constituent elements into the whole. The visualization-based reasoning test, therefore, consisted of items based on the hypothesis of Synthesis-Analysis with items assessing the ability to analyze and synthesize spatial relations.

Constructing the test items

The test consists of 30 items including two different types of items: Abstract Shape Construction and Box Recognition (Figure 1). Abstract shape formation items include two sets of items: a) synthesis of abstract wholes from constituent parts and b) analysis of the abstract whole into its constituent parts. These are the Simple Synthesis and Analysis problems. Box recognition items include two sets of items: a) synthesis of the box from constituent plain parts and b) analysis of the whole box into its constituent plain parts. These were renamed Complex Synthesis and Analysis problems. All items were multiple-choice items with three alternatives, one correct and two distractors. All the items were constructed using MS-Paint.

Assessing relevance judgment of the test items

The test items were rated by five senior psychologists with at least five years of working experience in the area of cognitive psychology. Scale-Content Validity Index obtained for the test items was .90 which indicates high relevance of the items following the acceptable criteria of .90 for average congruity (Waltz, Strickland, & Lenz, 2010).

Participants

150 typically developing high school students (Mean age=11.90 years; SD=2.66) with no apparent mental/physical mental or physical disability or disease and with normal or corrected-to-normal vision participated in the study. Children suffering from any form of organic brain disorder, mental retardation, and physical disability/ disease were excluded from the study. Girls having
menstrual cycles at the time of data collection were also excluded. Participants having school examinations at the time of data collection were also excluded.

**Measures**

a. The newly developed 30-item test was administered to the participants in a paper-pencil format. A correct answer was given a score of 1. There was no time limit given.

b. 12-item Advanced Progressive Matrices (APM Set I) (Raven, 1962) was used for estimating the concurrent validity of the SV test. The APM Set I measure fluid ability in a short time frame (Chiesi et al., 2012).

c. The newly developed test was correlated with a Mental Rotation Test (Datta & Dutta Roy, 2021), to estimate concurrent validity. The Mental Rotation test contains 24 items, including both 2D and 3D, rotated stimuli. Cronbach’s alpha for the test is .75 and the 24 items provided 92.3% information.

**Procedure**

Since the study used a non-clinical human sample, it was exempted from obtaining ethics clearance from the Research Ethics Committee of the university. However, the study was periodically reviewed by the university research committee and all necessary consent and permission were obtained. Permission was obtained from each of the schools participating in the study. Informed consent from the parents and assent from the participating child was also obtained. Data were collected in individual sessions in separate rooms in each school. Each session was of approximately 40 minutes. Instructions were clearly explained for the SV test using paper cuttings.

**Data analysis**

Statistical analyses for the data included: a) Average Difficulty Index (DI) and Item-Total correlation for items; b) fitting a 2-Parameter Logistic (PL) Item Response Theory on the test items for checking the psychometric properties; c) Internal Consistency of the test was checked and concurrent validity of the test was established by correlating with APM scores and scores obtained in the Mental Rotation Test.

**Results**

The average DI was found to be .52 indicating moderate difficulty levels of the items. Item-total correlation coefficients of all items were within the acceptable range (ranged .30 to .61). IRT parameters indicated that all the items have positive discrimination indices, ranging from .30 to 2.09. The difficulty indices of the items are also optimal. The total test information provided by the items is 88.7% (Figure 2). Further, the Kuder-Richardson coefficient for the test was .72, indicating moderately high internal consistency. Finally, the concurrent validity of the test was established, indicated by a moderately high correlation of the test scores with the APM scores (r=.51, p<.001) and with the scores of the Mental Rotation Test (r=.66, p<.001).
Table 1. Item parameters of the items of the Spatial Visualization test (n=150)

<table>
<thead>
<tr>
<th>Items</th>
<th>Average DI</th>
<th>Item-total Correlation</th>
<th>p-value</th>
<th>Difficulty Index</th>
<th>Discrimination Index</th>
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<tr>
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<tr>
<td><strong>Simple abstract analysis</strong></td>
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<tr>
<td>Item 1</td>
<td>.85</td>
<td>.40</td>
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<td>-2.30</td>
<td>.85</td>
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<td>.77</td>
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<td>-4.40</td>
<td>.14</td>
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<td>.81</td>
<td>.34</td>
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<td>-2.35</td>
<td>.66</td>
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<td>.18</td>
<td>.51</td>
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<td>1.40</td>
<td>1.50</td>
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<td>.43</td>
<td>.58</td>
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<td>.30</td>
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<td>.34</td>
<td>.85</td>
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<td>.58</td>
<td>.63</td>
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<td>.37</td>
<td>.32</td>
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<td>2.93</td>
<td>.20</td>
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<td>0.001</td>
<td>-.91</td>
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<td>-.05</td>
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<td>.34</td>
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<td>0.001</td>
<td>.11</td>
<td>1.50</td>
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<td>.28</td>
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<td>0.001</td>
<td>2.11</td>
<td>.50</td>
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<td>.45</td>
<td>.70</td>
<td>0.001</td>
<td>.10</td>
<td>2.09</td>
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<td>.70</td>
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<td>3.95</td>
<td>.10</td>
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<td>.47</td>
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<td>.33</td>
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<td>-.74</td>
<td>.50</td>
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<td><strong>Complex abstract synthesis</strong></td>
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<td>Item 23</td>
<td>.26</td>
<td>.52</td>
<td>0.001</td>
<td>1.13</td>
<td>1.09</td>
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<td>Item 24</td>
<td>.28</td>
<td>.31</td>
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<td>4.30</td>
<td>.22</td>
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<td>.42</td>
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<td>4.60</td>
<td>.32</td>
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<td>.44</td>
<td>0.001</td>
<td>-.53</td>
<td>.25</td>
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<td>.95</td>
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<td>.80</td>
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<td>.14</td>
<td>.55</td>
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<td>Item 30</td>
<td>.21</td>
<td>.30</td>
<td>0.001</td>
<td>3.60</td>
<td>.40</td>
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<tr>
<td><strong>Average DI of all items</strong></td>
<td>.45</td>
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Figure 2. Test Information Function for the Spatial Visualization test items

Study II

Objective
To explore the developmental trajectory of spatial visualization ability across the preadolescent and adolescent years.

Method

Participants
760 typically developing children of age range 7-16 years (Mean=11.54 years; SD=2.85) with no apparent mental or physical disability or disease participated in the study.

Measures
a. The newly developed 30-item Spatial Visualization test;
b. 12-item Advanced Progressive Matrices (APM Set I) (Raven, 1962) was used as a screening tool for the present study.

Procedure
Data were collected in individual sessions in a separate room in each school after obtaining necessary permissions. Each session was of approximately 30 minutes.

Data analysis
Statistical analysis included descriptive statistics, One-way Analysis of Variance (ANOVA) for checking age difference in the ability, and Trajectory analysis (TA) for tracking the developmental trajectory of SV ability.
Trajectory Analyses

Trajectory analysis (Thomas et al., 2009) is essentially a modified Analysis of Variance (ANOVA) model that is largely used in developmental studies using cross-sectional designs. Here, instead of comparing group means, the regression lines or "developmental trajectories" are compared, either between groups or for different conditions, or both. Trajectories may be linear or non-linear functions of age that may vary in terms of gradient (rate of change) and intercepts (Initial level of performance). The use of trajectory analysis in a cross-sectional study provides an approximation of the developmental trend which can be later confirmed using a longitudinal study. Thus, this method enables the researcher to overcome the limitations of a cross-sectional study design over a longitudinal study design, at least to some extent.

Results

Descriptive statistics

Average scores of the children across the ten age groups show a progressive increase in performance, although a slight discrepancy was noted in the 9-10-years age groups (Table 2).

Table 2. Descriptive statistics and F value show differences in SV ability across ten age groups (N=760)

<table>
<thead>
<tr>
<th>Age groups</th>
<th>n</th>
<th>Mean</th>
<th>SD</th>
<th>F</th>
<th>df</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 years</td>
<td>73</td>
<td>11.01</td>
<td>2.97</td>
<td>11.40</td>
<td>9, 750</td>
<td>0.001</td>
</tr>
<tr>
<td>8 years</td>
<td>76</td>
<td>11.28</td>
<td>2.88</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 years</td>
<td>69</td>
<td>13.75</td>
<td>5.05</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 years</td>
<td>80</td>
<td>12.06</td>
<td>3.94</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 years</td>
<td>75</td>
<td>13.11</td>
<td>4.08</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12 years</td>
<td>82</td>
<td>14.13</td>
<td>3.63</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13 years</td>
<td>76</td>
<td>13.58</td>
<td>3.92</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14 years</td>
<td>79</td>
<td>15.20</td>
<td>4.79</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 years</td>
<td>77</td>
<td>15.47</td>
<td>5.08</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16 years</td>
<td>73</td>
<td>15.21</td>
<td>4.72</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Mean differences

Spatial Visualization ability develops with age maturation. As indicated by ANOVA results, significant age differences exist across the ten age groups for SV ability. That is, greater the maturation, higher will be the accuracy of reasoning $[F_{SV}(9, 750)=11.40, p<.001; \eta^2=.12]$. Partial eta square values for the SV ability show that although significant age differences exist across the age groups, the effects are of moderate sizes (.04>$\eta^2$<.36). That is, age differences account for 12% variance in SV ability across the preadolescent and adolescent years.

That is, adolescents, performed significantly better than preadolescents on this test. Again, set-wise analysis of the SV test also shows that accuracy is the highest in the case of simple synthesis and analysis problems as compared to the complex synthesis and analysis problems (Figure 3). Response accuracy
keeps on increasing over time and reaches a more or less stable condition during the late adolescence period.

A detailed analysis of the average scores obtained in each set for each age group (Table 3) shows that for the first three types of item sets, children as young as 7 years old performed above chance while for the complex abstract synthesis items, children could perform above chance only after reaching 12-years of age (chance score\(^1\) for set 1, 2, 3 and 4 are 2.64, 2.31, 2.64 and 2.31 respectively). This suggests that although the understanding of simple abstract visualization-based reasoning ability emerges during early childhood, it is not until adolescence that the understanding of complex forms develops.

Nevertheless, the effect sizes of the mean differences are relatively low for the subsets, except for complex analysis problems where the effect size is extremely low (Table 4). This suggests that although significant difference exists, it is not well defined.

Table 3. Mean and SD of performances across the sets of the SV test across ten age groups (\(N=760\)).

<table>
<thead>
<tr>
<th>Age</th>
<th>Simple abstract analysis Mean</th>
<th>Simple abstract analysis SD</th>
<th>Simple abstract synthesis Mean</th>
<th>Simple abstract synthesis SD</th>
<th>Complex abstract analysis Mean</th>
<th>Complex abstract analysis SD</th>
<th>Complex abstract synthesis Mean</th>
<th>Complex abstract synthesis SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 yrs</td>
<td>3.60</td>
<td>1.12</td>
<td>2.48</td>
<td>1.30</td>
<td>2.90</td>
<td>1.60</td>
<td>2.04</td>
<td>1.15</td>
</tr>
<tr>
<td>8 yrs</td>
<td>3.32</td>
<td>1.46</td>
<td>2.90</td>
<td>1.37</td>
<td>3.40</td>
<td>0.89</td>
<td>1.67</td>
<td>0.96</td>
</tr>
<tr>
<td>9 yrs</td>
<td>4.06</td>
<td>1.78</td>
<td>3.40</td>
<td>1.61</td>
<td>3.84</td>
<td>1.50</td>
<td>2.46</td>
<td>1.78</td>
</tr>
<tr>
<td>10 yrs</td>
<td>3.98</td>
<td>1.50</td>
<td>2.91</td>
<td>1.90</td>
<td>3.07</td>
<td>1.45</td>
<td>2.08</td>
<td>1.37</td>
</tr>
<tr>
<td>11 yrs</td>
<td>4.30</td>
<td>1.65</td>
<td>3.30</td>
<td>1.96</td>
<td>3.17</td>
<td>1.46</td>
<td>2.33</td>
<td>1.22</td>
</tr>
<tr>
<td>12 yrs</td>
<td>4.40</td>
<td>1.53</td>
<td>3.80</td>
<td>1.67</td>
<td>3.15</td>
<td>1.20</td>
<td>2.81</td>
<td>1.50</td>
</tr>
<tr>
<td>13 yrs</td>
<td>4.45</td>
<td>1.42</td>
<td>3.54</td>
<td>1.76</td>
<td>3.06</td>
<td>1.47</td>
<td>2.52</td>
<td>1.56</td>
</tr>
<tr>
<td>14 yrs</td>
<td>4.85</td>
<td>1.83</td>
<td>3.91</td>
<td>1.82</td>
<td>3.40</td>
<td>1.50</td>
<td>3.08</td>
<td>1.62</td>
</tr>
<tr>
<td>15 yrs</td>
<td>5.00</td>
<td>1.80</td>
<td>4.10</td>
<td>1.95</td>
<td>3.53</td>
<td>1.20</td>
<td>2.84</td>
<td>1.70</td>
</tr>
<tr>
<td>16 yrs</td>
<td>4.81</td>
<td>1.80</td>
<td>4.10</td>
<td>1.60</td>
<td>3.27</td>
<td>1.66</td>
<td>3.03</td>
<td>1.53</td>
</tr>
</tbody>
</table>

\(^1\) Chance score calculated as the probability of correct response by chance for each item \(\times\) no. of items. For instance, the number of alternatives in each item of the spatial visualization ability test is three. Therefore, the probability of responding correctly by chance is 0.33 for each item. Therefore, chance score for set 1 (8 items) is 0.33 \(\times\) 8 = 2.64.
Table 4. One-way ANOVA showing mean differences in performances on the subsets of SV tests across ten age groups (N=760)

<table>
<thead>
<tr>
<th>SV Test subsets</th>
<th>F value</th>
<th>df</th>
<th>p</th>
<th>η²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple Analysis</td>
<td>8.72</td>
<td>9,750</td>
<td>0.0001</td>
<td>0.09</td>
</tr>
<tr>
<td>Simple Synthesis</td>
<td>7.81</td>
<td>9,750</td>
<td>0.0001</td>
<td>0.09</td>
</tr>
<tr>
<td>Complex Analysis</td>
<td>2.71</td>
<td>9,750</td>
<td>0.004</td>
<td>0.03</td>
</tr>
<tr>
<td>Complex Synthesis</td>
<td>7.67</td>
<td>9,750</td>
<td>0.0001</td>
<td>0.08</td>
</tr>
</tbody>
</table>

**Trajectory Analysis**

Developmental trajectory of SV ability was tracked by regressing the standardized scores hierarchically on age. Estimates for the regression were then checked for their overall fit. The linear and non-linear functions were fitted based on the best fitted regression model that fitted the score distribution (based on the Adjusted R square value). It was found that the SV ability follows a linear trajectory (Figure 4) across preadolescent and adolescent years (β=0.11, p<.0001). It is to be noted that the rate of change is constant for the ability. Since the trajectory of this ability follows a linear function, the rate of change is constant across all age groups.

![Developmental Trajectory of Spatial Visualization ability](image)

**Discussion**

Previous research on the development of spatial visualization focused chiefly on the emergence of this ability during infancy and early childhood (Stiles, Akshoomoff, & Haist, 2013; Stiles & Stern, 2001). Children's understanding of the organization of whole from parts is assumed to emerge and undergo changes during the preschool and school-age periods (Akshoomoff & Stiles, 1995). Nonetheless, the change in the ability in the subsequent years of preadolescence and adolescence is little understood.

The present study shows that adolescents also differ substantially from preadolescents concerning their SV ability. That is, as age increases, the ability to
analyze a whole into its parts and synthesize a whole from its’ parts also improves progressively. Interestingly, except for the complex abstract synthesis problems, the ability to visualize the synthesis and analysis of simple abstract shapes is present right at 7 years of age. This shows that even though visualization of complex shapes emerges a little later, the basic form of visualization-based reasoning ability develops quite early during middle childhood and gradually develops in the subsequent years. Synthesis of complex forms, however, emerges much later only after the child enters adolescence. This finding supports previous research advocating the importance of the adolescent period in the acquisition of visualization-based reasoning ability (Bishop, 1978; Piaget & Inhelder, 1959). This is probably because increased processing capacity and more sophisticated mental operators are acquired during the adolescent period as compared to the pre-adolescent years. However, contrary to Piaget's stage-wise development, the present findings show that the development of the ability to visualize both simple and complex abstract forms take place progressively across the preadolescent and adolescent years and undergoes qualitative changes in nature across the developmental phase. Thus, these findings lend more support to the neo-Piagetian theories of cognitive development which emphasize the systematic development of the entire cognitive process with age (Case, 1992; Demetriou & Mouyi, 2011; Demetriou et al., 2010; Halford et al., 2012; Pascual-Leone, 1970; Mascolo, 2015).

One of the major aims of the present study was to track the developmental trajectory of the SV ability across preadolescent and adolescent years, the underlying reason being exploring the differential pattern of development of the ability across the developmental period. So far, no empirical study has been reported that studied this development across the preadolescent and adolescent years. Nonetheless, theoretical approaches do exist in the form of the Piagetian and neo-Piagetian theories of cognitive development. Tracking the development of the SV ability thus, not only will provide empirical evidence of the development of the ability but also will help explore the validity of these theories of cognitive development in the case of spatial reasoning.

Present findings show that the developmental trajectory for the SV ability follows a linear function. Linear function implies a constant rate of development, that is, the change in the ability is constant for all age groups. Thus, the rate of development of SV ability across all the age groups is the same (0.11 units). That is, the change in the ability from age 7 to 8 years is equivalent to the change in ability from age 15- to 16 years. Thus, the ability has a constant rate of growth that continues even beyond the adolescent period.

Conclusion

The present study served two very important purposes: (a) to develop and validate a new test for assessing Spatial Visualization ability; and (b) to track the developmental trajectory of spatial visualization ability across the preadolescent and adolescent years. The test developed has been found to have sufficient
reliability and validity. Moreover, it was found that the developmental trajectory of spatial visualization ability follows a linear function of development.

The first purpose mentioned above concerns the practical implications of the study. Not only did the research make a significant psychometric contribution by developing the test, but also demonstrated the use of the most advanced psychometric techniques in the construction and validation process. Hence the newly developed test not only compensated for the lack of an instrument for measuring spatial visualization ability among preadolescent and adolescent groups but also contributed a very sophisticated tool to the field of research in spatial cognition.

The second purpose of the study also provided important insight into the literature on child development. To our knowledge, this is the first study that attempted to investigate and explore the developmental trajectory of spatial visualization ability. The understanding of this pattern has important implications in the literature of brain science and many practical areas of research.

**Theoretical and practical implications**

These findings have some major theoretical contributions to the literature on spatial cognition, by pointing to the fact that the development of Spatial Visualization ability is not limited to the attainment of adolescence but goes beyond it. In this respect, the Dynamic Skill theory of Fischer (1980) and Case's theory (1985, 1992) deserves special mention as opposed to Piaget's stage-wise development of formal reasoning during adolescence (up to 16 years of age). Both the neo-Piagetian theory advocated that the cognitive faculties continue to develop till adulthood (*Vectoral stage* in Case’s theory and *Abstract tier* in Fischer’s theory). Hence, the present findings are more supportive of the neo-Piagetian perspectives, rather than Piaget’s approach. The uniqueness of the present research lies in the fact that this is probably the first research reporting the linear trajectory of development for spatial visualization ability. These findings have important implications in justifying the role of other executive functions (like working memory, Kaufman, 2007) played in the development of scientific reasoning, geometric reasoning, and other abilities.

The practical implication of the study findings includes the construction and standardization of the Spatial Visualization Test for the preadolescent and adolescent groups. The test is found to be reliable and valid as indicated by the estimates obtained and IRT parameters. All the previously existing tests for assessing spatial visualization ability apply only to adolescents and adults (MASMI, Campos, 2009, 2012; Mental Cutting Test “Schnitte”, Quasar-Pohl & Fay, 2000; Fay & Quasar-Pohl, 1999; Purdue Spatial Visualization Test-Rotation, Guay, 1977), but not for preadolescents. Hence, the test developed in this study will have considerable use and application for assessing this ability across both preadolescent and adolescent periods. Most applications of the test will be in the educational/school counseling setting and also to identify dysfunctions among preadolescents and adolescents in the clinical setting.
Limitations and future research directions

Some of the limitations of the present study can be mentioned in this regard. Firstly, validation of the SV test could be done only in a small sample due to time constraints. A larger sample would have provided more statistically valid results. Moreover, for the application of the test, a developmental norm is essential. However, developing a norm for the test would have required humungous time and effort and therefore could not be done in the present context. Future studies, therefore, can be conducted to address this issue. Secondly, the present study explored the development of SV ability among children of age between 7 to 16 years. However, present findings clearly show that the ability continues to develop beyond the age of 16 years. This suggests that the study of the development of the ability should commence at an even younger age and should continue beyond late adolescence as well. Thus, future studies should be done to address this issue.

It can be, therefore, concluded that the study has undoubtedly important implications in the area of spatial cognition and psychometry as also applications in clinical and educational settings.

Ethics statement

This study was carried out following the recommendations of the Code of Ethics followed by the Ph.D. Committee, University of Calcutta. The research protocol was approved by the Ph.D. Committee for Research, Department of Psychology, University of Calcutta. In accordance with the Declaration of Helsinki, all parents gave written informed consent for adolescents’ participation in the study and students provided informed assent for their participation. Permission was also taken from all the participating school authorities.

Conflicts of interest

The authors declare no conflict of interest.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work, and approved it for publication.

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Data source

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