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## RESEARCH REPORT

# Designed and Spontaneous Gestures in Elementary Astronomy Education

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We make a case for using gestures and actions to understand and convey spatial and dynamic properties of systems. Problems in learning elementary astronomy are analysed in the context of demands of spatial thinking, in a system which is not amenable to direct perception, namely, the sun–earth–moon (SEM) system. We describe a pedagogy which uses gestures (most often in combination with concrete models and diagrams) to facilitate the visualisation and simulation required in elementary astronomy. These gestures are presented in terms of their purpose in pedagogy: to internalise a natural phenomenon, or an astronomical model, or general properties of space. In terms of design these pedagogical gestures mediate between concrete models of the SEM system and related spatial configurations on the one hand, and their corresponding abstract diagrammatic representations on the other: called here the model–gesture–diagram pedagogical link. Next we present some video data on students' gestures observed during collaborative problem-solving which took place in the course of our pedagogic intervention. Implications of these results are drawn for embodiment and multimodality of thought.

Keywords: *Astronomy education; Gestures; Model-based reasoning*

## Introduction

Elementary astronomy is an area prone to difficulties and misconceptions for students as well as adults (Bailey, Prather, & Slater, 2004; Lelliott & Rollnick, 2010). Models in elementary astronomy are built on spatial information such as shapes, sizes, distances, and patterns of motion of astronomical bodies. Understanding astronomy therefore should be facilitated by better spatial understanding. Two widely used spatial tools in science education are concrete (physical) models and

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diagrams. In this paper we introduce gestures, a relatively less used and less researched tool for spatial understanding in elementary astronomy.

Gestures have been identified as a powerful cognitive resource and their potential for learning is currently a topic of discussion in cognitive and developmental psychology. This discussion needs to be brought into science education, in order that the potential of gestures for teaching of subjects with significant spatial challenge (e.g. chemistry, mechanics, geology, and astronomy) begins to be exploited.

Assuming that gestures might be a useful spatial tool in learning elementary astronomy, we might ask, what cognitive functions do gestures serve in understanding elementary astronomy? Can we design gestures to teach elementary astronomy? What kind of content related gestures do students use spontaneously?

We address these questions in the following three parts of this paper:

(1) A literature review on the relation between spatial cognition, gestures, and science understanding, which provides the basis for our pedagogical intervention.
(2) A rationale and description of the astronomy-related gestures that were designed and used by the teacher-researcher as part of this pedagogy and,
(3) Data on students' spontaneous gestures that occurred during the course of the intervention.



## Spatial Cognition, Gestures, and Science Understanding

Understanding of space is essential to our survival. In pre-historic times skills of navigation were needed in order to track and hunt prey, locate and grasp food, avoid predators, and to design tools, houses and landscapes. Today spatial competence is required for everyday activities, and in specialised professions such as architecture, sculpture, sports, engineering, surgery, and in other areas of pure and applied science.

According to Piaget and Inhelder (1948/1956) understanding of spatial relations develops at two levels: perceptual space, and level of thought and imagination. Perceptual space develops predominantly through visual and haptic modes. Experimental studies confirm that the child's understanding of space develops through an interaction between visual and kinaesthetic-tactile experiences. The progressive use of environment-centred cues, leading towards the representation and coding of space that is not directly perceptible, indicates development in understanding of space at the level of thought and imagination, shaped through an interplay between visual and motor experiences (Newcombe & Learmonth, 2005).

Neurobiological studies confirm the link between visual-perceptual and motor experiences. Mental rotation tasks activate motor areas in the brain (Wraga, Thompson, Alpert, & Kosslyn, 2003) and complex visuo-spatial reasoning particularly is acknowledged to have not only perceptual but also motor foundations (Tversky, 2005). Blind subjects encode visuo-spatial stimuli through haptic input and by forming spatial more than visual mental representations (Vanlierde &

Wanet-Defalque, 2004). The significance of motor perception in our spatial understanding, and the use of body configurations to express movement, brings to attention the role of gestures and actions in capturing spatial, temporal, and dynamic aspects of the world.

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). Tasks calling for changing one's own orientation (heading) by imagination are greatly facilitated with use of kinaesthetic feedback, by carrying out the body motions required for that orientation change, even without the use of vision (Klatzky, Loomis, Beall, Chance, & Golledge, 1998).

Perception has limitations at very small and very large scales. Distances from a few millimetres to a few kilometres can be perceived through our direct senses, but microscopic distances of nanometres to fractions of millimetres and vast distances of the order of thousands of kilometres or even light years, are beyond our bodily apprehension. For such spaces we take the help of external representations like models, maps, and diagrams. To create functional internal representations of spaces beyond sense perception, one needs effective mediating cognitive activities. Building and manipulating concrete models, and constructing diagrams, preferably from multiple perspectives, are activities that might possibly facilitate the transition from external to internal representations. Interactive computer simulations are sometimes designed to play this role. However, the haptic and kinaesthetic affordances of computer simulations are limited in scope. We propose the use of gestures and body movements as cognitive tools to help apprehend space, specifically space that is beyond perception, a view that fits well within the theoretical frameworks of multimodality and embodied cognition (Barsalou, 1999; Clark, 1997).



### *Gestures as a Tool for Communication*

Gestures are produced as a part of intentional communicative act which usually involves speech (Goldin-Meadow, 2006a). They are produced by speakers from all cultural and linguistic backgrounds. Blind speakers also gesture, showing that gestures need not be learnt by imitation. They gesture even when speaking to a blind listener, showing that gestures require neither a model nor an observant partner. Gestures produced by blind people convey spatial information similar to those produced by sighted people (Ferris & Palenik, 1998; Iverson & Goldin-Meadow, 2001).

Vygotsky (1978) proposed that the child embellishes his first words with highly expressive gestures, which may compensate for his initial difficulty in communicating meaningfully through language. Goldin-Meadow (2006a, 2006b) and Singer and Goldin-Meadow (2005) show that gestures in students and adults may convey information that is independent of, or complementary to speech. Paying attention to gestures would not only provide information about the thinking process, which is not obvious from verbal discourse, but also, gestures may be designed so as to convey information that is not easily conveyed through speech.

*Designed Gestures for Pedagogy*

The use of gestures in instruction is recently being recognised in mathematics education. Wagner-Cook and Goldin-Meadow (2006) worked with pre-designed deictic gestures during instruction on solving math problems. Meaningful gestures produced by the teacher were found to increase both the type and number of the gestures produced by students. Students who were instructed using both speech and gestures benefited more than the students who were instructed only through speech, although explicit instructions to merely copy the gestures did not prove to be beneficial. The authors concluded that copying the instructor's hand movements can help children to solve problems but only if they understand what those movements stand for. A recent special issue of *Educational Studies in Mathematics* (Radford, Edwards, & Arzarello, 2009) brings together the arguments and evidence for the importance of gestures in maths education.

Some science teachers spontaneously use gestures and body movements to convey spatial-temporal concepts. However, we are not aware of any systematic documentation of such gestures in science education. We are also not aware of any research on specifically designed gestures for teaching science.

*Spontaneous Gestures in Science Learning*

Gestures are recognised as a form of non-verbal behaviour that is closely related to the content of a conversation.

The supporting role of spontaneous gestures in scientific thinking is indicated by studies which show that people use their hands while solving problems of mechanical reasoning (Hegarty, 2005; Schwartz & Black, 1996). Kastens, Agrawal, and Liben (2008) conclude, from a review of the literature and their own studies, that gestures are important to both learners and experts as they think about, and communicate about, spatially complex structures and processes that are common in the geosciences. In inquiry-based science learning, deictic and iconic gestures are found to precede and lead verbal scientific discourse. As students get more familiar with the domain, their gestures begin to coincide with talk. Gestures are precursors to arrows in scientific diagrams (Roth, 2000). Imagery-related behaviours in physics problem-solving include personal action projections—that is, spontaneously re-describing a system of actions (consistent with the use of kinaesthetic imagery), depictive hand, or pencil motions—and reports of static or dynamic imagery (Clement, Zietman, & Monaghan, 2005).

Crowder (1996) studied sixth-grade students' gestures while explaining the occurrence of seasons. She contrasted 'explaining in-the-moment', to predict, revise, and coordinate elements in a model, with describing a memorised or previously thought model. The in-the-moment explainer stepped into the gesture space, assuming an insider perspective, whereas students who described a memorised model timed their gestures to redundantly emphasise speech.

Subramaniam and Padalkar (2009) have found that educated adults used gestures while attempting to explain the occurrence of phases of the moon, particularly in cases where they did not know the correct explanation to begin with, and therefore had to reason through the situation. They found that imagined situations involving anthropomorphic models, for example a friend's half-lit face, are more effective than configurations replacing the friend's face with a half-lit ball, despite the fact that the latter model is more akin to the physical situation of a half-lit moon. Thus quite apart from the kinaesthetic feedback engendered by gestures, their anthropomorphic nature may help in visual and spatial learning.

There exist several different schemes of classification of spontaneous gestures. McNeill (as described in Radford et al., 2009) classified gestures into five types: 'deixis' (pointing to existing or virtual objects); 'metaphoricity' (referencing an abstraction); 'iconicity' (a form directly related to the semantic content of speech); 'temporal highlighting' (simple repeated gestures used for emphasis) and 'social-interactivity' ('affect displays', 'regulators' and 'adapters' as per the classification scheme described by Goldin-Meadow, 2006a). According to Roth (2000), 'deictic' gestures make salient an object which is the topic of the speaker's communication while 'iconic' gestures transparently depict aspects of objects or events that are difficult to put into words. Important for science learning are the first three of the above categories of gestures, 'deixis', 'metaphoricity', and 'iconicity', which are directly linked with the content of the discourse, made with conscious intent, and have the potential to convey scientific information. The existing classification schemes however need some modifications to take account of spatial information that is conveyed by gestures in science and astronomy.



## Understanding Astronomical Space

Elementary astronomy begins with positioning oneself on the earth, then positioning the earth and other prominent celestial objects in space, and positioning the planetary system in the universe. Regular and accurate observations of daily astronomical phenomena such as day-night, seasons, phases of the moon, eclipses and occultations, and changes in positions of stars and planets over the year are hardly sufficient for forming a basic mental model of the solar system. Even a qualitative model incorporates knowledge of the relative shapes, sizes, angles, distances, speeds, and patterns of movement of the celestial bodies: details that would be difficult to deduce from earth-based astronomical observations.

Historically, although fairly accurate observations and empirical rules of prediction of daily phenomena were available in many ancient civilisations, multiple cosmologies existed to explain these phenomena. Copernicus and Galileo faced opposition to their models not only on religious grounds but also, perhaps, due to the challenge of spatial thinking entailed by their theories. The discovery of planetary motion was driven as much by careful observations of natural phenomena that is the manifestations of this model, as by a series of leaps of imagination, supported by cognitive abilities such as switching frames of reference, spatial transformations, taking account of multiple evidences, and linking observations with model through corrective feedback loops.

Today the model of the spherical earth and the heliocentric model of the solar system are granted as a part of our common cultural understanding. Children are formally exposed to the round moving earth as early as seven years of age. Explaining daily astronomical phenomena using this model is a part of basic scientific literacy. We expect students to believe that the earth is round, it rotates, and it revolves around the sun.

But consider communities and groups of people who are not too exposed to modern science, or illiterate communities with no access to written knowledge, or inadequate access to communication media. Children from these backgrounds might find it difficult to accept the idea of a round rotating earth. Authoritative teaching practices may force them to produce expected answers, but one doubts whether those conceptual changes of great historical and scientific import might have indeed taken place.



Secondly, consider the fact that if children, even those who are exposed to the heliocentric model, try to construct a mental model based on their own experiences, it would be in conflict with the scientifically accepted model. We do observe a flat earth and all the celestial bodies moving around us. Evidence for such intuitive models, as well as of models which are made by synthesis of the intuitive and scientific models, has been found in young children (Vosniadou & Brewer, 1992). Students as well as educated adults have problems in understanding the heliocentric model and cannot explain daily astronomical phenomena (Baxter, 1991; Padalkar & Ramadas, 2008b; Subramaniam & Padalkar, 2009; Trundle, Atwood, & Christopher, 2007).

The third major difficulty is in imagining the vast sizes and distances in astronomy, which are essential to constructing spatial mental models (Feigenberg, Lavrik, & Shunyakov, 2002). Students often have little idea of the larger units of measurement. Astronomical dimensions begin from an order of magnitude of thousands of kilometres distances that are handled by using ratios and assumptions like, 'rays from a distant source are parallel'. All these problems of spatial thinking that must be resolved in a constructive way by providing access to experiences, evidences and arguments that are accessible to students.

## Research Design

This study is in the tradition of design-based, or conjecture-driven research (Brown, 1992; Confrey & Lachance, 2000), belonging to a group of research methods recommended by Lesh, Lovitts, and Kelly (2000) which 'have proven to be especially productive for investigating the kinds of complex, interacting, and adapting systems that underlie the development of mathematics or science students and teachers, or for the development, dissemination, and implementation of innovative programmes of mathematics or science instruction' (p. 17).

The study occurred in the context of a larger research project in which, first, Grade 4 and Grade 7 students' astronomical knowledge in four areas (observational, factual, cultural, and conceptual) was assessed before intervention. These tests showed that students, even at the age of 14 years, had incomplete and fragmented knowledge of astronomy. They had not formed a coherent mental model which could serve as a basis for explaining the given astronomical phenomena. Their observations about daily phenomena were also found to be incomplete and inaccurate (Padalkar & Ramadas, 2008b).

The intervention began with students who were about to complete Grade 7, and finished when they were about to complete Grade 8 (average age: 14 year, range 12.5–16.9 in the middle of the intervention). The first author who had no previous teaching experience carried out the teaching, which occurred in three parts of 15 days (each with 10–15 sessions of one and half hour including a short break). The pedagogy used concrete models, observations of phenomena, gestures/actions, and diagrams as spatial tools to help students construct a mental model of the sun–earth–moon (SEM) system and to explain phenomena on its basis (Padalkar & Ramadas, 2008a). The specific gestures in the three parts of the intervention are presented in Parts I, II, and III of Table 1. Between two parts of the intervention (separated by about five months gap) students were asked to keep records of astronomical observations and to complete home-work assignments.

As detailed in 'The Conjecture', gestures were used in conjunction with concrete models and diagrams, to teach the SEM system and explanations for day-night, shadows, seasons, eclipses, phases of the moon, and so forth.



### *Sample*

The sample for intervention consisted of three Grade 8 classes (total of 80 students) from three different schools in India from different but comparable backgrounds: 35 rural and 28 tribal (intact classes) and 17 urban-slum (volunteer students). Students from all three schools are either first-generation learners or have parents with minimal education. 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. The rural students come from an agrarian community whereas the tribal students come from nomadic tribes and attend a residential school run by a socially progressive organisation with leadership from within the community. The socio-economic status and educational background of the tribal students is lower than that of rural students (Padalkar & Ramadas, 2009).

### *Data Collection*

Problem-solving was an integral part of the intervention. Students' spontaneous gestures were observed in the course of guided collaborative problem-solving, within a naturalistic classroom setting with students working in mixed ability groups of three. Over the course of five classroom sessions these groups solved a graded sequence of problem tasks. Students in each group discussed the problems, negotiated the solutions on rough paper, and finally wrote and drew their consensus solutions. The questions and diagrams in the tasks were based on the content addressed and the anticipated conceptual problems. For details see 'Nature of Tasks'. Video data on spontaneous gestures was collected only for two groups of three students, one group of three boys (TB1, TB2, TB3) in the tribal classroom (TB group) and a group of three girls (RG1, RG2, RG3) in the rural classroom (RG group). The camera was placed 1 m away at a slightly higher level than the heads of the students. Each group contained one student with relatively high pre-instruction scores and better engagement in the classroom. The aim was neither to identify representative groups nor to draw comparison between the two selected groups. The duration of this video data was 263 minutes for the TB group and 231 minutes for the RG group.



## The Conjecture

This paper is motivated by the five research questions given below. The first two of these questions are addressed in this section and in the next section ('Designed Pedagogic Gestures'). They are addressed through argument and examples rather than through data. The next three questions are investigated empirically using the video data (section 'Students' Spontaneous Gestures').

(1) What can be a reasoned basis for designing gestures for teaching astronomy?
(2) How should these gestures be placed in relation to other common spatial tools?
(3) What types of spontaneous gestures are produced by students during collaborative problem-solving?
(4) Do these gestures vary according to the problem tasks?
(5) How do students' spontaneous gestures compare with the pre-designed gestures used in the intervention?

In model-based reasoning, concrete models, diagrams and gestures are all spatial tools, which represent either the phenomenon or the mental model, and further help to link the phenomenon with the mental model. Our conjecture about the role of gestures in astronomy, which guided the design of pedagogical gestures, has two dimensions as illustrated in Figure 1.

The vertical dimension in Figure 1 addresses Research Question 1. The connections suggested in this dimension are motivated by the limitation of perception for comprehending astronomical models. Gestures represent, communicate, and most importantly internalise the spatial-temporal properties of the scientifically accepted models and their related phenomena. 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 (these intended functions are elaborated with examples in the subsection 'Purpose of the Gestures'). Also one goes to and fro from one's mental model

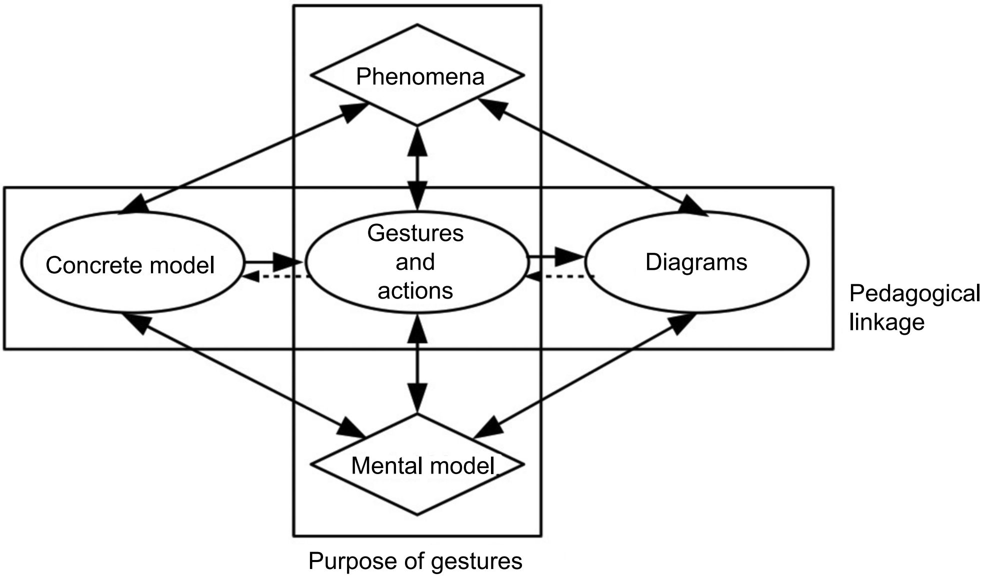


Figure 1. Purpose of gestures in linking phenomena with mental models and their pedagogical role in linking concrete models with diagrams



to the phenomenon, in order to refine one's understanding, a process indicated by the two-way vertical arrows in Figure 1. We call this the 'mental model–gesture–phenomenon' link of our conjecture. Its instances are indicated in Table 1 in the column 'Purpose'.

The horizontal dimension of our conjecture, shown in Figure 1, addresses Research Question 2. The motivation for these connections comes from 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 (Mishra, 1999). Concrete 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 2 summarises the properties that gestures share with concrete models and diagrams to hypothesise that gestures could provide a possible link between concrete models and diagrams. Figure 2 is an elaboration of our rationale for the 'concrete model–gesture–diagram' link in Figure 1. The arrows in it indicate the shared properties of gestures with either concrete models or diagrams. Instances of this link are indicated in Table 1 in the column 'Type of linkage'.

Given the economical and abstract nature of diagrams, the desired direction of the 'concrete model–gesture–diagram' link in Figure 1 is from concrete models towards

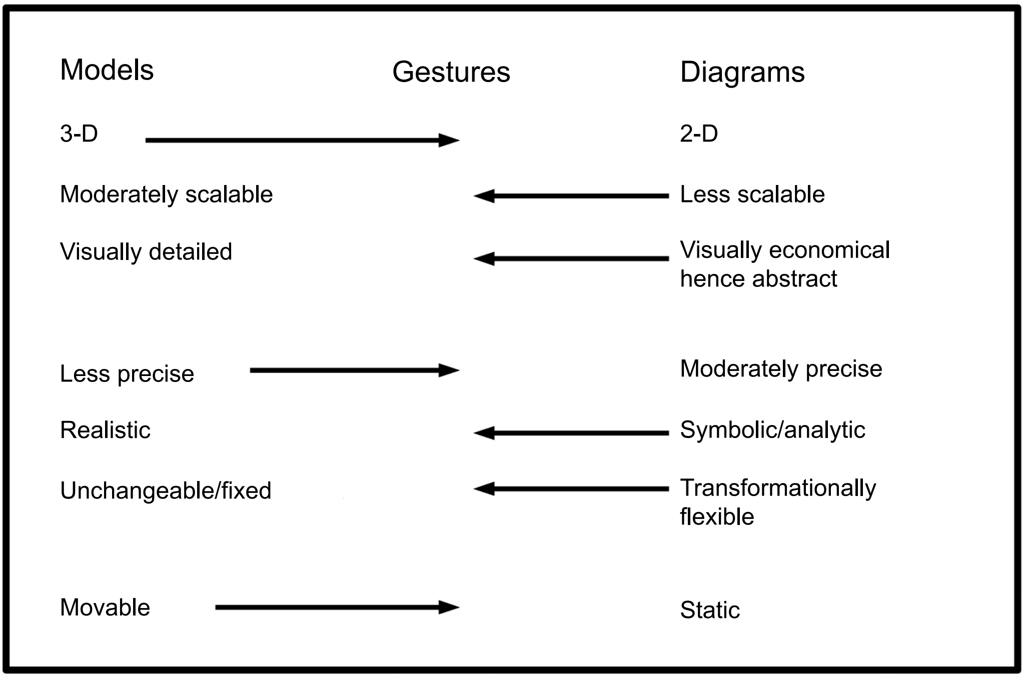


Figure 2. Gestures can be used to link concrete models with diagrams; arrows denote the properties that gestures share with either concrete models or diagrams

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 1.

In Figure 1, the focus of our interest is the central cell, 'Gestures and Actions'. However, links such as 'mental model–concrete model–phenomenon' or 'mental model–diagrams–phenomenon' and extended links such as 'mental model–concrete model–gesture–phenomenon' or 'mental model–gesture–diagram–phenomenon' are also possible, as indicated by the oblique arrows in Figure 1. Figure 1 may be modified to place any learning tool in the context of other tools; for example, the central cell 'Gestures and Actions' might well be substituted or complemented by Verbal (e.g. 'speech' or 'writing') or other Visual media.

## Designed Pedagogical Gestures

Table 1 lists 40 groups of gestures and actions (body configurations) aimed at illustrating a set of spatial concepts. These are metaphorical or iconic gestures designed to communicate specific spatial content to help students construct a dynamic mental model. The order of gestures is aimed at progressively introducing complexity in the model, and follows the order of teaching for the most part. Some gestures were carried out as an activity or a part of activity. As seen in Table 1, some of these were not 'gestures' but 'actions' during activities which gave kinaesthetic feedback. Some were whole body actions performed by individuals or groups, while others were performed in the presence of concrete props or diagrams. Video clips linked with Table 1 are at http://web.gnowledge.org/pedagogic-gestures/.

Typically, the teacher performed a gesture along with or after introducing a concrete model, and students were asked to imitate the gesture. Students were then asked to perform similar gestures for slightly different conditions. Then the same gesture was performed along with a diagram or leading up to a diagram. For example, the direction of rotation of the earth was shown by the direction of curl of fingers while aligning the right-hand-thumb with the axis near the North Pole (Gesture no. 13). The direction thus determined was shown to be consistent with the 'West to East' direction as identified by an earlier gesture (Gestures no. 12). Then students were asked to determine the direction of rotation of the earth for different orientations of the globe and for diagrams of the earth from different perspectives.

The number in the first column in Table 1 gives the placement of the gestures or actions in our pedagogical sequence. The second column gives the context of use, or the concept to be understood, along with the necessary concrete tools. The third column describes the specific gesture or action. The fourth column, 'Purpose', is derived from the 'mental model–gesture–phenomenon' link of our conjecture. It is further explained in the next sub-section, 'Purpose of the Gestures'. The fifth column of the Table 1 specifies whether the gesture communicates a static or a dynamic property of the system. The last two columns, labelled 'Type of linkage' and 'Stand-alone', are derived from the 'concrete model–gesture–diagram' link in our conjecture. These two columns are further analysed in the sub-section 'Gestures as a Link between Concrete Models and Diagrams'.

Besides these deliberately designed gestures, many fleeting metaphorical and deictic gestures occurred spontaneously during teaching as part of natural communication, which are not listed in Table 1. Of the deictic gestures used in the pedagogy a small number, which were designed to convey significant information (Gesture nos. 7, 10, 15, and 32 in Table 1) are considered in the analysis of pedagogical gestures.

Figure 4 summarises the classification of gestures according to their purpose and whether they convey a static or dynamic property, along with the number of gestures in each category.

### *Purpose of the Gestures*

The 'purpose' of the gestures, that is its intended function in the 'mental model–gesture–phenomenon' link of our conjecture, is specified in column 4 of Table 1. All of the gestures were meant to facilitate the internalisation of spatial and temporal properties. Spatial properties in relation to the SEM system could be derived from first-hand observation of a phenomenon from the earth (Ph. I.), or they could be inherent to the relevant astronomical model (Model I.). Through a set of supporting activities, we also addressed some general (Euclidean) properties of space which were not specific to this system (Space I.).

Table 1. Gestures and actions in our pedagogy

| Gesture no. | Context or concept +(accompanying tools) | Gestures and actions | Purpose | Static/ Dynamic | Type of linkage | Stand-alone |
|---|---|---|---|---|---|---|
| | | *Part I: Round rotating earth* | | | | |
| 1 | Night sky observation | Tracing star patterns by fingers/hands. | Ph. I. | S | G-D | N |
| 2 | Determining position (direction + degrees above horizon) of a star | Directions in local environment by extended arm. Angles estimate by fist/palm and arm. | Space I. | S | G-D | Y |
| 3 | Showing round earth by hand (photographs of the earth, globe) | Moving hands with palms open to show sphere. | Model I. | S | CM-G | Y |
| 4 | Showing round part of spherical earth on circular earth on the blackboard (Figure 3) | Moving arm with open curved palm to show half sphere of the earth coming out of the blackboard, imagining circle as circumference of the earth and other half sphere inside the black board. | Model I. | S | G-D | N |
| 5 | Understanding flatness of the earth (balls of different sizes) | Holding or imagine to be holding a very small to a very large ball and observe the change in curvature on palm and then arm. | Model I. | S | CM-G-D | Y |
| 6 | Axis of rotation (notebook, pencil box, other objects) | Rotating objects and body parts and identifying axis of rotation. | Space I. | D | CM-G-D | Y |
| 7 | Axis coming out of, or going inside the plane of diagram (Figure 3b) | Index finger pointing inside or outside, perpendicular to the diagram. | Model I. | D | G-D | N |
| 8* | Gestures in play 'Galileo' to mimic the earth's rotation and perspective changes (rotating chair) | Sitting on a rotating chair to see occurrence of day–night. | Model I. Ch.Ori. | D | CM-G | N |
| 9* | Gestures in play 'Galileo' to mimic the earth's rotation, perspective changes, and up-down (apple, toothpick) | Assuming apple to be the earth, and radially attached tooth-pick as a human. Rotating the apple around the axis passing through its stem to see day–night. | Model I. Ch.Ori. | D | CM-G-D | Y |
| 10 | Showing motion of the earth for the axis in the given diagram (axis either in the plane of diagram [Figure 3a] or perpendicular to it [Figure 3b]). | (a) Showing a vertical index finger in horizontal circle in front of blackboard (or in half circle, with axis as centre).<br>(b) Moving a horizontal index finger in a vertical circle around a point on the blackboard. | Model I. | D | G-D | N |

Table 1. (*Continued*)

| Gesture no. | Context or concept +(accompanying tools) | Gestures and actions | Purpose | Static/ Dynamic | Type of linkage | Stand-alone |
|---|---|---|---|---|---|---|
| | | *Part I: Round rotating earth* | | | | |
| 11 | Determining directions (down, up, north, south) of a person on the globe or in diagram of the earth (Figure 3a) | Down: pointing index finger towards centre of the earth.<br>Up: pointing index finger away from centre of the earth.<br>North: towards North Pole.<br>South: towards South Pole. | Model I. Ch.Ori. | S | CM-G-D | N |
| 12 | Determining directions (east, west) of a person on the globe or in diagram of the earth (Figure 3b) | East: orienting orienting one's self parallel to the north-facing person in the diagram so that the right hand indicates east in the diagram, or find the direction of motion of the earth (west to east) with right hand thumb rule. East is indicated by the direction of curl of the fingers (Gesture no. 13).<br>West: opposite to east. | Model I. Ch.Ori. | S | CM-G-D | N |
| 13 | Right hand thumb rule for determining direction of motion of the earth | Gesture of thumbs-up. In Figure 3, align thumb of the right hand in the direction of axis and pointing towards the North Pole, then curl the fingers to show the direction of earth's rotation (or revolution) (west to east). | Model I. | D | CM-G-D | N |
| 14 | Shadows and beams (cardboard cutouts, sunlight, torch, gnomon) | Shadow created by fingers to shadow of the body. | Ph. I. | S | CM-G-D | Y |
| 15 | Tracing ray diagrams | Tracing path of light-beam/ray by open palm (representing wave front)/finger on board. | Model I. | D | G-D | N |
| 16 Pair | Day night (globe/geosynchron) | One student becomes the earth, another student (or object) becomes the sun. Mark the objects around in egocentric frame (front/back/left/right). Observe how the field of vision and positions of objects change due to rotation from right to left. | Model I. Ch.Ref. Frame | D | CM-G-D | Y |

Table 1. (*Continued*)

| Gesture no. | Context or concept +(accompanying tools) | Gestures and actions | Purpose | Static/ Dynamic | Type of linkage | Stand-alone |
|---|---|---|---|---|---|---|
| | | *Part I: Round rotating earth* | | | | |
| 17 | Tracing path of the sun by extended arm. Simulating motion on different latitudes | Move the stretched hand in vertical or inclined half circle from east to west. Inclination towards north or south depending upon whether one imagines herself in the southern or northern hemisphere. | Ph. I. | D | G-D | Y |
| 18 | Position of the pole-star remains the same | Fix a point vertically overhead on the ceiling and check whether its position changes while rotating around the vertical body-axis. | Model I. Ch.Ref. Frame | D | CM-G-D | Y |
| | | *Part II: Sun–earth system* | | | | |
| 19 | Measurement (6-inch scale, foot-scale, meter-scale) | Measuring 1mm to few meters by using body parts. | Space I. | S | CM-G-D | Y |
| 20 | Angle (protractor) | Rotating hand from 0° to 180°. | Space I. | D | CM-G-D | Y |
| 21 | 1, 2, and 3 dimensions (model of three axes, other daily examples, locating an address) | Length: walking.<br>Area: flat palm.<br>Volume: filling up. | Space I. | S | CM-G-D | Y |
| 22 Pair | Rotation + Revolution gives motion of the earth | Only rotation (facing changes); only revolution (facing does not changes); 1 rev + 1 rot; 1 rev + 2 rot; 1 rev + 4 rot; imagine 1 rev + 365 rot. | Model I. Ch.Ref. Frame | D | G | Y |
| 23* | Shape of orbit of the earth (nails, thread, thermocol sheet) | Drawing ellipses using two nails: a series of diagrams which give kinesthetic feedback. | Model I. | D | G-D | N |
| 24* | Understanding ellipse with circle and line as extreme cases | Making circle, ellipse, and line by joining palm. | Space I. | S | G-D | Y |
| 25* | Perspective view of circle (bangle, bucket, other circular objects) | Observing loop made by thumb and index finger (or other objects) from top, side, and oblique view. | Space I. | S | CM-G-D | Y |
| 26* | Angle made by the earth's axis with the ecliptic plane | Show axis tilt by forearm bent at elbow. | Model I. | D | G-D | Y |

Table 1. (*Continued*)

| Gesture no. | Context or concept +(accompanying tools) | Gestures and actions | Purpose | Static/ Dynamic | Type of linkage | Stand-alone |
|---|---|---|---|---|---|---|
| | | *Part II: Sun–earth system* | | | | |
| 27 | Plotting the sun–earth distance on the ground (marbles, measuring tape, thread for measurement, chalk) | Find out ratios of distances considering an earth of diameter 1 cm and plot them on the ground. | Model I. | S | CM-G | Y |
| 28 Group of 10 | Solar system (picture of solar system, chart of distances and speeds) | Each student becomes one planet and revolves around the student who is the sun, taking account of the relative speeds. | Model I. Ch.Ref. Frame | D | CM-G-D | Y |
| 29 Group | Changes in the night sky over the year (calendar) | One student becomes the sun, another becomes the earth, and revolves around the sun. All other students become different *nakshatras* representing a star background. Students predict which Marathi month and which solar *nakshatra* is on, depending upon the position of the earth. | Model I. Ch.Ref. Frame | D | G-D | Y |
| 30 | Intensity changes as a function of angle of incidence | Put your hand above hot lamp (or in rain) in different orientation, to sense that collection of heat (or water) depends on angle of incidence. | Ph. I. | S | G-D | Y |
| 31 | Trace path of the sun in different seasons | Trace a semicircle with a stretched arm making different angles with horizon depending upon the season. | Ph. I. | D | G-D | Y |
| | | *Part III: The sun–earth–moon system* | | | | |
| 32 | Angle | Pointing and tracing acute, right, and obtuse angles in room, finding out parallel lines. | Space I. | S | CM-G-D | Y |
| 33 Pair | We see only one face of the moon | Only rotation, only revolution, both rotation and revolution together. | Model I. Ch.Ref. Frame | D | CM-G-D | Y |
| 34 | Phases of moon and eclipses | Rotating the ball around one's head in tilted orbit, with a strong light source on one side. | Model I. Ch.Ref. Frame | D | CM-G-D | Y |

Table 1. (*Continued*)

| Gesture no. | Context or concept +(accompanying tools) | Gestures and actions | Purpose | Static/ Dynamic | Type of linkage | Stand-alone |
|---|---|---|---|---|---|---|
| | | *Part III: The sun–earth–moon system* | | | | |
| 35 Pair | Phases of moon | Replace the ball by friend and watch friend's face (this sequence is explained in Subramaniam and Padalkar, 2009). | Model I. Ch.Ref. Frame | D | G | Y |
| 36 | Tilt in the moons orbit explains why there are no eclipses on all full and new moon nights | Showing tilt of moon's orbit by moving extended arm around (with or without ball in the hand). | Model I. | D | CM-G-D | Y |
| 37 Pair | Phases of moon and eclipses | Moving around the friend considering one's head as the moon and the friend's head as the earth. | Model I. Ch.Ref. Frame | D | G-D | Y |
| 38 Triad | Sun–earth–moon system | Moon moving around the earth while earth moving around the sun. | Model I. | D | G-D | Y |
| 39 Pair | Moon takes two extra days to complete the orbit with respect to the sun than with respect to the background sky | Moon moves around the earth while the earth forwards (considering the earth's orbit to be almost straight and the sun to be very far away). | Model I. Ch.Ref. Frame | D | G-D | Y |

Table 1. (*Continued*)

| Gesture no. | Context or concept +(accompanying tools) | Gestures and actions | Purpose | Static/ Dynamic | Type of linkage | Stand-alone |
|---|---|---|---|---|---|---|
| | | *Part III: The sun–earth–moon system* | | | | |
| 40 Group | Connection between apparent motion of the moon and indigenous months and *nakshatras* (calendars) | Moon moving around the earth against the background of stars behind (arrangement similar to gesture no. 29). | Model I. Ch.Ref. Frame | D | G-D | Y |

Key for Table

*Purpose*

Space I.: Gestures used for 'Space Internalisation'
Ph. I.: Gestures used for 'Phenomenon Internalisation'
Model I.: Gestures used for 'Model Internalisation'
Ch.Ori.: Change of Orientation
Ch.Ref. Frame: Change of Reference Frame

*Type of linkage*

CM-G: Gestures follow 'Concrete Models'
G-D: Gestures lead to 'Diagrams'
CM-G-D: Gestures follow 'Concrete Models' and lead to 'Diagrams'

*Stand-alone*

Y: Gesture can be done in absence of concrete model or diagram
N: Gesture has to be done in presence of concrete model or diagram

*Static/Dynamic*

S: Gesture conveys a static property
D: Gesture conveys a dynamic property

Gesture numbers marked with an asterisk were done at a different point in the sequence, but they are placed in Table 1 where they are thought to be more appropriate

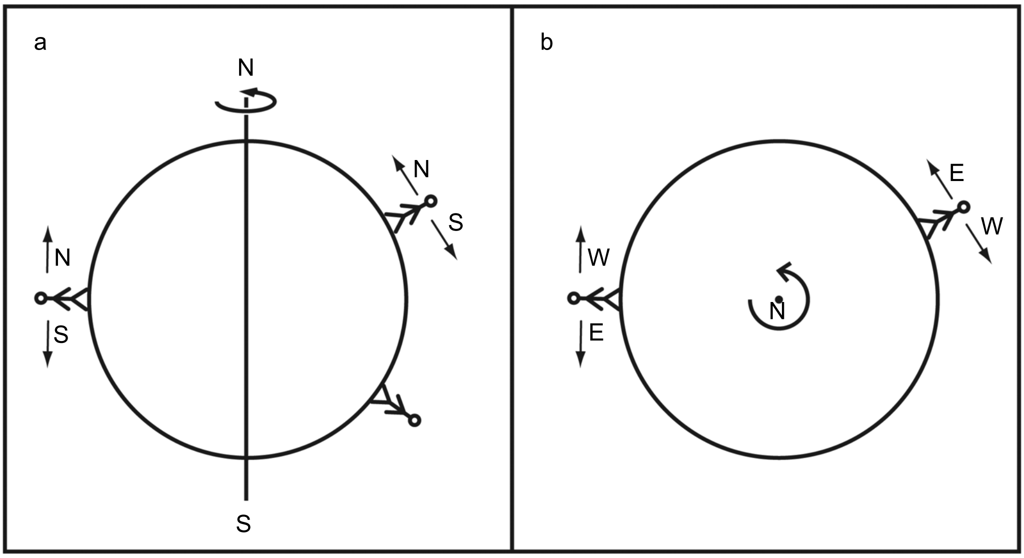


Figure 3. Determining directions for a person on globe: (a) Earth viewed from the plane of the equator; (b) Earth viewed from above the North Pole



*I. Internalising the phenomenon (Ph. I.).* Five out of the 40 (nos. 1, 14, 17, 30, and 31) sets of gestures were meant to enable internalising a phenomenon. Three of them illustrated static or almost-static properties, as in mimicking or tracing star patterns with configurations of fingers and hands (Gesture no. 1), casting shadows using parts of the body in different orientations (Gesture no. 14), and using the palm to detect changes of heat intensity with orientation (Gesture no. 30).

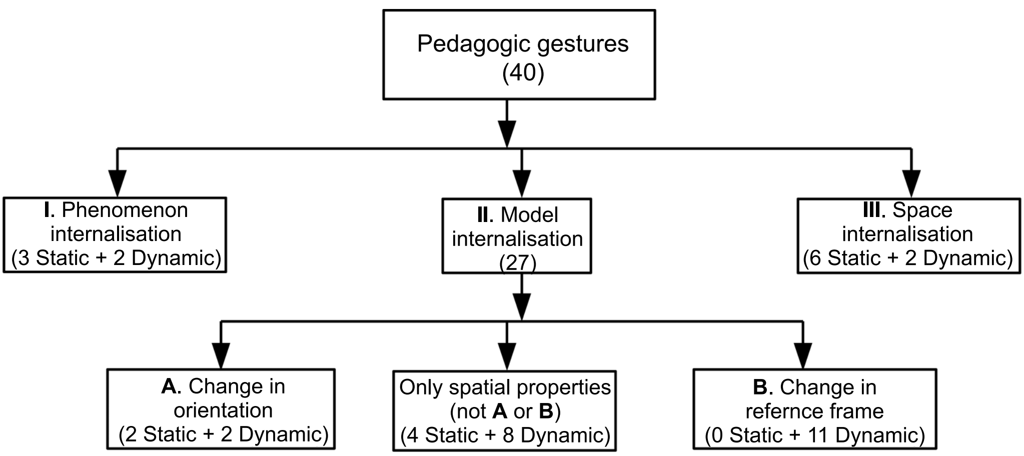


Figure 4. Tree-diagram for types of pedagogical gestures derived from columns 4 (Purpose) and 7 (Static/Dynamic) of Table 1

The other two of the five sets of gestures were dynamic, illustrating motion of the sun or the stars across the sky (Gesture nos. 17 and 31). These motions, sometimes done in the presence of concrete models of the globe or geosynchron (Monteiro, 2006; Padalkar & Ramadas, 2008a), related immediate observation to imagined observations, in one case from different latitudes, and in the second case to observations in different seasons.

The expectation motivating these gestures was that they would help students, while observing the phenomenon to internalise it, or achieve 'ownership' of it, through their body configurations. In the case of dynamic phenomena (relating to motions in the sky), learning of these body motions in turn would enable later enactment in the absence of that phenomenon. Repeated observations and enactment would, we hoped, help students understand and internalise the patterns in the phenomenon, for example, the path of the sun over the day from East to West at different latitudes (Gesture no. 17), and how this path moves North or South over the year (Gesture no. 31). When done in the presence of concrete models, these gestures could also help connect the phenomena with the models.

*II. Internalising the model (Model I.).* Twenty-seven out of 40 gestures were meant to facilitate internalising the scientific models. The spatial properties of the models to be internalised are, the round earth (Gesture nos. 3, 4, and 5), axis of rotation of the earth (Gesture nos. 7 and 10), direction of rotation (Gesture no. 13) and revolution (Gesture nos. 23, 26, and 27) of the earth, motion of the moon (Gesture nos. 36 and 38) and transition of light (Gesture no. 15).

The pedagogy included three sets of gestures to show the roundness of the earth: to connect it with the shape of the globe (Gesture no. 3), and reconcile this roundness with the flat diagram on blackboard or paper (Gesture no. 4 on Figure 3) on the one hand, and the apparently flat visible portion of the earth on the other (i.e. how curvature decreases as the radius increases, to show why the earth appears flat to us) (Gesture no. 5).

Three sets of gestures were designed to show the axis of rotation of the earth and its tilt with respect to the ecliptic plane (the axis of the earth makes an angle of 23.5° with the ecliptic) (Gesture nos. 7, 10, and 26). These gestures, when done in combination with diagrams (such as Figure 3), helped link the model of the rotating earth with diagrams of the earth drawn in different orientations.

Of the model-related gestures six illustrated predominantly static properties of the system. The other 21 sets of gestures illustrated dynamic properties, which constitute the major source of learning difficulties in astronomy.

The aim of these gestures and actions was to assimilate the abstract models of the system (e.g. the round rotating earth, and so forth) into one's internal mental model. Although, concrete external models were used with some of these gestures, other gestures were completely independent of concrete models, while in all others the aim was, as a consequence of internalisation, to make the concrete models ultimately dispensable. In addition to internalisation of spatial properties of model, two further types of tasks were involved here.

*A. Change of orientation (Ch.Ori.)*. Changing one's heading in imagination presents great difficulty even in simple everyday contexts, and kinaesthetic feedback helps significantly in performing such tasks (Klatzky et al., 1998). Thus we frequently encouraged students to partially orient themselves in the direction in which the person in a diagram (or problem) was standing on the earth.

Four sets of gestures had to do with specific changes of orientation, starting with 'up' and 'down' with respect to the earth (Gesture no. 11). Two sets arose in an enactment of an episode from the play 'Life of Galileo' by Bertolt Brecht (1947) (Gesture nos. 8 and 9). Another set was enacted in the presence of a globe and/or a diagram of the earth, and it illustrated, besides 'up' and 'down', the directions, North, South, East and West (Gesture nos. 11 and 12). These gestures were also meant to help link the concrete model with a diagram of the earth.



*B. Change of reference frame (Ch. Ref. Frame)*. A large subset (eleven) of model-related gestures were meant to facilitate a change of reference frame (Gesture nos.16, 18, 22, 28, 29, 33, 34, 35, 37, 39, and 40). In the context of mental models, two 'frames of reference' are identified: an intrinsic (or egocentric) frame of reference, in which the viewer is inside the model, and an extrinsic (or allocentric) frame in which viewer is outside the model. In the extrinsic frame it is relatively easy, for a middle-school or older child, to imagine one model from different perspectives. But it is extremely difficult to change one's frame from an extrinsic/allocentric to an intrinsic/ egocentric frame. The further task of moving from one intrinsic frame to another, for example, imagining the view alternatively from the earth or the moon, is even more demanding.

The allocentric–egocentric transformation, which calls for a high level of visualisation, often results in an inability to connect the external model to the observed phenomenon. We found group gestures to be a good way to make this transformation. When persons replace the objects in the model by themselves, they see the system from 'inside', which helps the allocentric to egocentric transformation.

To facilitate anthropomorphic models we designed group configurations and actions involving human forms (Gesture nos. 16, 22, 33, 35, 37, and 39). We felt that if the students enacted these anthropomorphic situations, it may help them to form mental representations which would be useful in the visualisation, even in the absence of actual situations or (later) the gestures.

Ten out of 40 gestures/actions were done either in pairs (Gesture nos. 16, 22, 33, 35, 37, and 39), triads (Gesture no. 38) or in larger groups (Gesture nos. 28, 29, and 40). All were done for the purpose of internalising the SEM model, and nine of them served to enact the changing of frame of reference. Thus, group gestures were most important in model internalisation and changing frame of reference.

We designed different group gestures to visualise different phenomena, though concerning the same system. For example, the following four classes of phenomena could be explained using the SEM model, with only two people, one acting as the moon and another as the earth, but each with different actions.

First the students mimicked the basic model of the earth moon system that is rotation and revolution of the moon around the earth, to explain why we see only one face of the moon, and demonstrates the falseness of the common belief that a particular half of the moon is always in darkness (Gesture no. 33). This apparently simple motion turned out to be a tricky one. At first when asked to perform it students would only do the revolution. So the student acting as the moon was asked to first only rotate and notice that the field of view changed during rotation. Then the 'moon' was asked to only revolve, in which case, the field of view did not change. Next the 'moon' performed the two motions in portions of 90°, in which the body rotated by 90° on completing a quarter of the revolution, so that the students' one side (conveniently, the face) remained always towards the earth.

In the action for visualising the phases of the moon, the face of the student acting as the moon denoted the lit part and the hair denoted the dark part of the moon. Thus in this action the student acting as the moon always faced the direction of sun rays (Gesture no. 35). The student who was the earth observed how much of the moon's face (i.e. its lit part) was visible. Although this action is at variance with the correct motion (as explained in Gesture no. 33), it was useful to 'see' the phases in terms of the quarter, half and three-fourths of the face. Gesture no. 35 had an advantage over Gesture no. 34 (where the moon was played by a lit ball), since the outline of a face is clearer to see than the line of illumination on a ball, the latter being not very sharp in the diffuse light of a room.

To explain the eclipses of the moon and the sun, and the phases of the moon, together, an additional feature was added to Gesture no. 33: instead of revolving in the horizontal plane, the moon lowered and raised her head appropriately to take account of the tilt in her orbit (Gesture no. 37). In this motion the earth was able to see, instead of a lunar and solar eclipse respectively, the full moon (fully lit face of a friend) and the new moon (fully dark face of the friend, on the same side as the light). In this motion, the tilt of the moon's orbit could be conveyed, from the viewpoint of the earth, and of the moon. Students then repeated this gesture to enact the orientation of the orbit at the time of the lunar and solar eclipses.

The next, more difficult, step was to explain why the synodic month is longer than the sidereal month (Gesture no. 39). The moon completes one revolution around the earth in 27 days against the background stars (due to which in the Indian calendars the sky is divided into 27 *nakshatras*, star-patterns in the lunar path sometimes called 'lunar mansions'), yet the phase cycle (revolution according to the sun, due to which a month in the Indian calendar is of roughly 30 days) is of 29.5 days. Conveying this idea to students only through a diagram is difficult because of the two simultaneous and interrelated motions that need to be shown. The student acting as the earth, which was stationary in the previous three gestures, now has to move slowly, to take account of her revolution around the sun. Suppose we start our observation on the full moon night when the angle between the sun, earth, and the moon is 180° and the moon is seen in *Ashwini nakshatra* on the background of stars (the role of the background stars is played by some fixtures in the wall). The moon comes back to its original position with respect to this star-background, that is in the

*Ashwini nakshatra*, in around 27 days. But by that time the earth has moved forward a little, and the moon has to catch up with the earth by covering some extra distance to arrive at the position of full moon, that is, to again subtend the sun–earth–moon angle of 180°. The tilt of the orbit was not important to understand the observation that the duration of the phase cycle was longer than the time required for the moon to come back to its original position with respect to the background stars.

Although this verbal explanation is long, the actions involved are simple enough that students could do them without much trouble. Thus specific aspects of a complex motion could be expressed in a simple and natural manner, through a series of actions.



*III. Internalising Euclidian space (Space I.).* Eight of the 40 sets of gestures were aimed at internalising properties of three-dimensional Euclidean space through appropriate configurations of the body. Six of them convey static properties and two convey dynamic properties of space. They encompass length and displacement (Gesture no. 19), area and volume (Gesture no. 21), angles (Gesture nos. 2, 20, and 32), rotations (Gesture no. 6), and shapes of trajectories (Gesture nos. 24 and 25). Specific and common units of measurement were also appropriated with the help of gestures.

*Summary of 'Purpose'*

The classification of the gestures in Figure 4 shows that most (27 out of 40) gestures served the purpose of 'Model internalisation' (Model I.), compared with eight meant for 'Space internalisation' (Space I.) and five gestures meant for 'Phenomenon internalisation' (Ph.I.). This according to us is a possible basis for designing gestures for teaching astronomy (Research Question 1). Use of gestures might be most important in model internalisation for the following reasons:

(1) Astronomical models, due to their vast scale, are not accessible to direct perception. Scaled concrete models, gestures, and diagrams are the only way to understand them.
(2) Out of 27 gestures which serve to internalise the model, 11 are useful in changing the frame of reference. In other words, the person who replaces the earth can observe the phenomenon from the frame of the earth. Thus these gestures are not only useful for internalisation of dynamic aspect of the model, but they are also the most accessible and perhaps unique medium through which we can change an allocentric (or extrinsic) frame of reference to an egocentric (or intrinsic) one. This is an important function of gestures, in astronomy, making explanations immediately evident without any formal means of reasoning.
(3) From Table 1 and Figure 4 we see that, out of 27 gestures used in model internalisation, 21 are meant to convey a dynamic aspect of the model. Both concrete models and diagrams could be made dynamic with a mechanical provision and computer animations respectively. However, these involve simultaneous

> motions which are difficult to comprehend (Tversky & Morrison, 2002). Following the phenomenon is easier since we concentrate on only one body and follow its motion, and that motion is perceivable. But comprehending this motion requires keeping track of the objects over long time scales, not an easy task. Gestures provide natural and effective ways to add dynamism to both concrete models and diagrams. They are important in internalising dynamic aspects of phenomena and play a vital role in internalising dynamic aspects of the models.

Thus the major function of gestures was to convey dynamic aspects of the phenomenon, model, or of space. Out of 40 gestures, 25 conveyed dynamic aspects of either phenomenon or model or space (Figure 4).



### *Gestures as a Link between Concrete Models and Diagrams*

The columns 'Type of linkage' and 'Stand-alone' in Table 1 exemplify the 'concrete model–gesture–diagram' link of our conjecture. Table 2, derived from these two columns of Table 1, summarises the number of gestures in our scheme which follow concrete models and/or lead to diagrams, and those which are necessarily done in the presence of concrete models and/or diagrams. The linkages in Table 2 address Research Question 2.

As seen in the last column of Table 2, there are 11 gestures which have to be performed (at first, necessarily) either in the presence of concrete models or in the presence of diagrams. For example, using the right hand thumb rule to decide direction of rotation of the earth (Gesture no. 13, Table 1) makes sense only if it is done along with the globe or a diagram to show its orientation. These gestures thus fill up the meaning that is missing in the concrete model or in the diagram.

The remaining 29 gestures are possible to do on their own but, as seen in Table 2, they can in a natural way follow a concrete model (1) or lead to a diagram (11) or

Table 2. Use of gestures to connect concrete models to diagrams derived from columns 6 (Type of linkage) and 7 (Stand-alone) of Table 1

| Type of linkage | From concrete models (CM-G) | From concrete models and to diagrams (CM-G-D) | To diagrams (G-D) | Total |
|---|---|---|---|---|
| Gestures necessarily done in presence of CM or D | 2 | 4 | 5 | 11 |
| Gestures which follow from CM or lead to D | 1 | 15 | 11 | 27 |
| Total | 3 | 19 | 16 | 38 |

both (15). These examples demonstrate that gestures can be used to link concrete models of systems to their diagrams. Two gestures (nos. 22 and 35 in Table 1), which were used for changing the frame of reference, were exceptional in that they were not naturally linked to either concrete models or diagrams. Note, however, that these gestures involved one more additional person, who provided a visual cue for that gesture.

## Students' Spontaneous Gestures

In the video analysis our interest was primarily in gestures, specifically those that were related to the content of the problem-solving tasks. This was not a comprehensive discourse analysis, as due to circumstances of language and sociocultural context (see description of sample), there was very little verbal interaction between the students. Added to this the unfamiliar nature of the subject matter and lack of exposure to problem-solving in general, may have resulted in students' low confidence in expressing their ideas verbally. Their utterances were thus brief and sometimes apparently disconnected, consisting of whispers, mutters, and suggestive words, often difficult to decipher in a noisy classroom. Under these circumstances gestures may have provided an especially useful tool for their communication. For these reasons, and because our interest was not in the logical process of argumentation (description, explanation, dispute, and so forth), the analysis of videos focused mainly on gestures, specifically those in the 'deixis', 'metaphoricity', and 'iconicity' categories that is excluding the social interactivity categories.

These content related gestures occurred against a background of continuous physical activity. Students constantly moved their hands and bodies, picked up relevant and irrelevant tools such as pencils, scale, eraser, and so forth, dropped one of these, bent down to pick it up, and so on. They also often scratched their heads, noses, and other parts, touched each other to seek attention, sometimes continuously hitting the pencil on paper while apparently lost in thought. In interactions they used body-language to show their agreement (nodding), dissatisfaction (looking away and not paying attention), questioning, showing urgency of the task (vigorous motion), and so forth, all involving gestures and postures of the whole body. Their level and pattern of activity changed in occasional interaction with other groups and with the teacher, yet they remained continuously active and involved in the task.

Coding of video data was done by the first author after which both authors reviewed about 17% of the data spread over all of the five sessions. These video segments, totalling 85 minutes and selected to include the relatively rare but important instances of metaphoric gestures, were watched by both authors together. Though there were no cases of disagreement over already coded gestures, occasional additional gestures were noted during the review, particularly when simultaneous gestures occurred in a group. Taking a conservative view, the numbers of gestures recorded here give a lower bound rather than a maximum limit, though we are reasonably confident that the actual numbers are not very much higher than the given numbers.

*Nature of Tasks*

All of the problem tasks required the students to produce and interpret diagrams, beginning with angles and parallel lines towards increasingly complex situations involving shadows, rotation and revolution of the earth. Students could use the globe if they wished. The situations addressed during the five videotaped sessions are indicated below. The original questionnaires are at http://www.hbcse.tifr.res.in/data/pdf/vthinking/pedagogic-questionnaires/ and their annotated translations at http://www.hbcse.tifr.res.in/data/pdf/vthinking/qnr-eng-trans.

- Session 1: 'Parallel rays'—parallel ray approximation for a distant light source.
- Session 2: 'Shadows'—correlating shadows with angles of elevation of a light source.
- Session 3: 'Rotating earth'—correlating global cues with local directions and angles of elevations; time differences.
- Session 4: 'Star-month'—observed night sky *nakshatra* and indigenous calendar.
- Session 5: 'Seasons'—day-night and north-south elevations of the sun during solstices and equinoxes.

Each session consisted of one to four questionnaires, each of which was segmented into step-wise key questions, and accompanied by a skeletal diagram, since we know from previous work that providing students with skeletal diagrams enables them to work within an abstract context and results in responses that are more explanatory than descriptive (Ramadas & Driver, 1989). As further support, oral hints were given to the entire class (e.g. 'you may need to extend the rays to locate the point of intersection'), of which some recurring hints were written on the blackboard (e.g. 'rays coming from a distant light source are parallel'), enabling the students and teacher to refer to them at different points of time for different groups who happened to work at differing speeds. These hints occasionally also involved gestures. Most of the groups required additional individual guidance, at times the same hints given with more explanations. Occasionally specific guidance had to be given to individual groups to correct specific mistakes. With groups who completed the task faster and more satisfactorily, the teacher engaged in further discussion, in which she asked them for explanations or posed more challenging questions.

The successive sessions and questions within a session were designed to be prerequisites to the later ones. However, the increasing familiarity with the tasks as the sessions progressed may have modulated the increasing difficulty level of the tasks during or between the sessions.

*Types and Rates of Students' Gestures*

In relation to Research Question 3, Table 3 gives the total number of gestures, rate of gesturing, and the number of occurrences of different types of gestures within each of the groups RG and TB. Figure 5 plots the student-wise rate of each type of gesture that is the number of that type of gesture occurring per minute, for each

Table 3. Total number of spontaneous gestures used by students (session-wise)

| | | Session 1 | | Session 2 | | Session 3 | | Session 4 | | Session 5 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Parallel rays | | Shadows | | Rotating earth | | Star-month | | Seasons | | Total | |
| No. | Gesture type | RG | TB | RG | TB† | RG | TB | RG† | TB | RG | TB | RG | TB |
| | Time (minutes) | 50 | 57 | 56 | 80 | 64 | 62 | 5 | 8 | 56 | 56 | 231 | 263 |
| | Total no. of gestures | 39 | 149 | 112 | 133 | 178 | 258 | 15 | 40 | 223 | 159 | 547 | 739 |
| | Average gestures/student/min. | 0.26 | 0.87 | 0.67 | 0.83 | 0.93 | 1.39 | 1.5 | 1.67 | 1.33 | 0.95 | 0.87 | 1.1 |
| 1a | Deictic point | 15 | 71 | 43 | 56 | 83 | 74 | 7 | 8 | 96 | 76 | 224 | 285 |
| 1b | D multiple pt | 1 | 26 | 7 | 26 | 45 | 62 | 5 | 17 | 53 | 40 | 111 | 171 |
| 2 | Deictic spatial | 16 | 14 | 53 | 16 | 36 | 67 | 2 | 13 | 61 | 27 | 168 | 137 |
| *2a* | *D line* | *12* | *6* | *37* | *9* | *19* | *32* | *0* | *1* | *33* | *21* | *101* | *69* |
| *2b* | *D multiple line* | *0* | *6* | *15* | *5* | *10* | *8* | *1* | *0* | *27* | *6* | *53* | *25* |
| *2c* | *D circular* | *1* | *2* | *1* | *2* | *5* | *20* | *1* | *10* | *1* | *0* | *9* | *34* |
| *2d* | *D simultaneous point* | *1* | *0* | *0* | *0* | *2* | *6* | *0* | *2* | *0* | *0* | *3* | *8* |
| *2f* | *D simultaneous line* | *2* | *0* | *0* | *0* | *0* | *1* | *0* | *0* | *0* | *0* | *2* | *1* |
| 3a | D portion | 0 | 0 | 0 | 0 | 0 | 4 | 0 | 0 | 0 | 5 | 0 | 9 |
| 3b | D instruction | 0 | 2 | 0 | 3 | 0 | 0 | 0 | 0 | 11 | 0 | 11 | 5 |
| 4 | Metaphoric | 7 | 36 | 9 | 32 | 3 | 31 | 0 | 1 | 1 | 11 | 20 | 111 |
| 5 | Iconic | 0 | 0 | 0 | 0 | 4 | 5 | 1 | 1 | 1 | 0 | 6 | 6 |
| 6 | Orientation change | 0 | 0 | 0 | 0 | 7 | 15 | 0 | 0 | 0 | 0 | 7 | 15 |

*Note*. RG, Rural girls; TB, Tribal boys; †Only two students were present in these sessions.

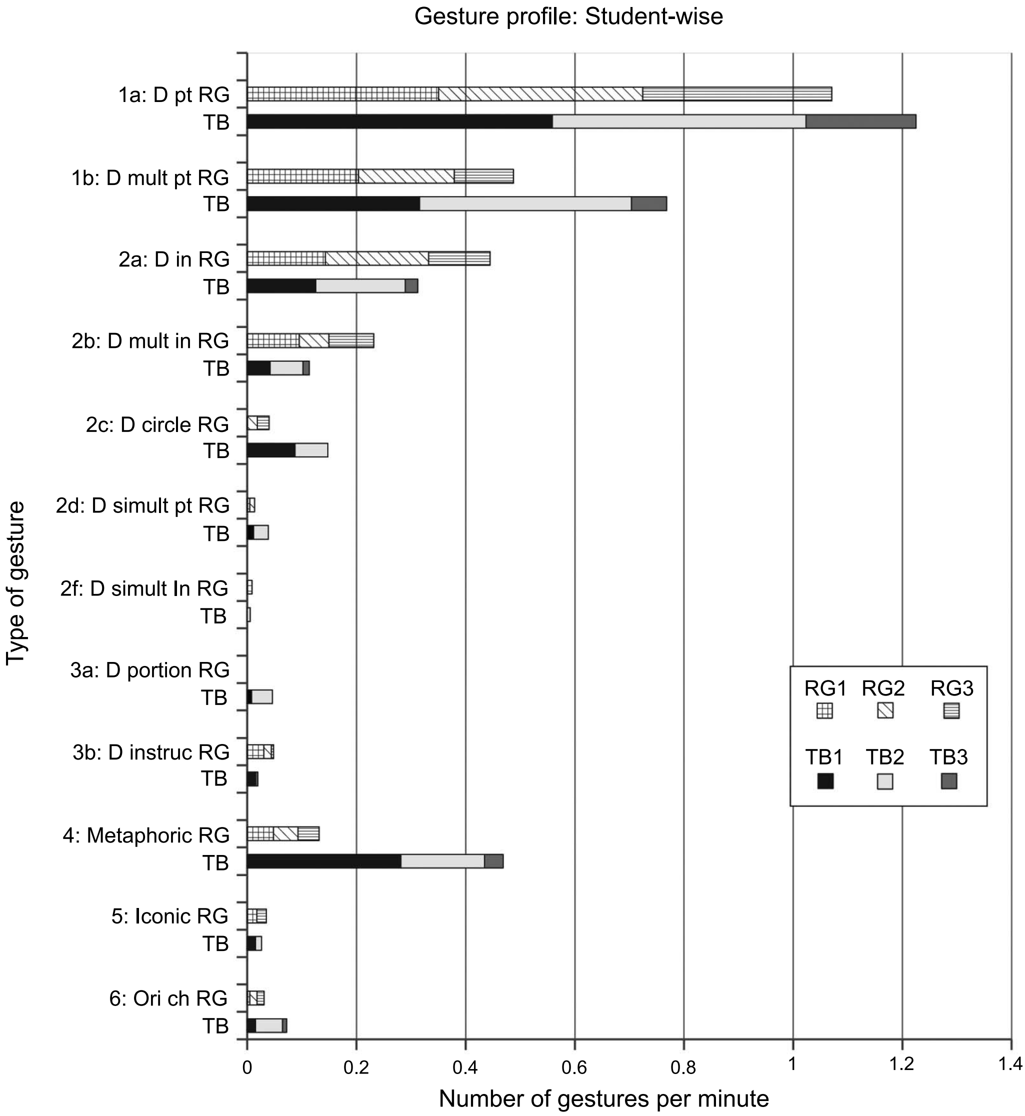


Figure 5. Type of spontaneous gesture used by students versus rate of use of that gesture for each student (Rural girls: RG1, RG2, RG3; Tribal boys: TB1, TB2, TB3)
*Note*. D, Deictic; pt, point; ln, line; simult, simultaneous; instruct, instruction; Ori ch, Orientation change.
Rate of gesturing of individual students: TB1=1.59, TB2=1.49, TB3=0.35; TB average = 1.1 gestures per minute; RG1=0.97. RG2=0.90, RG3=0.74; RG average = 0.87 gesture per minute.

student in the TB and RG groups. The categories of students' spontaneous gestures are derived from their observed features, in contrast to the categories of designed gestures which were based on their purpose in pedagogy.

Taken together, Table 3 and Figure 5 show the relative frequencies of different types of gestures, as well as the distribution of these gestures within each group of students. The rate of gesturing was higher in the TB group as compared with the RG group with the exception of TB3, who had the lowest rate of gesturing. Thus variability within the group of three students appeared to be higher in the TB group than in the RG group (Figure 5). It is interesting that RG1 and TB1, who carried out the most number of content related gestures within their group, performed outstandingly in the post-tests, and their interview performance at the end of the intervention was amongst the best in their cohort.

### *Types of Gestures and Content of Task*

In this sub-section, we address Research Questions 4 and 5. Since the profile of use of gestures over the different gesture types was similar in the two groups, we collapsed the data for all the six students to plot Figure 6, showing the total rate per student per minute of each type of gesture, for each of the five problem-solving sessions.

The categories of gestures in Table 3 and Figures 5 and 6 build on but go beyond existing classification schemes (Goldin-Meadow, 2006a; McNeill in Radford et al., 2009; Roth, 2000). The category of 'deictic gestures' includes all those gestures which involve pointing, usually on a diagram or text on paper, and also occasionally towards the blackboard or the teacher. We found our students using a large variety of deictic gestures, many of which had spatial significance, which we included in a new category, 'Deictic spatial', which (as explained later) was distinct from the 'Metaphoric' category. Thus we modified and expanded the 'deictic' category on the basis of empirical observations from our data. Further, we found that the 'Orientation change' gestures, which were introduced in our pedagogy, did not fit into the existing categories, hence we created a new category to include these.

*1. Simple deictic gestures.* The most frequent type of gestures in both TB and RG groups were deictic (pointing) ones, using a finger (or palm or tools such as a pencil or ruler) to point to parts of the text or of the diagram on paper (Category 1a in Table 3 and Figures 5 and 6). For example, in the RG group in first two sessions on 'parallel rays' and 'shadows' (106 minutes), out or 151 recorded gestures, 136 were of the deictic type. Of these, 95 were done by finger, 26 by hand, and 12 used an instrument such as ruler or pencil. Three of these 'deictic' gestures used 2 fingers, 2 hands, and 2 arms each.

Most of the deictic gestures were simple deictic ones consisting mostly of 'Deictic point' (Category 1a). A common variation of this gesture was to point to multiple points on paper (Category 1b, 'Deictic multiple point'). This gesture occurred in the course of reading, while pointing to successive portions of the text, in which case it had temporal significance (in McNeill's system, Radford et al., 2009), or while

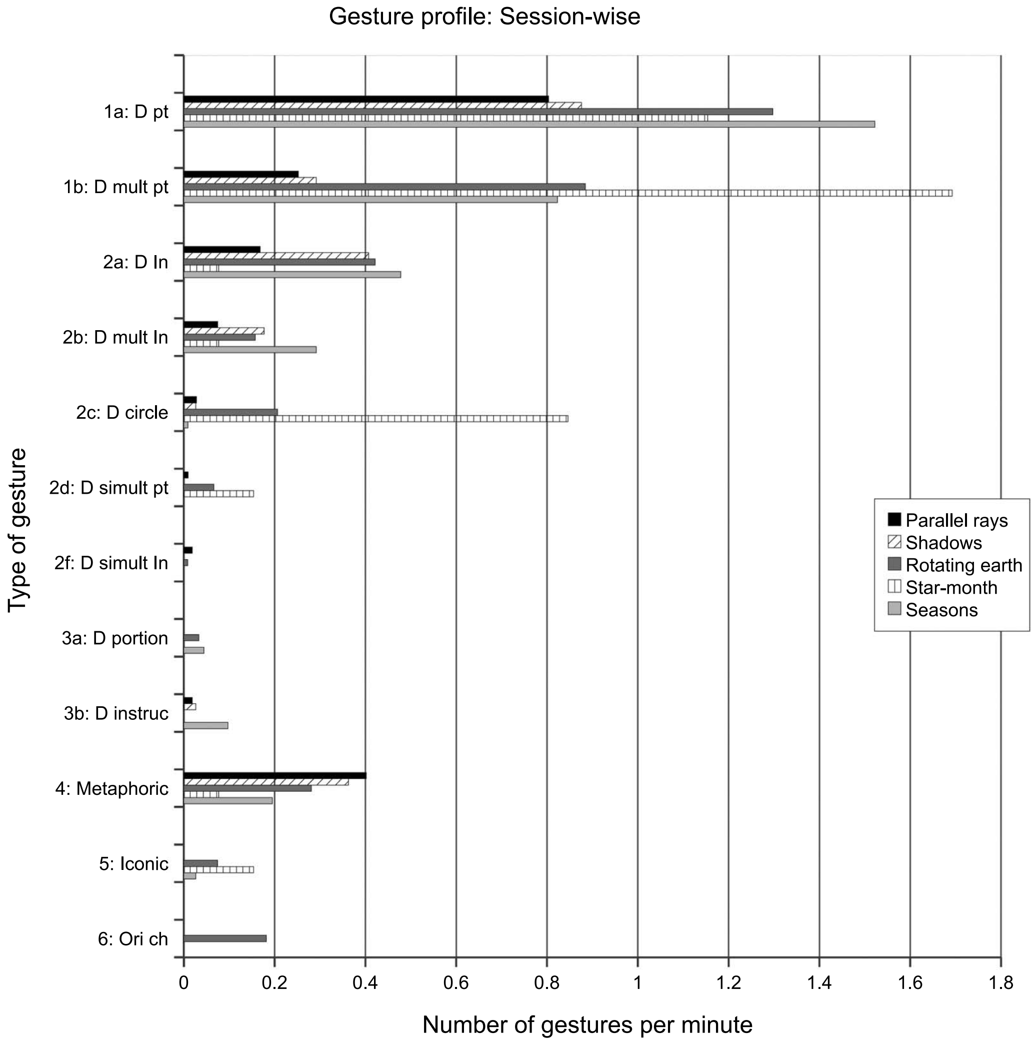


Figure 6. Type of spontaneous gesture used by students versus rate of use of that gesture in each session

*Note*. D, Deictic; pt, point; ln, line; simult, simultaneous; instruct, instruction; Ori ch, Orientation change.

successively pointing to parts of the diagram, in which case it may have had both temporal and spatial significance.

Figure 6 shows that over successive sessions the number of 'Deictic point' gestures increased, with the exception of Session 4 (Star month). It may be that more difficult tasks encouraged more pointing gestures. Session 4 had problem tasks in which 'Deictic multiple point' was natural to use for showing several constellations around the sun–earth system. In fact these gestures were used preferentially in Session 4 (see Figure 6).

*2. Deictic spatial gestures.* The next most frequent category was 'Deictic spatial' (Category 2), in which the finger or pencil followed one line, or more than one lines in succession ('Deictic line' and 'Deictic multiple line', 2a and 2b), an arc or part of a circle or a whole circle ('Deictic circular', 2c), or two or more simulations points or lines ('Deictic simultaneous point' and 'Deictic simultaneous line' 2d and 2e). The latter two were used in rare cases, when students were referring to parallel lines or simultaneous rays.

Category 2 gestures appeared to convey spatial properties such as length, orientation, or direction of a line or ray. Sometimes they stood for an element in diagram such as, a ray or several rays of light, the axis, equator, orbit, and so forth. They also could show motion such as rotation, revolution, or transition of light and simultaneous transition of rays. These attributes might ordinarily describe 'Metaphoric' gestures, hence 'Deictic spatial' gestures may lie on the borderline of 'Deictic' and 'Metaphoric' gestures. They are classified here as 'Deictic' because, they involved pointing and were invariably made on paper. In comparison with 'Metaphoric' gestures, they carried less meaning in themselves and could in principle have been translated into speech, had the speaker wished to do so. However, they did reflect students' process of thinking, particularly when they traced a proposed shape aimed to lead towards a solution of the problem, rather than an existing shape on paper. The frequent occurrence of 'Deictic spatial' gestures may therefore be seen as support for the 'mental model–gesture–diagram–phenomenon' links that were part of our research conjecture.

Several types of 'Deictic spatial' gestures occurred informally in our teaching. Our set of designed gestures (Table 1) contained four in the 'Deictic spatial' category (nos. 7, 10, 15, and 32), of which Gesture nos. 10 and 15 were used spontaneously by students. Gesture no. 10, showing motion of the earth for the axis in the given diagram, which is a version of 'Deictic circular', was used in Session 3 (0.08 times per minute for RG and 0.32 times per minute for TB), where the tasks were based on the rotation of the earth. Gesture no. 15 (in Table 1, tracing ray diagrams) was used in all of the sessions. Session 2 (Shadows), Session 3 (Rotating earth), and Session 5 (Seasons) involved problem tasks in which light rays were necessary to be drawn respectively to locate a shadow, to identify angle of a particular star above the horizon and to find out lit and dark parts of the earth. Figure 6 shows that 'Deictic line' and 'Deictic multiple line' gestures were in fact used most often in Sessions 5, 3, and 2. Similarly, the 'Deictic simultaneous line' was used only in Sessions 1 and 3, in which pairs of lines and beams of light were to be drawn. These examples further confirm our expectation that students' gestures would be closely connected to the content of the task.

Exact interpretation of deictic gestures was not feasible, especially when the pointing was done on the diagram, since (although the paper was visible) the focus of the camera was on the student and not on the paper. At a gross level, however, it was possible to characterise the purpose of the above deictic gestures as:

- to avoid referring to something each time by word;
- to refer to something whose name is less familiar or unknown;
- to communicate the position, orientation, or shape of an existing, or proposed, portion of the diagram;
- to compare the drawn diagram with another diagram (either drawn for an earlier question or on rough paper);
- to suggest corrections to the diagram ('not this way, but this way'); and
- to plan (for self as well as in the group).

'Deictic simple' and 'Deictic spatial' thus constituted the first two most frequent types of gestures, playing varied and important roles in the process of communication in solving spatial tasks in astronomy.

*3. Other deictic gestures.* Category 3a 'Deictic portion' refers to a gesture showing part of text or diagram on paper using the thumb and index finger. This gesture occurred rarely and was more akin to a style adopted by a couple of students, to refer to the text or relevant part of a diagram, without necessarily carrying any specific spatial significance.

Deictic gestures of first three categories (1, 2a–f, and 3a), which make up the largest fraction of the total gestures, were done on paper. Category 3b 'Deictic instruction' on the other hand, refers to pointing towards an instruction or a hint written on the board by the teacher, or occasionally directly pointing to the teacher to refer to her hints or instructions. The 'Deictic instruction' gesture did not relate to any specific content but referred to whatever hint happened to be written on the board. Figure 6 shows that the largest number of 'Deictic instruction' gestures occurred in Session 5, in which problems were based on the newly taught content of seasons, and hence teacher interventions too occurred frequently.

*4. Metaphoric gestures.* 'Metaphoric gestures' (Category 4) formed the fourth most frequent type of gestures. Their distinguishing feature was that they were performed in the air and, unlike spatial deictic gestures, did more than merely serve to trace parts of the text or diagram on paper. A second characteristic, that distinguished metaphoric gestures from the 'Deictic spatial' category, was that although often accompanied by speech, they carried in themselves significant meaning that was not easily expressible in words. Two instances of spontaneous metaphoric gestures were: two palms inclined to the vertical to denote the tilt of the earth's axis with respect to the ecliptic plane, and a flipping movement of the palm to denote formation of a shadow of a vertical object on a horizontal plane.

Metaphoric gestures formed the predominant component of our designed pedagogical gestures, yet students' spontaneous metaphoric gestures differed considerably from those used in our pedagogy. Firstly, the students' gestures were fleeting, not bold, well-defined and elaborated, as had been the practice during the teaching. Secondly, they occurred in chunks, spread over a minute or two, yet each gesture was done very quickly, typically within a fraction of a second. Thirdly, the students' gestures expressed discrete aspects of the model, for example, rays and beams of light, or individual objects such as the sun, earth or ground, rather than whole models as they were taught, for example, the rotating earth, or formation of shadows.

Fourthly, most of the metaphorical gestures happened to be not addressed to fellow students in the group, but were done in the presence of the teacher, or in response to the teacher's questions to the entire class. Though these gestures may have been a direct result of the teacher's earlier efforts to encourage gestures, they appeared spontaneous enough that other interpretations are possible. The teacher's interventions occurred mainly when a conceptual formulation was needed, or further explanations were called for: situations that might have been especially facilitated by metaphorical gestures. Another possibility is that, while for communication with fellow students, subtle, oral, or gestural hints sufficed, in communicating with the teacher, students needed to be more explicit, so that the teacher understood their explanation, or became convinced of their competence with the concept.

Finally, several of the metaphoric gestures in our pedagogy included whole body actions or were done in groups of more than one student: none of these were seen spontaneously in students.

Table 3 shows that the average number, of all types of gestures taken together, per student per minute, actually increased over the sessions (except for a slight decrease in the last session). Yet Figure 6 shows that the incidence of metaphoric gestures decreased from Session 1 to Session 5 (except for Session 4). This may imply that students used more gestures with more difficult content but in order to use metaphorical gestures they needed better expertise, or more familiarity with the content. A parallel might be drawn with verbal communication, where an expert may use fewer but more precise words than a novice to communicate the same content.

*5. Iconic gesture.* Strikingly enough, the only iconic gesture in the pedagogy for determining direction of rotation of the earth ('Right Hand Thumb Rule', Table 1, Gesture no. 13) also turned out to be useful for problem-solving (Category 5). Students spontaneously used this gesture while solving problems which required the direction of rotation of the earth in Session 3 (0.06 times per minute in RG and 0.08 times per minute in TB) and in Session 5 (0.05 times per minute in RG); and while solving problems based on the revolution of the earth in Session 4 (0.2 times per minute in RG and 0.13 times per minute in TB).

*6. Gestures for orientation change.* Another type of pedagogical gestures that were spontaneously adopted by students was the 'Orientation change' gestures (Category 6). Specifically Gesture no. 12 in Table 1 was used in Session 3 (0.11 times per minute in RG and 0.24 times per minute in TB). These gestures do not fit into any of the categories in the classification schemes currently used in the literature McNeill in Radford et al. (2009), Roth (2000), and Goldin-Meadow (2006a). The reason is that all the current schemes consider exclusively the communicative aspect of gestures, whereas in the 'Orientation change' category we have gestures with no necessary communicative purpose: the primary purpose of performing this gesture is to facilitate an imagined change in orientation. Many researchers believe that gestures are not only tools for communication but they also play an important role in thinking and reasoning, and continuous effort are made to find evidence for this claim (Goldin-Meadow, 2006a; Hegarty, 2005). The 'Orientation change' gestures are strong candidates to provide support for the above claim.

In summary, students freely and spontaneously used gestures many of which followed the patterns introduced in the pedagogy and were consistent with the requirements of the problem situations.



## Conclusions and Implications

### *Designed Pedagogical Gestures*

We propose that, just as we design models and diagrams for pedagogy, gestures too can be designed to convey and internalise concepts in science. The following two conjectures provided the rationale for design of gestures in our pedagogy for astronomy (Research Questions 1 and 2):

(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 and dynamic properties of a phenomenon or a scientific model can be readily conveyed through gestures (Research Question 1).
(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 (Research Question 2).

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 internalise patterns in, astronomical phenomena; to enact spatial properties of astronomical models or part of them; and to internalise space in general. In internalisation of astronomical models gestures give kinaesthetic feedback to facilitate change of orientation and enable the visualisation 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.

### *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 in them. These 'Deictic spatial' gestures, communicate spatial properties such as length, orientation, direction, shape, and so forth. 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 other cases, however, such linkages were difficult to detect (Research Question 3).

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 (Research Question 4). These results, in conjunction with the literature cited earlier, underscore the role of gestures in communication and thought.

In relation to Research Question 5 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.

The discrete or 'elementary' nature of students' gestures, as compared to the designed pedagogic gestures, may perhaps have been adequate to support their thinking in some of the problem-solving situations. In the pedagogic situation, in contrast, we do need to use fully elaborated gestures. We have also observed fairly elaborate gestures in students of architecture during problem-solving related to phases of the moon (Subramaniam & Padalkar, 2009). We feel that it would be good to develop this capability in school students too. On the other hand the students' elementary gestures may also suggest similar gestures for pedagogic use.

### *Multimodality and Embodiment in Science Learning*

Problem-solving in the context of spatial cognition is actualised in a natural and intuitive way through a dynamic interaction between the body and the environment—a philosophical viewpoint tantalisingly termed 'embodied cognition' (e.g. Lakoff & Johnson, 1999). In this view, our reasoning comes about, in part, through our ability to participate in various types of collective or environment-exploiting activities, leading to problem-solving of a kind very different from the classical, logical, symbol-manipulating internal cogitation that we know and analyse so well (Clark, 1997). A related and resonating theoretical perspective is that of perceptual symbol systems, which holds that abstract concepts are derived from complex configurations of multi-modal perceptual information, distributed over time (Barsalou, 1999). Multimodality in the context of science learning has been explored from a social semiotic perspective by Lemke (1998) and Kress, Jewitt, Ogborn, and Tsatsarelis (2001). Kress et al. (2001) examine the environment of science lessons in terms of multiple modes: language (speech and writing), action (including hand and body gestures) and visual (models and diagrams). The latter two are receiving attention in science education research, as seen in recent volumes edited by Gilbert (2005, 2008) and a 2009 special issue of the *IJSE* (Ramadas, 2009).

The perspective of embodiment and multimodality is particularly useful in science learning, for 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. 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 distance and time scales which are beyond direct perception, actions may provide the most accessible bridge from the phenomenon to the mental model.

Our approach may serve to integrate the spatial and temporal aspects of the body-environment interaction, as consistent with the formulations of embodied cognition and multimodality. 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 embodied cognition, multi-modality, and the study of gesture needs to be explored in science education, particularly in areas requiring significant spatial cognition, for example, chemistry, biochemistry, developmental biology, geosciences, mechanics, electromagnetism, astronomy, and so forth. The link between concrete models, activities, and experiments on one hand and science concepts on the other hand is likely to be facilitated through such embodied modes.

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