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TRACKING THE DEVELOPMENTAL TRAJECTORY OF DYNAMIC VISUALIZATION ABILITY ACROSS PREADOLESCENT AND ADOLESCENT YEARS

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Abstract

Dynamic visualization ability refers to the ability to visualize and compare spatial relations between moving objects and to predict their relative motions. This is achieved through the understanding of distance, speed, and time (DST). Research on the development of these concepts advocated a stage-wise development of these concepts, with the understanding of time emerging last. However, there still exists a huge lack of agreement concerning the age of achieving the integration of these three concepts. The present study explored the development of Dynamic Visualization ability (DV) across the preadolescent and adolescent years. Data were collected from 792 participants (Mean=11.55 years; SD=2.87) by administering a newly developed Dynamic Visualization task. The task consisted of two levels: Same speed and Variable speed. The difficulty level of the task across levels was varied by introducing several task parameters. Results showed that adolescents significantly outperformed preadolescents' inaccuracy of estimation across all task parameters, reaction time, and response time. The developmental trajectory of the ability was explored through Trajectory Analysis (TA). It revealed that the rate of development of the ability follows a quadratic function and is therefore non-linear by nature. While the same speed condition required considering only the spatial aspect of the motion, the variable speed required understanding of both the spatial and temporal aspects of the motion. Better performance with growing age indicated that the understanding of the spatial and temporal aspects of relative motion develops with age. Findings were discussed in light of developmental theories of DST understanding.

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Introduction

In the late 1980s and the beginning of the 1990s, Pellegrino, Hunt, Abate, and Farr (1987) proposed that a separate spatial domain should be considered wherein subjects will have to reason about the movement of objects. *Dynamic spatial ability* refers to the ability to deal with moving elements and relative motion (D'Oliveira, 2004). This includes predicting relative velocity and relative distance of moving objects, which necessitates the perception and understanding of three concepts: distance, speed, and time (DST). Since all these aspects form an integral part of the visuospatial understanding of relative motion, DST understanding can be considered to be a fundamental contributing agent in the development of Dynamic Visualization (DV) ability.

Piaget (1946b, 1970) recognized six stages of development of this understanding, moving from sensory-motor to intuitive understanding, and finally operational. Piaget's findings have been later tested by several other researchers. For instance, Lovell, Kellett, and Moorehouse (1962), in a replication study, studied the intuition of speed, the development of relations of speed in synchronous movements, the growth of understanding of relative speeds, and the conservation of uniform speeds, by administering the same tests as used by Piaget. They found similar age-dependent responses and a similar trend of variation in the responses as reported by Piaget. Again, Delorme and Pinard (1970) administered a modified version of the Piagetian task on relative velocity to concrete and formal operational children. Their findings also suggested a similar trend of development in the understanding of young children.

However, Neo-Piagetian theories not only criticized Piaget's choice of tasks but also rejected the theoretical assumptions of stage-wise acquisition of DST understanding. Wilkening (1981) criticized the Piagetian tasks for imposing excess memory load on the child and thereby distracting them from more pertinent information in the task. Instead, he designed tasks that were more valid in that children were presented with information about two other dimensions and were asked to infer the third dimension. Results from a different study (Wilkening, 1982) however, challenged the long-standing belief that the understanding of the concept of time is derived from the understanding of more basic concepts of distance and speed. Rather, 5-year-olds achieve an understanding of the direct relationships among the three concepts, while the understanding of the inverse relationship between time and speed develops much later, around age 7 (Matsuda, 2001; Albert, Kickmeier-Rust, & Matsuda, 2008).

In line with Piaget's assumption of six staged development of DST skills, Levin (1979) also proposed a two-staged model according to which the development of understanding of direct relationship is followed by the development of understanding of the inverse relationship. Later, after revising this two-stage model, Levin (1992) proposed a five-stage model of development which commences at age 4 and completes by adolescence. According to this model, children, in the first stage, understand only the concepts of distance and speed but not time. Following this, develops the understanding of direct relationships among distance and speed, while the concept of time is not considered. In the third stage, a partial understanding of the inverse relationship between time and speed develops, although the third concept is still ignored. In the next stage, all three concepts become understandable, but the coordination still lacks. Finally, in the fifth stage, full integration of the DST system occurs; the child is now able to make correct deductions based on the interrelationships among the three concepts. Matsuda (2001) proposed a similar model, with an additional sixth stage by which the integration of the triadic system takes place.

Recent trends in studying the development of DST understanding

Recent studies investigating the development of DST understanding focused on the ability to derive information on time-to contact (TTC) phenomenon using two different types of task: the *coincidence anticipation* (CA) or the *prediction motion* (PM) tasks and the *relative judgment* (RJ) tasks (Tresilian, 1995; Keshavarz et al., 2010). The coincidence anticipation task requires the subject to predict the coincidence of two moving objects based on their spatiotemporal interrelations by making a simple response (like pressing a button). One important variant of the prediction motion task is one where the moving object disappears before it reaches the destination, in which case the subject has to press a button by judging the temporal lapse such that pressing the button concurs temporally with the coincidence of the moving objects or the arrival of the object at a specific location (Tresilian, 1995). In a relative-judgment task, on the other hand, the subject has to predict which among two or more moving objects will arrive earliest at a certain destination when the arrival is scheduled beyond the exposure time.

While the PM tasks place more emphasis on temporal judgment, the RJ type of task is based on ordinal judgment. As pointed out by Tresilian (1995), the perceptuomotor processes involved in PM and RJ tasks are entirely different. While a timed response is the core of a PM task, it is absent in an RJ task. In typical PM tasks, the display terminates when the remaining time is still quite large, leaving the initiation of the response occurring only after the disappearance of the target object. Thus, the time-to contact (TTC) information is not available while making the response and the respondent has to rely entirely on some internal frame of reference while making the response (Tresilian, 1995). In RJ tasks, on the other hand, TTC information can be easily used to make the correct response even though no actual timing is involved. Also, several other cues are used adequately, when available, to make an inference (Law et al., 1993). In a way, this makes the RJ task easier as compared to the PM task.

In a PM task, often the moving object is occluded before it coincides with another object in motion or arrives at a specific location. While some studies suggest a linear relationship between the arrival-time estimates after occlusion and the actual arrival-time (Schiff & Oldack, 1990; Caird & Hancock, 1994), other studies concluded that this relation holds only when the time of occlusion is greater than or equal to 200 ms (Yakimoff, Mateff, Erhenstein, & Hohnsbein, 1993). For occlusions below 200 ms, studies found an undermined performance, leading to a belief that visuomotor delay might account for this degradation (Bootsma & van Wieringen, 1990; Savelsbergh, Whiting, & Bootsma, 1991).

Objective

Previous literature indicates that there are ample reasons to believe that the Dynamic Spatial ability develops across the preadolescent and adolescent years. However, empirical evidence supporting the hypothesis is less. Levin (1993) and Matsuda (2001) attempted to study the stages of development of DST understanding but the paradigms used in these studies lacked the sophistication of an RJ task or a PM task and therefore are empirically inconclusive.

The present study, therefore, aimed to track the development of dynamic spatial ability among preadolescents and adolescents using a task that involved predicting the motion of dots in a relative judgment format. To fulfil this objective, a relative judgment task was developed. Following this, the development of the Dynamic Visualization (DV) ability was explored through:

- Examining whether age-wise differences exist in DV ability across the age groups considered;
- Examining whether there is an improvement of the ability across the developing years;
- Examining whether age-wise differences exist across the different parameters of the task used; and,
- Exploring the developmental trajectory of the DV ability across the developing years.

Method

Participants

792 typically developing children of age range 7-16 years (M=11.55; SD=2.87) with no apparent mental or physical disability or disease from Kolkata metropolitan and suburban outskirts participated in the study.

Tools used

Dynamic Visualization task. A new task was developed for measuring the Dynamic Spatial ability.

Description of the task. The task was programmed and presented in an HP laptop with a 13.3-inch display with a screen size of 31×16 cm and a resolution of 1366×768 pixels. There were two conditions: *same speed* condition with 27 trials and *variable speed* condition with 30 trials. Apart from these, there were 6 practice trials, 3 trials for each condition. In both conditions, two or multiple dots of varying colors were used. The subjects would see these dots moving at a varying distance either constant speed or variable speed towards a vertical line representing the destination for the dots. The moving dots were exposed for 4 seconds after which the dots were occluded. The subjects were asked to predict which among the dots would reach the destination line first. The task conditions were varied based on several parameters: *number of dots* (two/multiple), *type of track* (parallel, opposite, and angular), and *varying destination lines* (one or multiple). There were 8 levels of the task, 4 for each of the same speed and variable speed conditions. The levels varied in terms of the types of tracks and the number of dots. In each of the conditions, 12 trials were included in which dots move in crossover tracks that is the dots move across each other in either opposite or angular tracks. The rest of the trials included moving dots in parallel, opposite or angular track but with no crossover. Multiple dot trials included trials with 3, 4, or 5 moving dots (blue, yellow, or pink dots) while the two-dot trials included two moving dots (either red or green). In multiple destination trials, the color of the lines was matched with the respective colored dots, that is, a red dot would move towards a red line and a green dot would move towards a green line. The speed of the dots in the same speed condition was 1 cm/second while the speed of the dots in the variable condition was varied depending upon the initial point of the dot and the respective destination line. For each trial, as soon as the occlusion occurs (after 4 seconds of exposure), the screen navigates to the response page. The response page contained the question: "Which dot will reach the destination line first?" For each trial, there were either two, three, four, or five alternatives (representing each color). The sequence of each colored dot was kept constant for all the trials. The response could be given by pressing the number keys from the keyboard, "1" for the red dot, "2" for the green dot, "3" for the blue dot, "4" for the yellow dot, and "5" for pink dot. Subjects could change their response if they wanted. On each response page, a "NEXT" button was provided at the lower right corner. Navigation to the next trial was made possible either by clicking on the "NEXT" button or by pressing the "ENTER" button from the keyboard. In between each level, a blank page was inserted with the instruction "Press ENTER when you feel ready…" This was done so that the subject would not feel fatigued in between trials. At the beginning of the task, and information schedule page was inserted for acquiring the personal details of the subject (*e.g.*, name, gender, class, father's occupation, mother's occupation, number of siblings, etc.). For each trial, a measure of response accuracy, reaction time (time taken by the subject to the first response), and total response time for each trial were calculated. There was no time constraint to complete the task. However, the maximum time taken to complete the task was not more than 8-10 minutes.

Difficulty index for the Dynamic Visualization items was found to be optimum (D=0.66; n=93; Mean age=11.65 years; SD=2.43). The task also has sufficient internal consistency (KR=0.88; n=93) and external validity (Correlated significantly with Standard Progressive Matrices scores; r=0.40, p<.001; n=93).

Advanced Progressive Matrices Set I. The 12-item Advanced Progressive Matrices (APM Set I) (Raven, 1962) was used as a screening tool for the present study. The chance score that can be obtained for the test is 1.5 and therefore the cut-off was set to be 1.5. Any participant scoring less than 2 in APM Set I was not considered for the study.

Procedure

Permission for data collection was obtained from the school authorities as also informed consent was sought from the parents of the child and assent from the child itself. Following this, rapport was established with the child, and instructions for solving the test were clearly explained. Data were collected in individual sessions in a quiet and isolated room of the school. Each session was of 20 minutes approximately. All participants were provided with small incentives in the form of pens and chocolates.

Statistical analyses

Development of Dynamic Visualization (DV) ability across age groups was studied using Analysis of Variance (ANOVA) and Trajectory Analysis (TA).

Trajectory Analyses (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). Thus, the use of trajectory analysis in the cross-sectional study provides an approximation of the developmental trend which can be later confirmed using longitudinal study. 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

Development of the Dynamic Visualization ability

Table 1 shows the means and SDs for DV scores across the ten age groups. More or less for all the age groups, the scores obtained improved with growing years. Nevertheless, the pattern of scores varied a little during the late preadolescent years, specifically between 9-11 years. For instance, for 9-years-old, the average score obtained is 40.69 while for 10- and 11-years-old children, the average score obtained is 39.55 and 42.24 respectively. Score patterns in adolescent years, however, are more stable.

Table 1. Mean and Standard Deviation of the DV ability across the ten age groups (N=792)

Age groups	7yrs (*n*=77)	8yrs (*n*=79)	9yrs (*n*=72)	10yrs (*n*=84)	11yrs (*n*=76)	12yrs (*n*=83)	13yrs (*n*=80)	14yrs (*n*=80)	15yrs (*n*=80)	16yrs (*n*=81)
Mean	34.43	39.27	40.69	39.55	42.24	42.59	43.18	45.19	45.32	45.84
SD	7.98	6.32	6.95	6.08	5.06	4.56	5.41	5.01	5.47	4.15

As indicated by the Analysis of Variance results, significant age differences exist across the ten age groups. That is, the greater the maturation, the higher will be the accuracy of reasoning [FDV (9, 782)=28.79, p<.001]. The partial eta square value shows that although significant age differences exist across the age groups, the effect is of moderate size ($0.04>\eta 2<0.36$). That is, age differences account for a 25% variance in Dynamic Visualization ability (Figure 1).

Dynamic visualization ability improves across all ten age groups. The same speed level assessed the understanding of distance while the variable speed level assessed the understanding of speed and time. Present results reveal that as the child grows up, their understanding of distance, speed, and time also improves gradually. Nonetheless, for both the levels of the dynamic visualization task, the children obtained scores above chance (Chance scores[1] for level 1 is 9.90 and level 2 is 11.4). This implies that children possess the understanding of both the spatial and temporal aspects of dynamic spatial reasoning even at the age of 7-years. Average scores obtained in level 2 are a little lower than that for level 1 for all age groups. This indicates that the child performs better when only distance is to be considered as compared to when speed and time also need to be considered. Thus, the concept of distance develops earlier, followed by the conception of speed and time.

One-way Analysis of Variance shows that significant age differences also exist (p<.001) for all the task parameters of Dynamic Visualization (Table 2). The magnitude of partial eta square for all the F-values indicates that the effect

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[1] Chance score calculated as probability of correct response by chance for each item × no. of items. For instance, if the number of alternatives in one item of dynamic visualization reasoning test is three, then the probability of chance response is 0.33 for that particular item. Therefore, chance score for level1 (27 trials) is calculated to be [(0.5*6)+(0.5*6)+(0.33*3+0.25*3+0.20*3) + (0.33*2+0.25*2+0.20*2)]=9.9.

size of all the mean differences is moderately high, indicating the fact that age differences account for a considerable amount of variance in the dynamic visualization ability across the ten age groups (Figure 1; Figure 2).

Table 2. One-way ANOVA showing mean differences in performances on the parameters of Dynamic Visualization task across ten age groups (N=792)

Task parameters	Levels	Mean	SD	F value	η^2
Speed	Same speed	22.11	3.54	22.89**	0.21
	Variable speed	19.75	3.70	23.77**	0.21
No. of Dots	Level 1: Two dots	11.88	1.97	15.69**	0.15
	Level 1: Multiple dots	10.24	2.15	16.81**	0.16
	Level 2: Two dots	9.27	1.84	13.70**	0.14
	Level 2: Multiple dots	10.49	2.50	18.73**	0.17
No. of destinations	Level 1: Single destination	12.93	2.34	23.02**	0.21
	Level 1: Multiple destination	9.65	1.93	12.61**	0.13
	Level 2: Single destination	11.53	2.36	14.68**	0.14
	Level 2: Multiple destinations	8.23	2.05	18.21**	0.17
Angle of motion	Level 1: Straight track	12.63	2.53	18.19**	0.17
	Level 1: Angular track	9.48	1.63	14.03**	0.14
	Level 2: Straight track	11.81	2.21	29.42**	0.25
	Level 2: Angular track	7.94	2.03	9.80**	0.10

Note: **p<.001

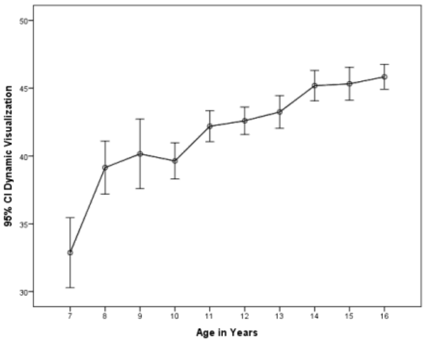

Figure 1. Mean plot for development of Dynamic Visualization across age groups

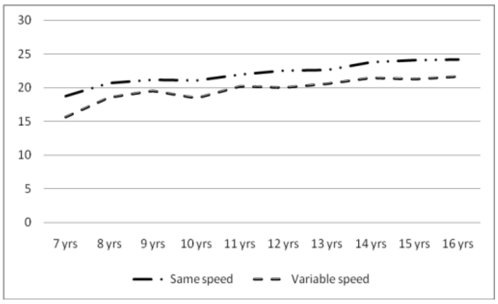

Figure 2. Line graph showing the performance on Dynamic Visualization levels across age groups

Further evidence for the age-wise development of Dynamic Visualization comes from the reaction time and response time taken by the participants to complete the task. As the children developed from being preadolescents to adolescents, the average reaction time and average response time taken for the trials decreased. One-way Analysis of Variance also shows that the average reaction time and average response time for each age group differ significantly [$F_{Reaction\_time}(9, 782)=24.90$, $p<.001$; $F_{Response\_time}(9, 782)=28.50$, $p<.001$] (Figure 3).

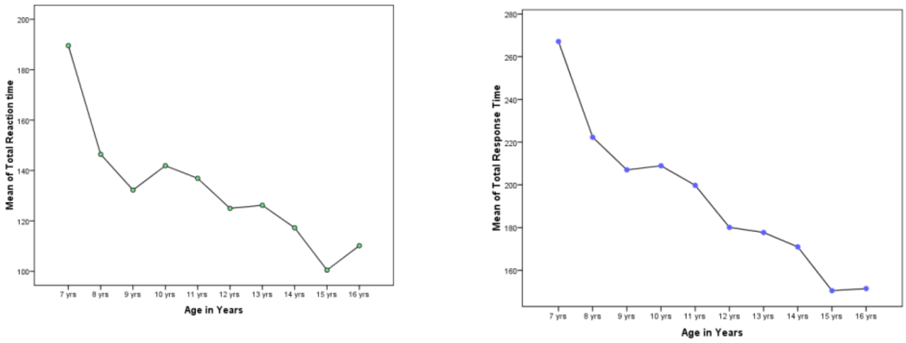

Figure 3. Mean plots for Reaction time and Response time of Dynamic Visualization task across age groups

Tracking the Developmental Trajectory of the DV ability across preadolescent and adolescent years

The developmental trajectory of the Dynamic Visualization (DV) ability was tracked by regressing the standardized DV scores hierarchically on age. An estimate for the regression was then checked for its' overall fit and accordingly, the best fitting line to the score distribution was selected. The non-linear function was fitted based on the best-fitted regression model that fitted the score distribution.

It was found that the developmental trajectory for dynamic visualization ability follows a quadratic function ($\beta=-0.012$, $p=.004$). The magnitude of the d values represents the overall growth in the ability across the ten age levels (Figure 4). The d value for dynamic visualization ability is quite high ($d=1.4$), suggesting a considerable change in this ability across the pre-adolescent and adolescent years.

Moreover, it should be noted that the estimate for Dynamic Visualization ability is negative. This is because the trajectory for the ability is quadratic, that is, the change in the rate of development is high during the early years but gradually decreases towards late adolescence. That's why the estimate is negative, indicating that the rate of change in the development of Dynamic Visualization stabilizes over time.

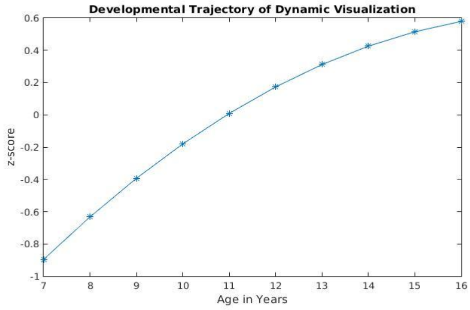

Figure 4. Developmental Trajectory of Dynamic Visualization ability across age groups

Table 3 shows the rate of change in the development of the DV ability across the ten age groups. The change for Dynamic Visualization ability is considerably high for the younger age group (0.28 units for 7-years-old) but gradually decreases over the preadolescent and adolescent age groups before stabilizing during late adolescence (0.05 units for 16 years old).

Table 3. Rate of change in Dynamic Visualization ability across ten age groups (N=792)

Age in years	7 years	8 years	9 years	10 years	11 years	12 years	13 years	14 years	15 years	16 years
Dynamic Visualization	0.28	0.25	0.23	0.20	0.18	0.15	0.13	0.10	0.08	0.05

Discussion

Age-wise development of Dynamic Visualization ability

As children grow up, their understanding of distance, speed, and time (DST) increase progressively. Following previous researches (Lovell, Kellett, & Moorehouse, 1962; Delorme & Pinard, 1970; Piaget, 1970), the present study also shows that the concept of distance emerges first, followed by the conception of speed and time. Nonetheless, the performance of the children above chance in both the same speed and variable speed conditions implies that the conception of all three dynamic properties, as well as the understanding of their direct and inverse relationships, is present at age 7-years. This finding provides more support to the Neo-Piagetian theories of DST understanding which argued that the concept of direct relationship among distance and speed and distance & time are already present at age 5 while the concept of the inverse relationship among the properties emerges at age 7-years (Matsuda, 2001; Albert, Kickmeier-Rust, & Matsuda, 2008). Present findings provide contrary evidence for the five-stage model of DST development proposed by Levin (1992). The model hypothesized the development of the DST understanding across the childhood and adolescent years through five stages, commencing at age 4-years and continuing till adolescence. Similar to Levin's model, present findings suggest that the understanding of the three concepts emerge at a much younger stage, most likely during early childhood. At age 7-years, a partial understanding of the direct as well as the inverse relationships among the three concepts is present since the average score obtained in both the conditions at age 7-years is much lower in comparison to the older groups. However, contrary to Levin's model, as the child grows the understanding of the direct relationship as well as the inverse relationship among the three properties improves progressively. Levin had proposed a *stage-wise development* of DST understanding, the direct relationships emerging first while the understanding of inverse relationships emerges later. On contrary, present findings rather advocate a *qualitative progression in the understanding* of both the direct and inverse relationships among the three dynamic properties. That is, instead of stage-wise understanding, judgment regarding the relationships among the three properties progresses qualitatively with age. As the child grows and enters adolescence, the DST understanding becomes more and more sophisticated and efficient. Also, contrary to Levin's model, present findings show that the DST understanding continues even after adolescence, into early adulthood. This finding partially provides support for Matsuda's model (2001) concerning the sixth stage of development where integration of the triadic system takes place, most probably in the early adult years.

Developmental Trajectory of Dynamic Visualization (DV) ability across preadolescent and adolescent years

Present findings show that the developmental trajectory of Dynamic Visualization (DV) ability follows a quadratic function. This implies that the DV ability develops as a quadratic function of age. The quadratic function of age implies a variable rate of development, faster initially but gradually slowed.

Thus, the DV ability develops at a faster rate during preadolescence (>.20 units during 7-10 years of age) but the rate gradually slows down as the child enters the adolescence period (<.10 units during 15-16 years of age). A possible reason for such an observed pattern might be that the adolescence period witnesses an integration of all three aspects of DST understanding (Matsuda, 2001) *i.e.*, assimilation of the spatial as well as the temporal aspect of relative motion. An integrated understanding of DST concepts rather facilitates the stabilization of the Dynamic Visualization ability during this phase. Hence, the rate of change in the ability decreases to a large extent during the late adolescent years.

Conclusions

These findings have some major theoretical contributions to the literature of spatial cognition. The development of DV ability slows down during late adolescence, indicating the fact that the understanding of distance, speed, and time (DST) are more or less achieved almost perfectly during this period. This finding provides empirical support to Levin's model of DST understanding (1992) as well as Matsuda's six-stage model which hypothesizes that integration takes place between the distance, speed, and time during this last stage of development during adolescence. The decreased rate of development of DV ability during late adolescence implies that this integration among the triadic system (DST) is already achieved during this period. Tracking the development of the Dynamic Visualization ability thus not only has provided empirical evidence of the development of these abilities but also will help explore the validity of earlier Piagetian and Neo-Piagetian theories of DST understanding. One limitation of the present study is that the study included adolescents till 16-years of age. However, tracking the developmental trajectory revealed that the ability hardly stabilizes during the adolescent years. Future research, therefore, can be done to explore the development of the ability beyond adolescence and in the young adulthood years. Moreover, the present study did not analyze sex differences in the development of DV ability since it would have interfered with the focus and objective of the study. However, studying the pattern in which sex difference can influence the development of DV ability would be truly intriguing and therefore can be explored in future research.

In a nutshell, the study explored the development of Dynamic Visualization ability across the preadolescent and adolescent years. Considerable differences exist among the preadolescent and adolescent age groups concerning their DST understanding. Moreover, the developmental trajectory of the ability revealed that the rate of change in the ability varies differentially and follows a quadratic path across the developmental period. Findings have immense implications in understanding the emergence of Dynamic Visualization ability during the preadolescent and adolescent years and empirical validation of earlier theories.

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