# Spatial Cognition and Visualization in Elementary Astronomy Education

Synopsis

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by

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# 1 Introduction

Motion of celestial bodies across the sky and everyday astronomical phenomena are significant to human life; they are easily observable and their explanations do not always require knowledge of advanced mathematics or complex theories of physics. Celestial phenomena, therefore, present a perfect context in which to introduce students to the scientific method, including of careful observations to generate a hypothesis, to predict its consequence, and test it against evidence. Astronomy education is also important from the perspective of scientific literacy. Indigenous knowledge of astronomy, usually integrated with astrology, is common in society and students (Mohapatra, 1991; Narlikar and Rana, 1997) and needs to be addressed. If meanings of the terms in common use are explained in terms of observations, school science could be brought into the daily context and superstitions related to the subject challenged.

Yet, elementary astronomy is an area prone to difficulties and common alternative conceptions for students as well as adults (Bailey et al., 2004; Lelliott and Rollnick, 2009; Trundle et al., 2002). Section 2 of this Synopsis summarizes important empirical results from astronomy education and from relevant literature in cognitive science, in order to explore the underlying sources of difficulties in elementary astronomy, and their possible remedies.

# 2 Literature Review

Early studies in astronomy education explored young students notions about the earth (Nussbaum and Novak, 1976; Mali and Howe, 1979; Klein, 1982; Sneider and Pulos, 1983). It was consistently found that students have notions about the earth that are different from the scientifically accepted notions. The earliest categorization of students' ideas by Nussbaum and Novak (1976), which was confirmed in the later studies with minor variation, was as follows:

**I.** The earth we live on is flat and not round like a ball. The earth's roundness is just the road's curves, or the mountain's shape, or the shape of the sky. The globe represents some other planet in the sky.

**II.** The earth is like a ball. Students could suggest some proofs for the spherical shape, but lacked the notion of unlimited space. They believed that the ground limits the space below, and the sky limits the space above the earth.

**III.** The earth is like a ball. Students had some idea of unlimited space, but still held a frame of absolute up-down directions.

**IV.** The earth is like a ball. Students did relate up-down directions to the earth; but up-down were directed only in the "vertical" direction instead of away or towards the center of the earth.

**V.** Scientific notion: a spherical planet surrounded by space and things falling towards its center.

The findings from Nussbaum and Novak (1976); Mali and Howe (1979); Klein (1982); Sneider and Pulos (1983) can be summarized as:

**1.** Intuitive notions as above were present in the majority of students and were robust.

**2.** A developmental trend was seen. In general, students from lower grades held initial notions and students from higher grades held advanced notions.

**3.** Thus, the 'conceptual change' involved here is a series of identifiable steps rather than a single 'conceptual leap'.

**4.** Students from different cultural and social backgrounds (e.g. Nepalese, Mexican-American, Anglo-American, Israeli) held similar notions, with minor differences in the ages at which they held the respective notions.

Studies in the next decade (1983-94) explored alternative conceptions and explanations from broader content related to the sun-earth-moon system along with alternative notions of the earth (Jones and Lynch, 1987; Baxter, 1989; Schoon, 1992; Bisard et al., 1994). Similar studies were later carried out by Trumper (2000, 2001). Some common alternative conceptions found in these studies are:

**1.** Students' cosmographies fell under five distinct spatial models. Three of them were earth-centered, and two were heliocentric (out of which one was the accepted scientific model) (Jones and Lynch, 1987).

**2.** Explanations for occurrence of day and night: Younger students gave more occultation based explanations (the sun goes behind the hill or it gets covered by clouds or by the moon) while the older students gave more explanations involving the movement of astronomical objects (the sun orbiting around the earth or the earth orbiting around the sun once a day) (Baxter, 1989).

**3.** Explanations for occurrence of seasons: The most popular alternative explanation was 'the sun is farther away in winter'. Two other alternative explanations were, 'the sun moves to the other side of the earth to give them their summer' and 'changes in plants cause the seasons'. Two occultation-based explanations (a planet takes heat from the sun and the winter clouds stop the heat from the sun) were rare.

**4.** Explanations for occurrence of phases of the moon: The most popular alternative explanation was, 'shadow of the earth cast on the moon', which happens to be the correct explanation for the lunar eclipse. Some variations of this notion, such as shadow cast by some object (a planet, or the sun) on the moon, were also found. Only the younger students held that phases occur because the moon gets covered by clouds.

**5.** Many students think that:

- The sun is directly overhead at noon.
- In May, June and July, the sun sets in the (exact) West.
- The phase of the moon is not the same all over the world at the same time.
- The direction North is straight up (Schoon, 1992).

General findings from these studies were:

**1.** The alternative conceptions were prevalent in all ages, both genders and among different cultural, racial and social (urban and suburban) groups tested in these studies.

**2.** A positive relationship between grade level and selection of advanced notions, or conceptions which are close to scientifically accepted concepts, was found again. Early notions were based on observable features while intermediate notions involved motions of astronomical bodies which at the end were (not always) replaced by scientifically accepted notions.

**3.** Importance of direct observations was realized.

**4.** Similarity between students' responses and historical development, and potential use of history of astronomy in astronomy education was pointed out.

These studies were influenced by 'conceptual change' framework which was then influential in science education research. Interest in students' notions about the earth revived in the early 90's, now influenced by an emerging framework of 'mental models'. Vosniadou and Brewer (1992, 1994) proposed that young students hold mental models of the earth and day-night cycle. They argued that students have 'initial' or 'intuitive' mental models, and when they are exposed to scientific information they form 'synthetic' models, where some of the assumptions in the initial models get revised and some do not. Culturally influenced synthetic mental models were found in India (Samarapungavan et al., 1996). However, Nobes et al. (2003), Siegal et al. (2004) and Hannust and Kikas (2007) claimed that students' knowledge comprised of fragmented facts as opposed to coherent mental models. This view fits into the theoretical framework developed by diSessa, according to which intuitive physics consists largely of hundreds or thousands of elements, called p-prims (phenomenological primitives) (diSessa, 2006).

A mental model is an internal representation of a concept (e.g. the earth), or an inter-related system of concepts (e.g. the solar system) that corresponds in some way to the external structure that it represents (Gentner and Stevens, 1983; Chi, 2008). Mental models can be 'run' or mentally simulated to draw inferences (Norman, 1983; Hegarty, 1992). Mental models may be incomplete, unstable, unscientific and parsimonious (Norman, 1983). Even if children's knowledge is fragmented, the relationships between different entities are not always present, or if they are present they may not be correct or coherent. We can still call that representation a 'mental model' and the challenge is to change this incorrect, incoherent mental model to the scientifically accepted model.

The place of mental models and of visualization in scientific discovery as well as in science education is recently recognized in the literature (Gilbert, 2005). Spatial properties are fundamentally embedded in the models in elementary astronomy and thus spatial cognition is an important aspect of understanding elementary astronomy. Consequently, the reasoning involved in explanations and predictions of the observable phenomena also involves visualization, spatial transformations and modeling. Study of such kind of reasoning is comparatively recent in contrast to the reasoning and argumentation using conventional cognitive resources such as logic (inductive and deductive), language and numbers. Conventional reasoning could be characterized as propositional reasoning, while by nonconventional reasoning we mean imagistic reasoning, which may include reasoning by analogy, geometrical reasoning, transformational reasoning and other forms, which use visual images as the basis of the reasoning, though often in combination with propositions and symbols. We consider model-based visuospatial reasoning to be a kind of nonconventional imagistic reasoning, which exploits spatial properties, such as size, shape, position, motion, etc., of the mental model, and needs spatial cognitive abilities such as mental rotation and perspective taking for the process of reasoning (Ramadas, 2009; Subramaniam and Padalkar, 2009).

Although visual and spatial cognition are often integrated, and together referred to as 'visuospatial', this is not a necessary connection. Two different brain pathways have been found for processing of visual and spatial information (Kosslyn, 1994). Blind people are seen to have good spatial abilities, but lack visual experiences and hence perhaps visual imagery. Properties which are available only to vision such as colour and brightness are primarily visual, whereas shape, size, distance and manner of movement, available to the visual as well as other modalities, are visuospatial properties (Tversky, 2005). Further, psychometric studies found that spatial ability is an amalgam of several correlated factors (Hegarty, 2005), out of which 'mental rotation' of an image and 'perspective taking' were found to be distinct but correlated properties (Hegarty and Waller, 2004).

Concrete models and diagrams are commonly used to represent, communicate and think about spatial information, and their usefulness in pedagogy is undisputed (Gilbert and Boulter, 1998; Tversky, 2005). Concrete models lack the analytical power of diagrams. On the other hand, diagrams are two-dimensional and static representations and hence have limitations in representing three-dimensional reality and motion (Tversky, 2001). Diagrams omit or distort perceptions or add extra information, which is not there in perception (Tversky, 1999). The conventions and assumptions on which scientific illustrations are based need to be learnt, to interpret diagrams correctly. Diagrams therefore need support of other spatial tools when presented in pedagogy.

Our body, in occupying and moving through space, acts as perceptor of space. Studies of reaction times show that we code locations in our immediate vicinity with respect to our three body axes: up-down, front-back and left-right (Tversky, 2005). Motor perception is crucial to our understanding of imagined space, as is seen in experiments on orientation change. Tasks calling for changing one's own orientation (heading) by visual imaging are very difficult to perform, but they get greatly facilitated with use of kinesthetic feedback, i.e. by carrying out the body motions required for that orientation change, though it be (even in sighted subjects) without the use of vision (Klatzky et al., 1998). Gestures play several roles such as communication (Goldin-Meadow, 2006), language-acquisition (Vygotsky, 1978), precursors of graphic signs (Roth, 2000) and as a tool for spatial and scientific thought (Hegarty, 2005; Schwartz and Black, 1996; Clement et al., 2005; Kastens et al., 2008; Subramaniam and Padalkar, 2009). Thus gestures and actions play an important role in spatial cognition. In our work we propose a systematic way to use these spatial tools in pedagogy (see Section 5.1).

# 3 Astronomy Curriculum in the State of Maharashtra

Analysis of the Maharashtra State Textbooks shows limited use (or suggestion for use) of concrete models. The Geography textbooks of Grades 5 and 6 have several diagrams that are pedagogically appropriate and they also suggest interesting activities to students. But some of the astronomy related diagrams in the textbooks may communicate incorrect information, are open to misinterpretation or may create misconceptions in students. The views (perspectives) are not specified nor used consistently, nor is effort made in general to sensitize students to the scale (sizes and distances) and assumptions in the diagrams. Most of the diagrams (especially the explanatory ones which are difficult to comprehend) are not well connected to the text. The content is presented more in an informative fashion rather than as reasoned arguments. Some of the concepts such as revolution of the earth are introduced too early, some such as elliptical shapes of orbit are overemphasized, though they have no role to play in explanations, and some concepts which play an important role in basic explanations such as horizon and local directions, are not introduced at all. In practice teaching is driven by the limited expectations from students in examinations, in which neither is knowledge probed in detail nor are any problems posed, that could be based on new or hypothetical situations. Consequently even when the diagrams are well designed, in the overall context of their treatment in the textbook it turns out that they are rote-learned simply for the purpose of reproducing in the examinations. This is the situation we are addressing.

# 4 Aims and Research Questions

With this background on students' difficulties in astronomy (Section 2) and the inadequacies of textbooks in use (Section 3), this work has the following three broad aims, each of which naturally suggests several interrelated research questions to explore.

**Aim 1. To investigate Indian students' understanding of elementary astronomy**

Students need to build a model that is consistent with their observations about the phenomena which they are expected to explain. Our first question therefore is, What are students' observations about celestial bodies and phenomena (sun, moon, stars, planets, shooting stars)? Have the students noticed the patterns in the cyclic phenomena (day-night, daily motion of stars and moon, phases of the moon, changes in the path of sun due to seasons, changes in night sky over the year)? What kind of observations (qualitative/ quantitative, observations about visual/ spatial/ temporal properties) do students record?

Do students know the basic facts (which are taught in their textbook) about the solar system?

Given the close connection between astronomy and astrology and the active influence of indigenous knowledge related to astronomy, do students know about the connection between observational astronomy and indigenous calendars? Do they know the common terms and their meanings used in indigenous astronomy?

What is the level of students' understanding about the model of the round rotating earth? Can they present this model coherently? Can they provide satisfactory explanations of the phenomena they have learnt in their textbooks? Can they make prediction in hypothetical situations based on the model?

What aspects of students' knowledge change with level of schooling? In which aspects of knowledge do students from rural, tribal and urban background differ?

...These questions are addressed in Section 7.

**Aim 2. To design a pedagogic sequence of intervention, based on insights from literature on spatial cognition and visualization, to teach elementary astronomy to Grade 8 students**

What are the visuospatial or conceptual difficulties related to content and how can these difficulties be handled?

What are some useful cognitive tools in pedagogy of astronomy? If concrete models, gestures and actions, and diagrams are identified as useful spatial tools, how should they be placed in the pedagogy with respect to each other? (Subsection 5.1)

What are some useful concrete models that can be used to teach the sun-earth-moon system? (Subsection 8.1)

Assuming that gestures might be a useful spatial tool in learning elementary astronomy, we ask:
What can be a reasoned basis for designing gestures for teaching astronomy?
How should these gestures be placed in relation to other common spatial tools?
What types of spontaneous gestures are produced by students during collaborative problem solving?
Do these gestures vary according to the problem tasks?
How do students' spontaneous gestures compare with the pre-designed gestures used in our intervention? (Subsection 8.2)

What do diagrams in astronomy represent and what are the characteristics of each of these kinds?
What characteristics of diagrams can be used as criteria to evaluate students', teachers' and textbook diagrams? (Subsection 8.3)

**Aim 3. To test the effectiveness of the pedagogic sequence**

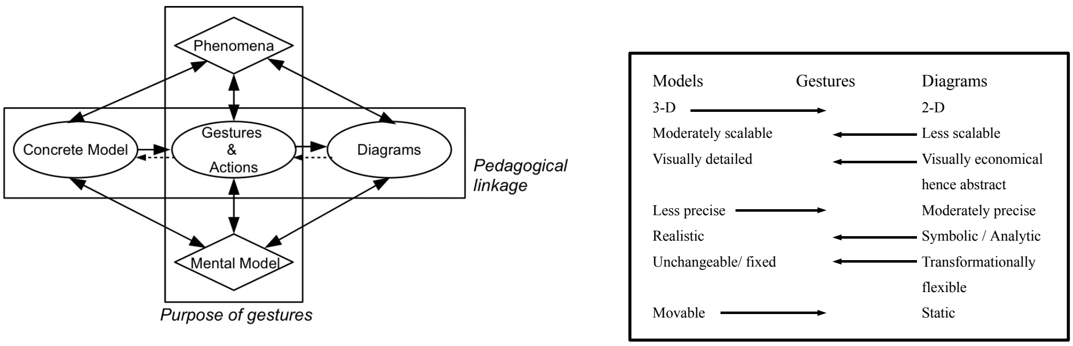
Which aspects of students' knowledge changed significantly after the intervention?
Which aspects of students' diagrams changed after intervention?
With respect to which aspects of knowledge did students from the treatment group perform significantly better than students who did not go through intervention (comparison group)?
Which alternative conceptions and explanations continued to exist even after instruction? (Section 7)

# 5 Research Design

The study follows a 'conjecture driven research design'. A conjecture is an inference based on inconclusive or incomplete evidence drawn from literature and the researcher's experience. It is situated in a broader theory and influences the choice of content and pedagogy. It is not an assertion waiting to be proved or disproved, but a means to reconceptualise the way in which to approach both content and pedagogy. Conjecture based design is situated in a real classroom setting rather than in a laboratory setting and it aims to come up with new widely applicable instructional strategies. In this kind of research, researchers come up with a conjecture, design an instructional method assuming that the conjecture is true and finally test the effectiveness of their instructional method. The planned intervention takes place over a significant period of time. As the intervention proceeds, the conjecture evolves and becomes precise and the study is usually fairly flexible to incorporate the insights gained during the intervention (Confrey and Lachance, 2000).

## 5.1 The conjecture

For model based reasoning, concrete models, diagrams and gestures are all spatial tools. These tools, interlinking and reinforcing one another, serve to connect the phenomenon with the mental model. We begin with some known concrete models and some analytical diagrams, some adapted and some novel, designed on the basis of our knowledge of elementary astronomy. We then formulate a conjecture about the role of gestures in astronomy, which helps us to design the pedagogical gestures. This conjecture has two dimensions which are illustrated in Figure 1a.




(a) Purpose of gestures in linking phenomena with mental models and their pedagogical role in linking concrete models with diagrams

(b) Gestures can be used to link concrete models with diagrams: Arrows denote the properties that gestures share with either concrete models or diagrams.

Figure 1: The Conjecture

The vertical dimension of our conjecture, shown in Figure 1a, arises from the limitation of perception for comprehending astronomical models. Gestures represent, communicate, and most importantly internalize the spatial-temporal properties of the phenomena and scientific models. We further conjecture that gestures help in changing the orientation and frame of reference, and through these two functions, the link between the scientific model and the phenomenon is manifested and strengthened. Also, one has to go, to and fro from the one's mental model to the phenomenon and back, in order to refine one's understanding, a process that is indicated by the two-way vertical arrows in Figure 1a. We call this the 'mental model - gesture - phenomenon' link of our conjecture.

The horizontal dimension of our conjecture, shown in Figure 1a, arises from the limitations of use of any single representation like a concrete model or a diagram. Diagrams are visually economical and precise in capturing analytical relationships, but diagrams being two-dimensional, static and abstract, pose difficulty for students (Tversky, 2005). Models on the other hand, are easily constructed, three-dimensional and movable, but because of their crude and often inflexible nature, they are not amenable to the abstraction and manipulability required for reasoning. Gestures too are three-dimensional and dynamic, and in addition they are fluid and transformationally flexible, so they can potentially be used to traverse the conceptual distance from concrete models to diagrams. Figure 1b summarizes the properties that gestures share with concrete models and diagrams to hypothesize that gestures could provide a possible link between concrete models and diagrams. The arrows in Figure 1b indicate the shared properties of gestures with either concrete models or diagrams. Figure 1b is an elaboration of our rationale for the 'concrete model - gesture - diagram' link in Figure 1a. The instances of gestures with their purpose and pedagogical linkage are elaborated in the Thesis.

Given the economic and abstract nature of diagrams, the desired direction of the 'concrete model - gesture - diagram' link in Figure 1a is from concrete models towards diagrams. In terms of pedagogy however, at the initial stage one needs to go to and fro until mastery over the diagrammatic medium is achieved. This backward link is shown by the dotted arrows in Figure 1a.

## 5.2 Research methodology

Exploratory interactions with students at different grade levels gave us an initial broad view of their range of development over the school years. This information was used in preparing a set of four tests (on observations, textbook facts, indigenous knowledge and the sun-earth model) which were administered to Grade 4 and Grade 7 (referred to as 'Gr4' and 'Gr7') students.

Based on the findings from pre-tests and the conjecture above, we developed a one-year pedagogy. The pedagogical intervention was undertaken only for students who were about to complete Grade 7 (Section 6).

One year later, at the end of the intervention the pre-tests were repeated as post-tests on the treatment group which had by then progressed to Grade 8 (referred to as 'Gr8t'). The test on the sun-earth model included four new advanced questions. An additional (fifth) test on 'knowledge about moon' was administered towards the end of the intervention as a pre-test and (2 weeks later) after completion of the intervention, as a post-test (with one extra question included). The same tests were administered (once only) to the comparison groups of Grade 8 ('Gr8c') to compare the improvement of students who went through intervention against students who did not go through intervention but had, of course, gone through the astronomy portion of the textbooks.

## 5.3 Data analysis

The three main sources of the data and the methods by which they were analyzed are given below:

**1. Assessment of Astronomical Knowledge**

Responses from all five tests were coded and a pair-wise z tests for each category of response was carried out between grades (Gr4-Gr7, Gr7-Gr8t, Gr8t-Gr8c) by collapsing rural, tribal & urban samples at 5% level of significance. This enabled assessment of how the quality of students' responses differed between the grades and changed after the intervention.

The difference between total scores for each grade on each test were seen through pair-wise t tests carried out between the grades (Gr4-Gr7, Gr7-Gr8t, Gr8t-Gr8c) by collapsing the rural, urban & tribal samples (Section 7).

Pair-wise t tests were carried out between the rural, tribal & urban samples for each grade for each test to see whether there were any differences between these samples.

**2. Guided Collaborative Problem Solving** (explained further in Section 6)

Students' questionnaires were analyzed to find the number of groups which produced specific responses. This data was used to gain qualitative insights into students' problem solving process and the kinds of difficulties they encounter. Video data on students' gestures was also recorded during these sessions.

**3. Videos data** All the classroom sessions were videotaped and this data was used for the analysis of role of spatial tools, namely concrete models, gestures & actions and diagrams in pedagogy. The video data of problem solving sessions of two of the groups (TB, RG) was used to analyzed nature and frequency of students spontaneous gestures. The results from this data analysis are summarized in Subsection 8.2.

General observations and specific episodes during the teaching and problem solving sessions were noted down after each session which complemented all the data.

## 5.4 Sample

The sample consisted of students who were about to finish Grade 4 (end of primary school) and Grade 7 (end of middle school). Considering the population profile of India and the low resource situation in the majority of schools, we chose our samples from three groups in the State of Maharashtra, which we feel are fairly representative. One sample is from a rural school, another is from a residential school for nomadic tribal children and the third sample is from a school which serves a slum area in Mumbai. In the rural and tribal areas equivalent schools were selected for treatment and comparison samples; in the urban school the comparison sample was selected from the same school. The representation of girls in both treatment and comparison groups was around 30% because of high drop-out rate among girls in the primary school years. The number of students in each Grade in the pre and post tests is given in Table 1.

Students from all three schools are either first generation learners or have minimal educational background at home. Coming from disadvantaged communities, they are not exposed to scientific information through books and other media. In addition they have a language disadvantage because their mother-tongues differ from the formal Marathi language used in their textbooks. In terms of both talk and gesturing, these students tend to be shy and reticent in the classroom and in the presence of adults. Elders in their family may possess traditional knowledge (particularly in astronomy), which may facilitate or conflict with modern science and school learning (Padalkar and Ramadas, 2009).

Table 1: Number of students who attempted the questionnaires (Gr7 is equivalent to 'pre-tests' and Gr8t is equivalent to 'post-tests'; R = Rural, T =Tribal and U = Urban)

| Class | Girls + Boys | Test 1 | Test 2 | Test 3 | Test 4 | Test 5 |
|---|---|---|---|---|---|---|
| Gr4-R | 16 + 16 | 32 | 30 | – | 32 | – |
| Gr4-T | 8 + 5 | 10 | 13 | – | 11 | – |
| Gr4-U | 21 + 27 | 45 | 45 | – | 45 | – |
| **Gr4** | **45 + 48** | **87** | **88** | **–** | **88** | **–** |
| Gr7-R | 12 + 23 | 27 | 26 | 27 | 26 | 24 |
| Gr7-T | 7 + 21 | 17 | 15 | 15 | 17 | 19 |
| Gr7-U | 4 + 14 | 18 | 17 | 17 | 16 | – |
| **Gr7** | **23 + 58** | **62** | **58** | **59** | **59** | **43** |
| Gr8t-R | 12 + 23 | 26 | 28 | 27 | 28 | 24 |
| Gr8t-T | 7 + 21 | 21 | 20 | 21 | 21 | 23 |
| Gr8t-U | 4 + 14 | 6 | 6 | 6 | 6 | 6 |
| **Gr8t** | **23 + 58** | **52** | **54** | **54** | **55** | **53** |
| Gr8c-R | 16 + 24 | 34 | 37 | 37 | 37 | 35 |
| Gr8c-T | 11 + 33 | 35 | 37 | 38 | 36 | 42 |
| Gr8c-U | 0 + 3 | 3 | 3 | 3 | 3 | 3 |
| **Gr8c** | **26 + 60** | **72** | **77** | **78** | **76** | **80** |

# 6 Pedagogic Sequence

Our intervention was divided into three parts each of about 10 classroom sessions of one and half hour each. The first part dealt only with the earth, its roundness and rotation. These ideas were sufficient to explain the change in apparent position of the celestial bodies due to change in one's position on the globe, as also their daily apparent motion as seen from a given position on the globe (Padalkar and Ramadas, 2008). The second cycle dealt with the sun-earth system and consequences of revolution of the earth around the sun such as, seasons and changes in the night sky over one year. The third cycle dealt with the sun-earth-moon system and hence explanation of phases of the moon and eclipses. The following were the features of the pedagogy:

• **Teaching by Socratic questioning**: We avoided telling facts; instead students' models and explanations were continuously questioned and they were encouraged to upgrade their models and explanations.

• **Use of spatial tools**: The pedagogy was built around three main spatial tools:

concrete models, gestures and actions, and diagrams. These were used in the sequence concrete model-gesture/action-diagram, with gestures overlapping many times with either or both of concrete models and diagrams, as suggested in the conjecture. Total of 22 types of concrete models, 40 sets of gestures and 40 sets of visuals (diagrams + photographs) were used during the intervention.

• **Collaboration**: The classroom situation was designed such that students needed to collaborate in different ways.

*Teacher directed class*: Concrete models were introduced and students collectively added different elements to it. Students together listed the differences between the model and the real system, correcting and adding into each other's responses. As for gestures, ten out of the 40 pedagogic gestures needed two or more persons to enact them. Diagrams too were collaboratively constructed on the board. Students added the required elements in a diagram in combination with an ongoing dialogue.

*Guided collaborative problem solving*: Students were given 12 sets of questionnaires to solve in groups of three. While solving these problems, students used concrete models and gestures to communicate their ideas to their group-mates. Skeletal diagrams were followed by step-wise instructions to construct a diagrammatic solution to the problem. Note that spatial tools were used to create the collaborative situation and to study students' learning, rather than using verbal discourse, which is a more common method in studies of collaboration.

*Use of sociocultural tools*: The commonly available calendar (combination of Gregorian and indigenous calendars) turned out to be an important sociocultural tool for learning. Students were familiar with this calendar, which contains notes related to observational astronomy. These calendars helped place problems in astronomy within a cultural context, thus helping to bridge the gap between formal science and the shared cultural knowledge which was available to students. A calendar is a complex text, but it becomes easier to comprehend through discussion among students, each of whom may notice a different feature in it. In the class students read aloud and interpreted notes from calendars. Sometimes calendars were provided in groups to find out the pattern in a particular phenomenon. Observations from other tools such as gnomon and star charts complemented the notes from calendars.

*Observations*: Observations of positions of stars, shadows of gnomon, shape and position of the moon, etc. were carried out in groups. It is acknowledged that keeping notes of observations of any scientific experiment is difficult and less reliable when done by a single person. This is more true in the case of astronomy, where observations need to be taken sometimes throughout a day or a night, and sometimes over a long period (a month or a year). Students shared common tools (astrolabe) and charts, sometimes shared responsibilities for data collection and discussed them to arrive at pattern: a process that is similar to scientific research.

• **History of astronomy**: We tried to bring in the historical aspect in each part of intervention by giving the historical reading material in groups, and having them watch a short portion of Bertolt Brecht's play "Life of Galileo" enacted by teachers (in Marathi translation, with activities and gestures as suggested by Brecht (1947)).

# 7 Assessment of Astronomical Knowledge

The results from tests administered to Grade 4 and Grade 7 students (before intervention), Grade 8 students (after intervention) and Grade 8 students from a comparison group, are summarized here qualitatively. Detailed responses and their analysis are reported in the thesis.

## 7.1 Observations

Quantitative observations are important in explanations of phenomena (e.g. time and position of the rising and setting sun help explain occurrence of seasons). However students' observations of daily phenomena in the sky were qualitative in nature (colour, brightness), rather then quantitative (position/ time). Most of the students (76%-95%) had observed the rising and setting of the sun and could describe the rising and setting sun in terms of its its colour, shape, size brightness etc.. Similar percentages of students knew the (East/ West) direction of rising and setting of the sun. Before intervention (Grade 7), 44% & 50% students respectively know that the direction of sunrise and sunset changes every day, and 65% & 66% students knew that the time of sunrise and sunset changes every day. The percentage of these correct responses increased in Grade 8 (74%, 70%, 93% & 91% respectively). A small percentage of students without intervention (Grade 7 - 3% and Grade 8c - 4%) knew that the sun does not come overhead every day and, even after intervention, although this percentage increased significantly, only 34% of the students knew it.

Before intervention, visual properties (as above) were readily given by the students in their descriptions (rising sun, stars, differences between the setting sun & the sun at noon, day & night), followed by spatial (sometimes combined with temporal) responses and responses based on other sensory properties depending upon the context (heat, temperature related responses were common for difference between the setting sun & the sun at noon and day & night and spatial responses (size, shape, motion) were more common in description of stars, shooting stars and the rising sun). Human centric responses were common. Living world related responses were present, particularly for the difference between day & night.

Night sky observations are often lacking in students' normal experiences. Initially, in the star-gazing sessions, students name a few, but they could not identify any of the planets, stars, *Nakshatras*[1] and *Rashis*[2] in the sky. They could not name any stars though they could name (though not identify) the planets which are given in their textbook. Most of the students (77%) knew about the phases of the moon, but they had problems in drawing the gibbous and naming the phases. For example, only 2% could draw the correct gibbous shape and 10% could name the full moon correctly as '*Pournima*' in Marathi (the percentages were less for other phases) in Grade 7.

## 7.2 Indigenous knowledge

The results indicate that students' astronomical knowledge might have come from cultural practices rather than from observations or textbooks, and that this knowledge was associated with astrology. As an example, a large number (66%) of students knew before intervention that the time of moonrise and moonset changes every day, but fewer knew the directions of rising and setting of the moon before the intervention (47-48%). The percentage of students before intervention who knew that the time of sunrise and sunset changes every day was almost same as the percentage of students who knew that the time of moonrise and moonset changes every day (65%, 66%). The latter fact is not mentioned in textbooks, but it has religious significance. Another observation was that students knew the common terms in indigenous astronomy, and could name the Marathi months, *Rashis* and *Nakshatras*. Naming a *Rashi* (0.46 *Rashi*/ student) was somewhat more common than naming a *Nakshatra* (0.04 *Nakshatra*/ student). *Rashis* or 'star-signs'

[1]Twenty-seven lunar mansions in the indigenous system
[2]Twelve Zodiacs in the indigenous system

has significance in popular astrology (though *Nakshatras* are also used in more technical astrological predictions).

The connection between the indigenous calendar and observable astronomy was not known to students. They knew the names of the *tithis* (days of the forthnight), but did not know the equivalence between the phases of the moon and the *tithis*. Similarly they did not know about the observational context in which the terms *Rashi* and *Nakshatra* are used. The intervention helped them understand the meanings and context of the indigenous terms. For example, 22% students could explain the meaning of term 'starting of a *Nakshatra*' after intervention.

We conclude that it is possible to use indigenous knowledge in a positive way in teaching. Indigenous astronomical knowledge integrated with astrological beliefs is already prevalent widely (about half the students before the intervention stated that they believed in astrology). Therefore one needs to address the issue while teaching formal astronomy. Yet there is a danger of reinforcing superstitious beliefs while using indigenous knowledge. In the intervention we emphasized the scientific part of this knowledge and we connected cultural tools such as calendars to actual observations. Our study showed that the percentage of students who state that they believe in astrology (45%) sharply decreased (to 19%), and those who state that they do not believe in astrology (17%), sharply increased after the intervention (to 48%). Although the teacher's views relating to these beliefs were reflected in her teaching, any head-on criticism of astrology was avoided, which appears to have been a reasonably effective strategy.

## 7.3 Mental models, explanations, and predictions

Before intervention many Grade 7 students knew the basic facts about celestial objects in the solar system, such as the number of planets (66%) and their names, but their understanding about sizes of the celestial bodies and their distances from the earth was poor (percentage of correct responses ranged from 4% - 41% for distances and from 2% - 54% for sizes). Rote learning was evident in the pre-intervention responses. Most students remembered the numbers related to the time periods of rotation and revolution (the percentage of correct responses was 62% & 67% respectively), but sometimes interchanged them (22% - 24%), or some forgot to mention the units (9% & 2% respectively).

Students knew that we live on the earth but students from all three Grades suggested alternative shapes for the earth (such as egg - 22%, bowl - 2%, and plate - 9% in Grade 7). Pre-intervention, very few could produce evidences for the spherical shape of the earth (11% or less). They were unfamiliar with the concept of horizon and local directions for a person on the globe.

Students knew that the earth exerts gravitational force on the objects on it, but they could not reconcile this fact with the spherical shape of the earth. Pre-intervention they did not know that all the celestial bodies exert a mutual gravitational force on each other. We found that students had problems in placing model human beings on the globe (none of the students drew a human being in orientation other than vertical (head up) in the pre-test), hence we carried out an activity of pasting toy human figures on the globe in Part I of the intervention. Yet, when in the last part of the intervention students mimicked the gesture of rotating an apple (representing the earth) around a horizontal axis, so that the human figure appeared to be up-side-down, they became very uncertain about their gesture, and tended to stop the rotation before the person became up-side-down, as if they were taking a risk of falling. However, 87% students drew a human being in an orientation other than vertical (head-up) in the post-test. We conclude that gravitational force of the earth and other celestial bodies need to be addressed explicitly during the instruction. Newton's law of gravitation can be qualitatively explained: we found students had difficulty when the mathematical expression was introduced.

In the context of the coherent verses fragmented knowledge debate (Section 2) we found that students' mental models were fragmented. The relationships between different entities were unclear and were not always constant (5% diagrams were coherent and 1% were incoherent in the pre-test and, rest of the diagrams could not be judged for coherency because of absence of sufficient number of elements).

Before instruction students had not understood the causal relation between rotation of the earth and the apparent motion of the stars. The pattern of motion was also not clear to them, although many students (60%-66% in two questions) knew that the stars change their place overnight, and also through the year (68%). We were surprised to find that many (68%) students did not know that stars are present in the sky during daytime but are not seen because of sunlight (75%).

We found in the pre-tests common alternative explanations consistent with those identified in the earlier literature (Section 2) such as, apparent motion of the sun in the sky (or occurrence of day-night) is due to revolution of the earth around the sun (22% &10% respectively for the two questions); and shadow of the earth fallen on the moon causes the phases of the moon (24%). These sadly remained persistent even after intervention.

Some advanced explanations such as appearance of the same face of the moon from the earth, and inconsistency between time periods of synodic and sidereal month, were absent before intervention, but about one third of the students could satisfactorily produce them after the intervention.

Many students could partially or correctly predict the observational consequences in hypothetical situations. In Test 4 when students were asked to predict what will happen if the earth stopped rotating, many (about two thirds) of the students from all three grades responded that day-night will not occur (more correctly, day-night will occur once in a year). However, only one fourth of the students gave partially correct responses related to the effect on apparent motion of the stars and the moon (stars and the moon will be seen at the same place). About 15% students after intervention gave a fully correct response (only the moon will appear to move).

Generally while explaining, and more often while predicting, students tended to guess the answers rather than approaching the problem through geometrical construction. For example, when students were asked to predict which stars a person in the given diagram would be able to see, before intervention they students did not draw line of horizon and parallel rays from a star. During the intervention however there was a shift in the tendency to use diagrams for prediction.

In the post-intervention interviews, those students who could answer all of the questions satisfactorily (a rural girl, 2 rural boys and a tribal boy), were asked to predict some consequences in a hypothetical situation. These students could predict the seasons on a planet whose axis is in the plane of ecliptic, phases of the earth as seen from the moon, and how the earth and the sun will appear at the time of the solar and lunar eclipses.

## 7.4 Effect of maturation and schooling

Grade 7 students' performance was better than that of Grade 4 students in all three tests (Test 1: Observation, Test 2: Textbook facts, and Test 4: The sun-earth model), which were administered to Grade 4 students. This improvement in observation, knowledge of facts and model understanding perhaps involved an interaction between effect of schooling and maturation.

## 7.5 Effectiveness of the pedagogy

Overall, the designed pedagogy appears to have been successful since scores on all five tests significantly improved after the intervention (Gr8t > Gr7) and the Grade 8 students from treatment group performed significantly better than the Grade 8 students in the comparison group (Gr8t > Gr8c). Thus in all aspects, namely, observations, indigenous knowledge and understanding of the sun-earth-moon model the students improved after intervention. Intervention helped them towards constructing the accepted mental model of the sun-earth-moon system, as seen from improvements in their understanding of shapes, patterns of motions and quality of explanations, both verbal and diagrammatic.

# 8 Analysis of Spatial Tools

As explained earlier (Sections 5 and 6) the pedagogy was built around concrete models, gestures and actions, and diagrams. The functions of these tools, and how they can be appropriated for pedagogy, are summarized here. This analysis is a central contribution of the thesis.

## 8.1 Concrete models

Concrete models along with photographs present realistic details of a system, and hence form a good starting point to introduce any system. An important pedagogic exercise to be carried out at the outset is listing the differences between the concrete model and the real system which is being represented through that model.

In our pedagogy, concrete models were used flexibly, and were made out of materials that was easily available and could be easily replaced by other material. For example, a model of three axes could be made out of chopsticks, pencils or wooden twigs. Models used to revise concepts in geometry were concrete objects in the surroundings, or those the students could recall (e.g. rail-tracks for parallel lines), which helped place abstract concepts in a concrete context.

The globe proved to be of great importance, far beyond showing the geographical locations of places. Manipulating the globe (without its stand) was an important experience to understand the earth as an astronomical object. Students used this model extensively during classroom sessions in various activities and in problem solving sessions to aid their reasoning. Using the globe as a geosynchron was a further enlightening experience for students. Even teachers in the schools (who were rather skeptical about educational experiments) became interested when students were working with the globe outdoors.

The telescope and photographs of celestial bodies (accessed by the teacher-researcher from the internet) are difficult to access for teachers in rural areas. These should be provided to schools, along with a globe, maps and other laboratory material.

## 8.2 Role of gestures in pedagogy

First we see how gestures and actions can be used in a systematic manner in combination with concrete models and diagrams. Then we present the results about spontaneous gestures produced by students during collaborative problem solving. We explored if these gestures varied according to the problem tasks. Finally we compared the students' spontaneous gestures with the pre-designed gestures used in our intervention.

### 8.2.1 Designed pedagogical gestures

We have proposed that, just as we design models and diagrams for pedagogy, gestures too can be designed to convey and internalize concepts in science. The following two conjectures provided the rationale for design of gestures in our pedagogy for astronomy:

**1. The 'phenomenon - gesture - mental model' link**: distance and time scales in astronomy being beyond direct perception, actions may provide the most accessible bridge from the phenomenon to the mental model. Both spatial as well as dynamic properties of a phenomenon or a scientific model can often be readily conveyed through gestures.

**2. The 'concrete model - gesture - diagram' link**: gestures can be used along with concrete models to make these fluid, and with diagrams to add a third dimension. Both concrete models and diagrams can be made dynamic with the use of appropriate gestures. Out of the 40 gestures designed for instruction, 38 either followed concrete models, or were followed by diagrams, or both.

Although a good teacher may intuitively use some hand gestures or actions, like getting students to enact the solar system, such activities need to be designed and performed with specific motivation. We have shown that gestures can be used to achieve ownership of, and internalize patterns in, astronomical phenomena; to enact spatial properties of astronomical models or part of them; and to internalize space in general. In internalization of astronomical models, gestures give kinesthetic feedback to facilitate change of orientation and enable the visualization required in the process of change of reference frame from egocentric to allocentric. These are critical functions in the context of elementary astronomy education.

Such pedagogy may have several extensions. For example, with appropriate modifications, it may be found useful for visually challenged students. The two conjectures above could also be used to design gestures in other branches of science, which rely on spatio-temporal content. Gestures are flexible and they do not make any permanent mark on space. Their role in the construction of a diagram may be akin to the role of speech in loud thinking before arriving at a well structured, written argument.

### 8.2.2 Students' spontaneous gestures

Students in our sample spontaneously used six main types of gestures at an overall rate of about one gesture per minute. Along with the known categories of 'Deictic', 'Metaphoric' and 'Iconic' gestures, we found the need to construct a new category of 'Orientation change' gestures as part of instruction, and found that students too adopted this kind of gestures during collaborative problem solving, apparently as a tool for thought (rather than for communication). In the predominant category of deictic gestures, we found several that carried spatial content. These 'Deictic spatial' gestures communicate spatial properties such as length, orientation, direction, shape, etc.. The pointing in these gestures, when showing a proposed shape on the diagrams, appeared to support the hypothesis of gestures facilitating the 'mental model-diagram-phenomenon' link. In most cases, however, such linkages were difficult to detect.

The frequency of different kinds of students' spontaneous gestures varied across the sessions in accordance with the content of the problems which were to be solved in that session. These results, in conjunction with the literature cited earlier, underscore the role of gestures in communication and thought.

Students used a few gestures which they learnt during instruction, but their gestures were not an exact copy of the teacher's gestures. They also used many new gestures, especially metaphorical ones. A correspondence between the designed pedagogical gestures and students' spontaneous gestures was seen in the categories of 'Deictic spatial', 'Iconic' and 'Orientation change' gestures. Gestures that occurred spontaneously in the 'Metaphoric' category were simpler and less elaborate than the pedagogical gestures in the same category.

### 8.2.3 Multimodality in science learning

The perspective of multimodality (Lemke, 1998) is particularly useful in science learning, for a number of reasons. At a fundamental level, the physical world exists in space and time, hence our understanding of space (and time) is essential and intrinsic to our understanding of the physical world, which in turn develops from our bodily experiences. For example, our vestibular sense provides the only way to experience acceleration, force and 'gravity', the most basic concept in astronomy.

Experimentation is a component of scientific inquiry which, in its simplest form, uses the senses to understand manipulations of the world. In modern methods of experimentation, where the data is collected indirectly and often in digital form, it becomes useful to convert it back into visual (graphs, computer simulations) or other sensory forms, in order to apprehend patterns in it. In science pedagogy as well it is important to exploit all the sense modalities. Finally, as argued earlier, for very large distance and time scales the phenomenon and mental model may be linked through actions. Our approach serves to integrate the spatial and temporal aspects of the body-environment interaction.

## 8.3 Functions of diagrams and criteria for using them effectively

Diagrams in elementary astronomy represent either models, or phenomena, or explanations which relate models and phenomena, and each of these kinds of diagrams has certain distinct properties. We have suggested four criteria for a diagram being pedagogically effective:

**1. Integration with other spatial tools**: Diagrams should be used in combination with other spatial tools such as concrete models and gestures, so as to overcome their limitations such as their two-dimensional, static and abstract nature.

**2. Interactivity**: Providing a skeletal diagram and individual and collaborative additions in it proved to be useful in learning and problem solving.

**3. Transformability**: Representing motion using conventions and using multiple perspectives makes diagrams more amenable to mental simulations and transformations. It again helps in overcoming the two-dimensional and static nature of diagrams.

**4. Inclusion of explanatory elements**: The reasoning process of a teacher becomes accessible to students through drawing of explanatory elements, perhaps similar to the process of writing intermediate steps in solving an equation. Such practices develop in students the habit of approaching a problem by reasoning rather than by guesswork. Also, since students' thinking gets reflected via explanatory elements, these elements can be used to assess students' diagrams. Elements which help define the local environment of an observer, and ray-diagrams, were found to be particularly useful in constructing explanations.

### 8.3.1 Students' diagrams

A general observation related to students' diagrams was that many students could draw the required elements on the earth (equator, poles) and in the sun-earth-moon system (the sun, earth and the moon), but few could correctly show the axial and orbital motion. The number of diagrams which included motion (axis - 35%, orbit - 15%) increased after intervention, and students started to use more scientific conventions.

In general, students diagrams were corrupt copies of textbook diagrams. The relationships between elements were coherent in 5% diagrams before intervention, which increased to 16% after intervention. The perspective from which each element was drawn was preserved in 4% diagrams before intervention, which increased to 23% after intervention. However, the percentage of incoherent diagrams (1%) and diagrams with inconsistent perspective (0.85%) also increased after intervention (to 11% & 16% respectively). Students in the treatment group included more parts of the model in their drawings after the intervention. It appears that students were taking more risks in expressing ideas in drawings, and often the results were positive, but there was also an increase in errors. Further practice with diagrams may have addressed this problem.

Before intervention, students' diagrams lacked explanatory elements and elements representing motions. Their ray diagrams were not predictive but descriptive and drawn by guesswork. After intervention students started to draw more schematized diagrams in place of realistic picture-like representations and included more specific explanatory elements in their diagrams. For example, none of the diagrams included local directions and horizon before intervention but, taking an average over 3 related questions, 65% diagrams included a horizon and 64% diagrams included local directions after intervention.

Diagram-centered pedagogy is quite possible to integrate into a normal classroom without requirement of any special equipment. Blackboards, wall charts, workbooks with skeletal diagrams for problem solving and tabular formats for recording observations, are all easily provided, once diagrams are seen as an essential learning tool. Simple models and gestures to complement the diagrams, can also be integrated into classroom discourse. These measures will help bring visual and spatial thinking back into the science classroom.

# 9 Conclusions

The practice of systematic (qualitative and quantitative) observations and their representation in different forms, such as tables, graphs and diagrams, needs to be cultivated among students. Indigenous knowledge related to astronomy is present in students, and is often integrated with astrology. Careful efforts need to be taken to connect the formal and indigenous astronomy, while de-emphasizing and challenging the related belief system and superstitions. Although students learn several facts about astronomy, they fail to build consistent mental models. Sensitivity towards consistency (in depicting all the elements in a diagram from the same perspective and in showing the correct spatial relationship between them) needs to be developed among students. Understanding of dimensions (distances and sizes) and motions are the areas of key difficulty.

Our designed pedagogy and specifically, the novel attempt of designing pedagogic gestures turned out to be useful. Diagrams too were used in a novel way and the heavy reliance of this pedagogy on diagrams gave useful insights about pedagogic diagrams in astronomy. Since the analysis of gestures and diagrams in science reasoning and learning is relatively recent, developing a useful scheme for analyzing content specific diagrams and gestures was, for us, a novel and challenging task. The gesture-related research in cognitive psychology has considered spontaneous gestures. In education however, pedagogic and students' diagrams or gestures influence each other. Therefore any scheme of analysis needs to address both of these and also their mutual influence.

This study may hold implications also for laboratory studies in cognitive psychology, which usually address fairly abstract and content-lean tasks, like mental rotation and scanning, or consider simple two-dimensional mechanical situations. Problems in complex domains and real-life classroom settings may provide useful insights for cognitive psychology. The potential of multi-modality and the study of gesture and diagrams needs to be explored in science education, particularly in areas requiring significant spatial cognition, for example, chemistry, biochemistry, developmental biology, geosciences, mechanics, electromagnetism, X-ray crystallography, astronomy, etc.. The link between concrete models, activities and experiments on the one hand, and science concepts on the other hand, is likely to be facilitated through such embodied modes.

# 10 Organization of the Thesis

The correspondence between Chapter numbers of the Thesis and Section numbers in the Synopsis is given in Table 2.

Table 2: Correspondence between Chapter numbers of the Thesis and Section numbers in the Synopsis

| Chapter numbers of the Thesis | Section numbers in the Synopsis |
|---|---|
| Chapter 1 | Sections 1 & 3 |
| Chapter 2 | Section 2 |
| Chapter 3 | Sections 4 & 5 |
| Chapter 4 | Section 6 |
| Chapter 5 | Section 8 |
| Chapter 6 | Section 7 |
| Chapter 7 | Section 7 |
| Chapter 8 | Section 9 |

# References

Bailey, J. M., Prather, E. E., and Slater, T. F. (2004). Reflecting on the summary of astronomy education research to plan for the future. *Advances in space research*, 34:2136 – 2144.

Baxter, J. (1989). Children's understanding of familiar astronomical events. *International Journal of Science Education*, 11:502–513.

Bisard, W. J., Aron, R. H., Francek, M. A., and Nelson, B. D. (1994). Assessing selected physical science and earth science misconceptions of middle school through university preservice teachers. *Journal of College Science Teaching*, 24:38–42.

Brecht, B. (1947). *"Galileo" -Marathi Translation of "The Life of Galileo" by Naik, R.* (Latkar Prakashan 1997). London: Methuen and Co.

Chi, M. T. H. (2008). *Three types of conceptual change:Belief revision, mental model transformation, and categorical shift*. Hillsdale, NJ: Erlbaum.

Clement, J., Zietman, A., and Monaghan, J. (2005). *Visualization in Science Education*, chapter Imagery in science learning in students and experts, pages 169–184. Number 9. Springer.

Confrey, J. and Lachance, A. (2000). Transformative teaching experiments through conjecture-driven research design. In Kelly, A. E. and Lesh, R. A., editors, *Handbook of Research Design in Mathematics and Science Education*, number 10. LEA Publishers, Mahwah, NJ, London.

diSessa, A. A. (2006). *A history of conceptual change research: Threads and fault lines*, chapter 16, pages 265–281. Cambridge University Press.

Gentner, D. and Stevens, A. L., editors (1983). *Mental Models*. LEA Publishers, Hillsdale, NJ, London.

Gilbert, J. and Boulter, C. J. (1998). Learning science through models and modeling. In Fraser, B. J. and Tobin, K. G., editors, *International Handbook of Science Education*, pages 53–66. Kluwer Academic Publishers: Great Britain.

Gilbert, J. K. (2005). *Visualization in Science Education*, volume 1 of *Models and Modeling in Science Education*, chapter Visualization: A metacognitive skill in science and science education, pages 9–27. Dodrecht: Springer.

Goldin-Meadow, S. (2006). *Handbook of Child Psychology*, volume 2, chapter Nonverbal communication: The hand's role in talking and thinking, pages 336 – 369. John Wiley, 6 edition.

Hannust, T. and Kikas, E. (2007). Children's knowledge of astronomy and its change in the course of learning. *Early Childhood Research Quarterly*, 22:89–104.

Hegarty, M. (1992). Mental animation: Inferring motion from static displays of mechanical system. *Journal of Experimental Psychology*, 18(5):1084–1102.

Hegarty, M. (2005). The role of gestures in mental animation. *Spatial Cognition and Computation*, 5(4):333–356.

Hegarty, M. and Waller, D. (2004). A distinction between mental rotation and perspective taking spatial abilities. *Intelligence*, 32:175–191.

Jones, B. L. and Lynch, P. P. (1987). Children's conceptions of the earth, sun and moon. *International Journal of Science Education*, 9(1):43–53.

Kastens, K. A., Agrawal, S., and Liben, L. S. (2008). Research in science education: The role of gestures in geoscience teaching and learning. *Research in science education*, 54(4):362–368.

Klatzky, R. L., Loomis, J. M., Beall, A. C., Chance, S. S., and Golledge, R. G. (1998). Spatial updating of self-position and orientation during real, imagined, and virtual locomotion. *Psychological Science*, 9(4):293–298.

Klein, C. A. (1982). Children's concepts of the earth and the sun: A cross cultural study. *Science Education*, 65(1):95–107.

Kosslyn, S. M. (1994). *(1994) Image and Brain*. MIT Press: Cambridge, Massachusetts; London, England.

Lelliott, A. and Rollnick, M. (2009). Big ideas: A review of astronomy education research 1974–2008. *International Journal of Science Education*, 32(13):1771–1799.

Lemke, J. L. (1998). Teaching all the languages of science: words, symbols, images and actions. In *Conference on Science Education in Barcelona*, page last retrived on 18 Aug. 2010 (http://academic.brooklyn.cuny.edu/education/jlemke/papers/barcelon.htm).

Mali, G. B. and Howe, A. (1979). Development of earth and gravity concepts among nepali children. *Science Education*, 63(5):685–691.

Mohapatra, J. K. (1991). The interaction of cultural rituals and the concepts of science in student learning: a case study on solar eclipse. *International Journal of Science Education*, 13(4):431–437.

Narlikar, J. V. and Rana, N. C. (1997). Education in astronomy and astrophysics: an indian experience. *Advances in space research*, 20(7):1401–1404.

Nobes, G., G, M. D., Martin, A. E., Clifford, B. R., G, B., Panagiotaki, G., and Siegal, M. (2003). Children's understanding of the earth in a multicultural community: mental models or fragments of knowledge? *Developmental Science*, 6(1):72–85.

Norman, D. A. (1983). *Mental Models*, chapter Some observations on Mental Models, pages 7–14. Number 1. LEA Publishers, Hillsdale, NJ, London.

Nussbaum, J. and Novak, J. D. (1976). An assessment of children's concepts of the earth utilizing structured interviews. *Science Education*, 60(4):535 – 550.

Padalkar, S. and Ramadas, J. (2008). Modeling the round earth through diagrams. *Astronomy Education Review,*, 6(2):54–74.

Padalkar, S. and Ramadas, J. (2009). An indigenous approach to elementary astronomy - how cognitive research can help. In Subramaniam, K. and Mazumdar, A., editors, *Proceedings of Conference epiSTEME-3, Mumbai, India, 5-9 Jan 2009*, volume 3 of *Advanced Research Series*, pages 69–75, Mumbai, India. HBCSE, MacMillan.

Ramadas, J. (2009). Visual and spatial modes in science learning. *International Journal of Science Education (Special issue on 'Visual and spatial modes in science learning')*, 31(3):301–318.

Roth, W.-M. (2000). From gestures to scientific language. *Journal of Pragmatics*, 32:1683–1714.

Samarapungavan, A., Vosniadou, S., and Brewer, W. F. (1996). Mental models of the earth, sun and moon: Indian children's cosmologies. *Cognitive Development*, 11:491–521.

Schoon, K. J. (1992). Students' alternative conceptions of earth and space. *Journal of Geological Education*, 40:209–214.

Schwartz, D. L. and Black, J. B. (1996). Shuttling between depictive models and abstract rules: Induction and fallback. *Cognitive Science*, 20:457–497.

Siegal, M., G, B., and Newcombe, P. A. (2004). Culture and children's cosmology. *Developmental Science*, 7(3):308–324.

Sneider, C. and Pulos, S. (1983). Children's cosmographies: Understanding the earth's shape and gravity. *Science Education*, 67(2):205–221.

Subramaniam, K. and Padalkar, S. (2009). Visualisation and reasoning in explaining the phases of the moon. *International Journal of Science Education*, 31(3):395–417.

Trumper, R. (2000). University students' conceptions of basic astronomy concepts. *Physics Education*, 35(1):9–14.

Trumper, R. (2001). A cross-college age study of science and nonscience students' conceptions of basic astronomy concepts in preservice training for high-school teachers. *Journal of Science Education and Technology*, 10(2):189–195.

Trundle, K. C., Atwood, R. K., and Christopher, J. E. (2002). Preservice elementary teachers' conception of moon phases before and after instruction. *Journal of research in Science Teaching*, 39(7):633–658.

Tversky, B. (1999). What does drawings reveal about thinking? Invited talk at First International Workshop on Visual and Spatial Reasoning in Design, Cambridge, MA, June, 1999.

Tversky, B. (2001). *Spatial Schemas and Abstract Thought.*, chapter Spatial schemas in depiction. Cambridge: MIT Press.

Tversky, B. (2005). *The Cambridge Handbook of Thinking and Reasoning*, chapter Visuospatial reasoning, pages 209–240. Number 10. Cambridge, MA: Cambridge University Press.

Vosniadou, S. and Brewer, W. F. (1992). Mental models of the earth: A study of conceptual change in childhood. *Cognitive Psychology*, 24:535–585.

Vosniadou, S. and Brewer, W. F. (1994). Mental models of the day/ night cycle. *Cognitive Science*, 18:123–183.

Vygotsky, L. S. (1978). *Mind in Society.* Cambridge, MA: Harvard University Press.