Visual-Spatial Modes in Science Learning

Review talk at epiSTEME-2
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Why this review?

The epiSTEME series:

An integrated conception of Science, Technology and Mathematics Education

Uniting themes in:

- Cognition
- Pedagogy

- History
- Philosophy
- Social and Cultural context

…Why this review?

Visual-spatial modes in science learning

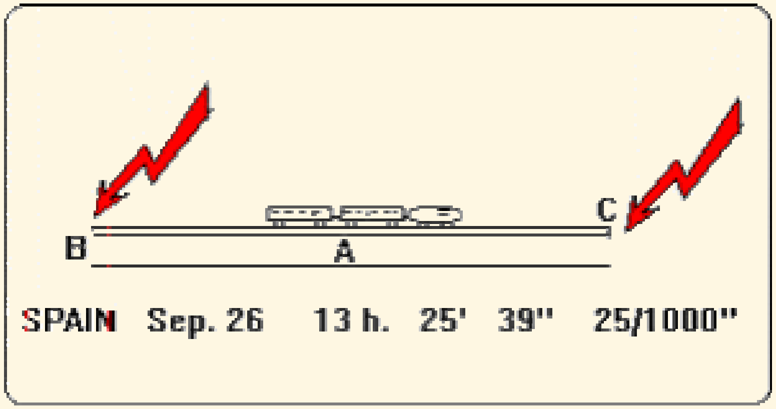
- A largely unexplored area
- Inadequacy of purely propositional models
- Research interest at HBCSE
  - Visual-spatial thinking in science, technology and mathematics education
  - Three faculty, five courses in 5 semesters, three Ph.D. projects
  - Science education: learning, curriculum

Review and Overview

- Visual-spatial aspects of doing and learning science
- Integration of visual-spatial with verbal and other modes (creativity, memory, communication and collaboration)
- Multi-modal nature of cognition
- Model-based transformational reasoning
  - evidence in science
  - cognitive analyses
  - through drawings
  - by experts
  - in learning of science
- Two ongoing research programs: in biology and in physics

Doing science

1. Conception of great ideas



"... The psychical entities which seem to serve as elements in thought are certain signs and more or less clear images which can be 'voluntarily' reproduced and combined ... The above mentioned elements are, in my case, of visual and some of muscular type. Conventional words or other signs have to be sought for laboriously only in a secondary stage ... ... the play with the ... elements is aimed to be analogous to certain logical connections one is searching for. ... In a stage when words intervene at all, they are, in my case, purely auditive, but they interfere only in a secondary stage ..."

A. Einstein, quoted in J. Hadamard, 1949

- Introspective reports of mental imagery; historical documentation

  (J. Hadamard, E. Ferguson, G. Holton, R. Shepard, A. Miller, C. Kierns)

…Doing science

2. Everyday practice of experimenters and theoreticians

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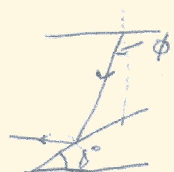
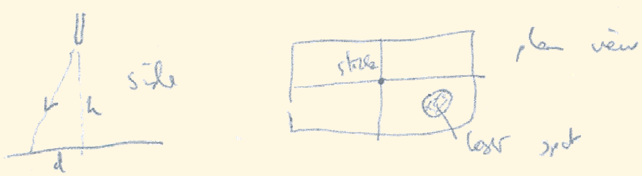
Experiments – Toulouse…

Trying to reduce fibre signal (again), using angle of fibre bundles, tried to do something scientific.
Situation is that laser light comes out at an



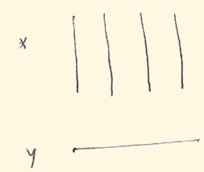
angle φ, & bounces off sample at an angle which is 8° from perpendicular.
First try to measure φ. Put stick pointing vertically (using a plumb line) & placed a cross on a piece of paper under it to measure angle



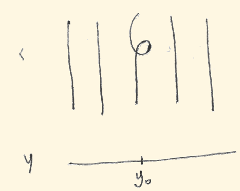
$f : X \to Y$, $X \xrightarrow[f]{} Y$ } a function ("map(ping)") from X to Y

$X \underset{f}{\hookrightarrow} Y$ an injective ("one-one") function

$X \overset{f}{\downarrow} Y$ a surjective ("onto") function



a surjective function where for each $y \in Y$, $f^{-1}(y)$ $(= \{x \in X \mid f(x) = y\})$ is the 'same'. (Also called a fibration)



a surjective function where all fibres are the same except for $f^{-1}(y_0)$. The crossing also signals that the "special fibre" has singularities whereas the others are smooth.

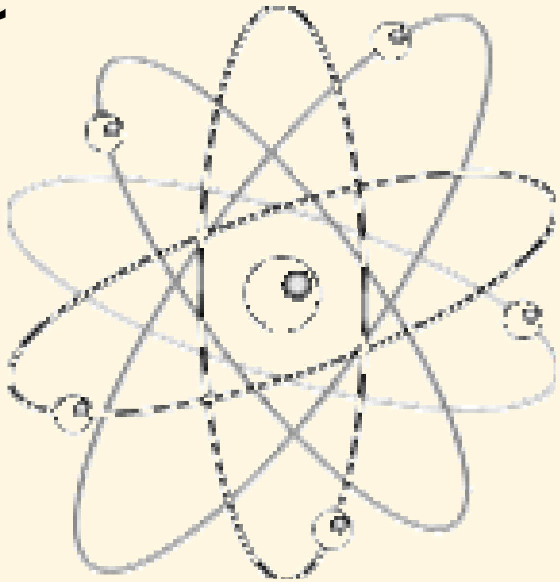
…Doing science

3. Communication and argumentation in science

- visual depictions
- verbal communication of visual experiences

Learning science

- Memorable diagrams



…Learning science

- Visual descriptions in pedagogy

Atomism is by no means self-evident. If we can trust our senses, most types of matter seem "all one piece". A sheet of paper or a drop of water does not seem to be composed of particles.

This, however, is not conclusive. The sand making up a beach, if viewed from a distance, seems all one piece. It is only upon a close view that we can make out the small grains of which the sand actually consists. Perhaps, then, paper or water is made up of particles to small to see.

...

If a cloud chamber is placed between the poles of a magnet, charged particles travel in curved paths, and the water droplets indicate that. From the direction of the curve, one can determine whether the charge is negative or positive; and from the sharpness of the curve, one can make deductions as to the e/m ratio.

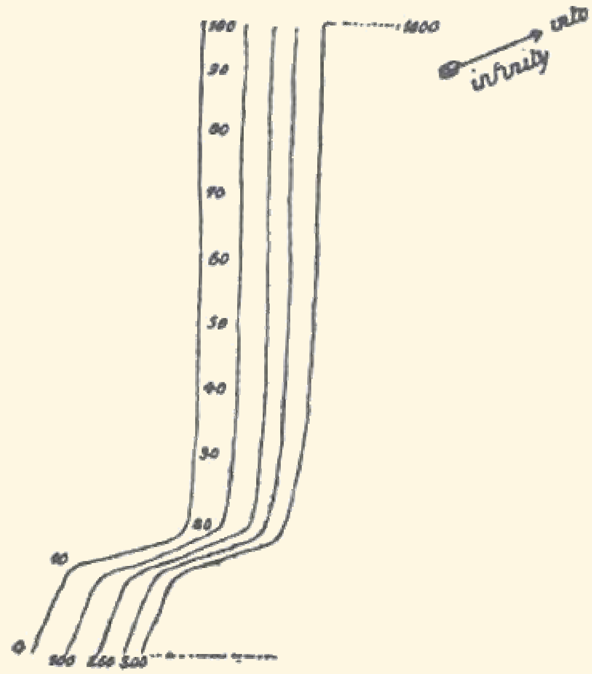
(I. Asimov, Understanding Physics, 1966)

Psychological research on visual modes of thinking

- Early introspective methods

T. M. "The representation I carry in my mind of the numerical series is quite distinct to me, so much so that I cannot think of any number but I at once see it (as it were) in its peculiar place in the diagram. My remembrance of dates is also nearly entirely dependent on a clear mental vision of their *loci* in the diagram. This, as nearly as I can draw it, is the following :—

Francis Galton's studies of imagery



…Psychological research on visual modes of thinking

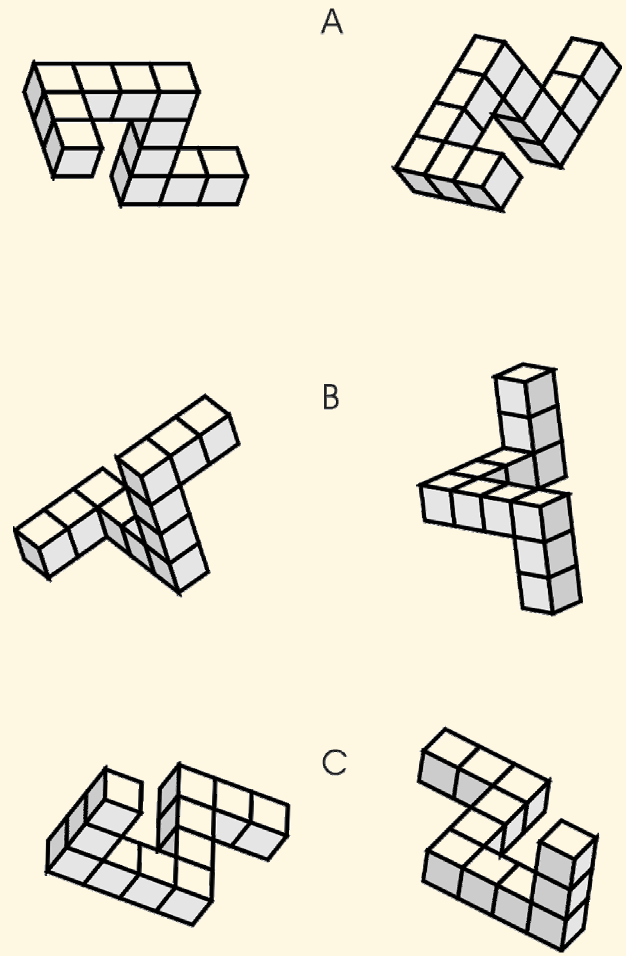
- Recent experimental approaches
  - chronometric studies
  - memory studies
  - spatial reasoning

- Documentation of practice
  - visual communication of ideas in science
  - and in learning
  - visual tools mediating cognition
  - collaborative learning

…Psychological research on visual modes of thinking

"a spontaneous kinetic image of three dimensional structures majestically turning in space"
– R. Shepard

☆ How do we conceptualize molecules in stereochemistry?



Shepard and Metzler (1971). Mental rotation tasks

Creativity and discovery in the laboratory

Daniel Reisberg and Friderike Heuer

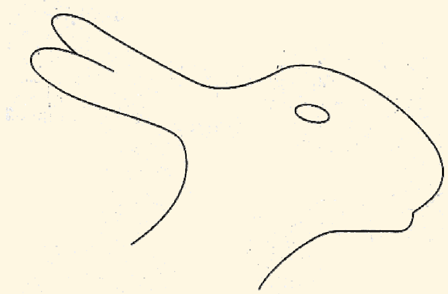


FIGURE 2.2. The duck/rabbit figure used by Chambers and Reisberg (1985).

- Mental processes are linked with perceptual processes BUT

- Mental "images" have both depictive and descriptive qualities

- Mental images carry abstract elements too

Apparently simple and de-contextualised mental images carry meaning that is not entirely captured by their visual and spatial properties

Creativity and discovery in the laboratory

Creativity and discovery is helped by

- Mental manipulation / transformation of images
- Transforming information between verbal and imaginal. Interference between imagery and language is also possible.
- Doodling, drawing, seeing and hearing, gesturing

Conclusions

- Multi-modal nature of cognition
- hence, mental models
- "Transformational" reasoning with models

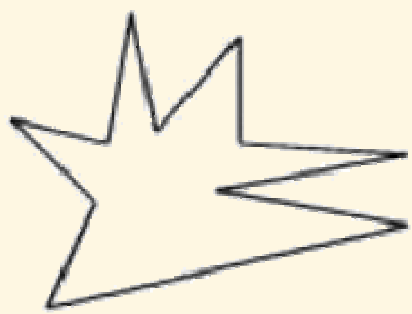
Multi-modal nature of cognition

- Synesthesia

e.g.

  - Numbers as colours
  - Cross-wiring between adjacent areas in the fusiform gyrus (V. S. Ramachandran)

Bouba



Kiki

V. S. Ramachandran and E M. Hubbard (2001). *Synaesthesia—A Window Into Perception, Thought and Language*. *Journal of Consciousness Studies*, 8, No. 12, pp. 3–34.

Cognition is inherently perceptual

- Abstract concepts are derived from complex configurations,
- of multimodal perceptual information,
- distributed over time (Barsalou, 2003)

- Visual, kinetic and auditory images
  (Hadamard, 1949)

From mental images to mental models

- Not a picture in the mind
- But a scheme for depicting and processing visual, spatial (and other) information
- Other = broadly conceptual

Cognitive – historical studies of visual thinking in science

- Knowledge-rich domains

- Long-term commitment to model
  (in contrast to milliseconds to minutes)

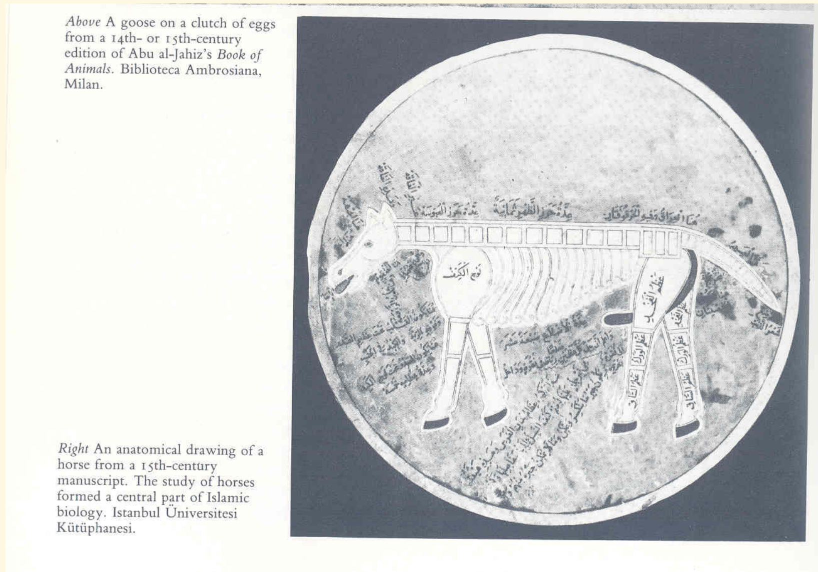
- Social context of science
  - Styles and tools of discourse

(Nersessian, 1995; Giere, 1996; Kierns, 1999)

Transformational reasoning in science example: Early biology

Visual images recorded as drawings

- Depictions of individual specimens transformed into idealised representations of types, ideals or species
- Generalisations drawn from visual images codified and elaborated into taxonomy
- Comparative anatomy (G. Cuvier (1769-1832))
- Transformations of biological forms (D'Arcy Thompson, 1917)
- Structure (static) - Function (dynamic)



Above A goose on a clutch of eggs from a 14th- or 15th-century edition of Abu al-Jahiz's *Book of Animals*. Biblioteca Ambrosiana, Milan.

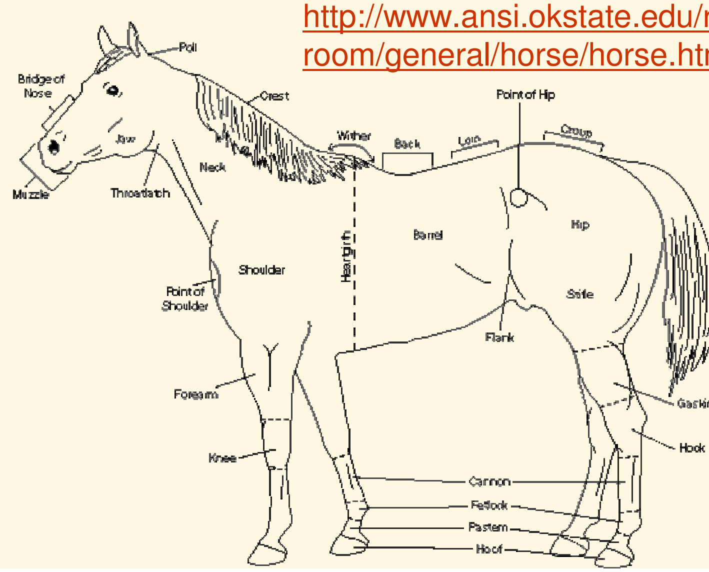
Right An anatomical drawing of a horse from a 15th-century manuscript. The study of horses formed a central part of Islamic biology. Istanbul Üniversitesi Kütüphanesi.

From Ronan, Colin A (1983). The Cambridge Illustrated History of the World's Science. Cambridge: Cambridge University Press.

Leonardo da Vinci, (1452-1519) Renaissance master made detailed drawings of the anatomy and physiology of the horse

Diagram of a horse

http://www.ansi.okstate.edu/resource-room/general/horse/horse.htm

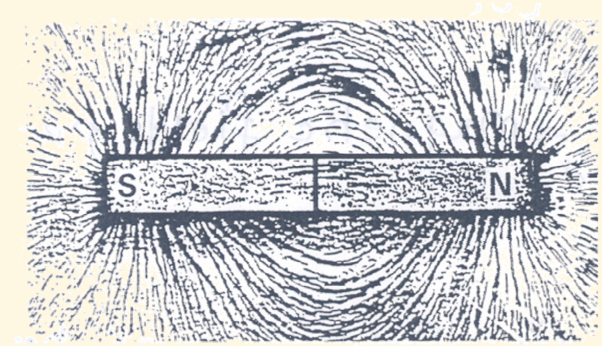


Transformational reasoning in science

Example: Electromagnetic theory

Faraday's lines of force

Mutually embracing curves



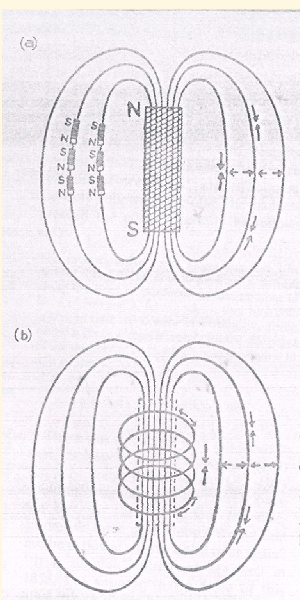


Fig. 4 (left). (a) Dynamics of Faraday's magnetic lines of force. Each line tends to contract along its length, but adjacent lines repel laterally. The result is a dynamic balance. (b) Bundle of current loops and associated lines of magnetic force. When the two sets of lines are taken as a system it is apparent that electric and magnetic effects are reciprocal. Longitudinal contraction in the magnetic lines has the same effect as lateral attraction between current lines, and lateral repulsion between magnetic lines has the same effect as longitudinal extension of current lines. Fig. 5 (right). Faraday's symbol of oneness between electric and magnetic axes of power. This would soon become the central image of Maxwell's first paper on electromagnetism, where he would label it mutually embracing curves.

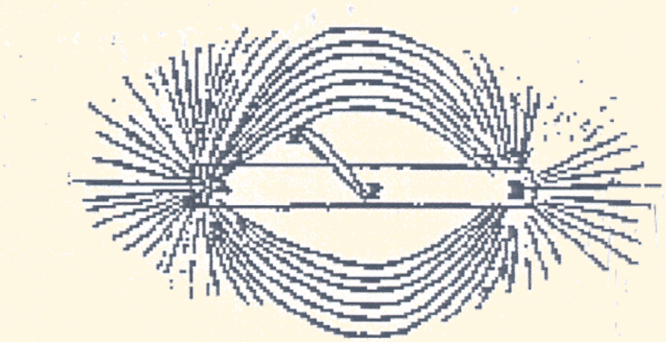


Figure 3. Faraday's drawing of the lines of force surrounding a bar magnet (Faraday 1839-1855, Vol I, Plate I).

Cognitive analyses of transformational reasoning

Early childhood:

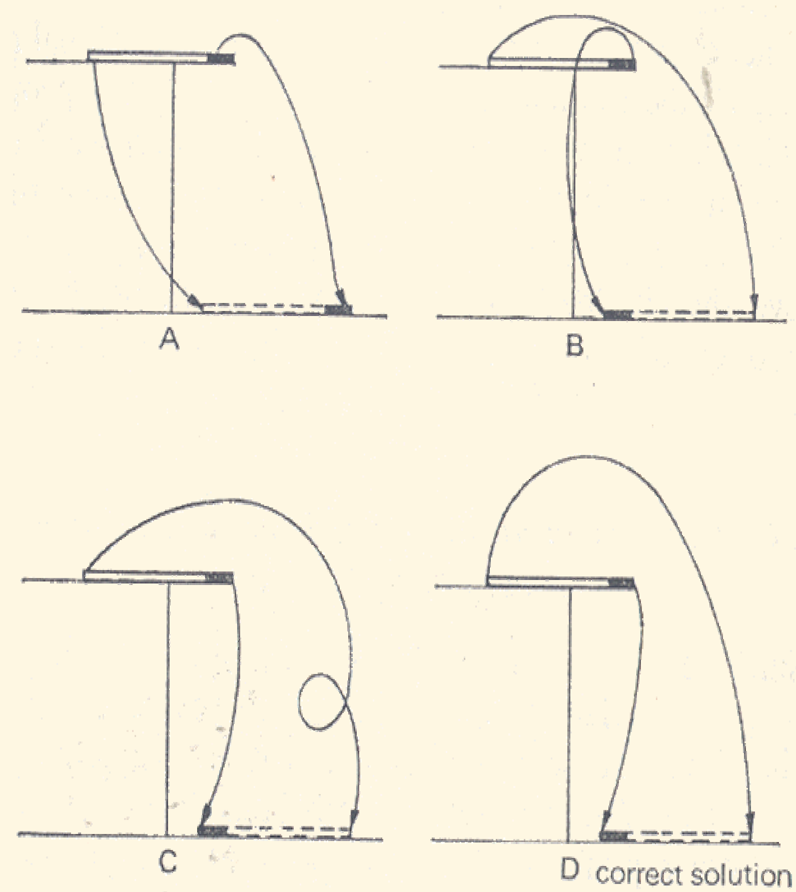
"reproductive imagery"

Late childhood:

"transformational reasoning"

But large individual differences in the adult population

Piaget, 1971



… Cognitive analyses of transformational reasoning

- Psychometric data
  (Hegarty and Waller, 2005)

  Two cognitive processes:
  1. Construction of an image (limited by time)
  2. Its transformation in memory (limited by complexity)
     - Object-centered
     - Viewer-centered

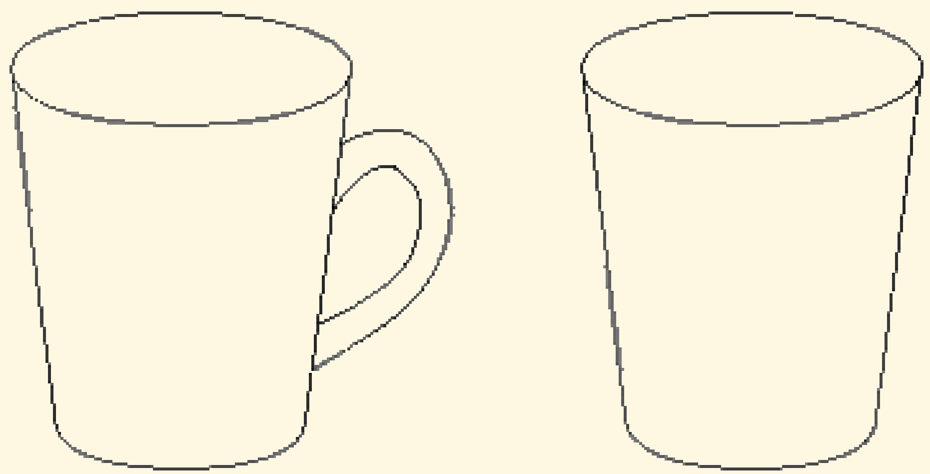
  Transformational ability is correlated with success in mechanical occupations, mathematics, physics and medical professions (Hegarty and Waller, 2005; Tversky, 2005).

Transformational reasoning through drawings

- Two functions of children's drawings: expressive and depictive

- Two ideas about depictive drawings:
  1. Transition from what we know to what we see

     Schematic stage to visual realism.



Wales, 1990

Transformational reasoning through drawings

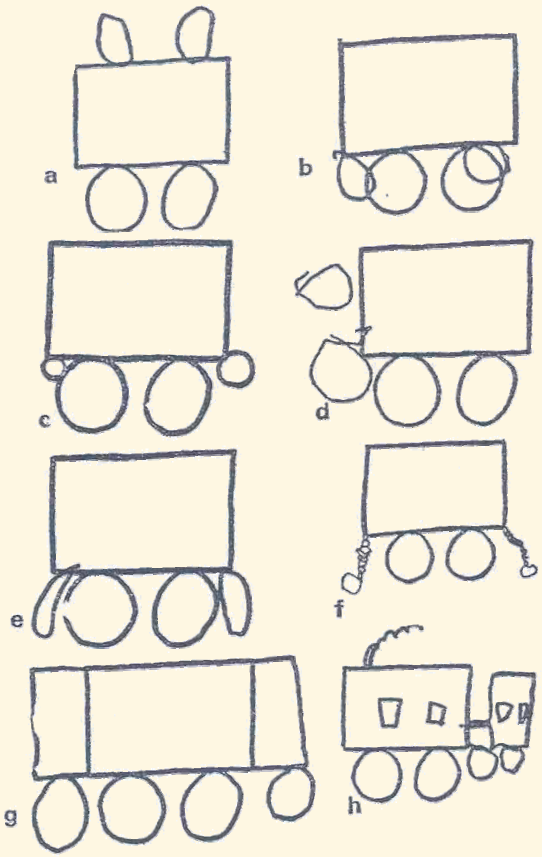
2. Procedural view - conceptual schemata constructed through activity, reflection and the influence of culture

   (Olson, 1970)

Problem-solving - task-specific conventions, strategies and organising principles

(Freeman, 1975; Goodnow, 1977)

56 Children's drawing



(23) How do you add two more wheels to a train, where wheels have pre-empted much of the lower space?

problem has been overcome by redefining the initial constra
the initial terms or premises that created the bind. In ef
the problem has been redefined and the difficulty wiped

Transformational reasoning through diagrams

Diagrams exploit properties of the visual system

- detecting spatial and geometrical relations
- efficiently encoding such information
- going beyond it to form generalisations

(Larkin and Simon, 1987; Pylyshyn, 2003)

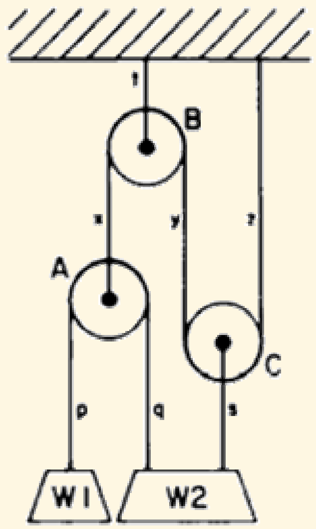


Figure 1. Diagram of the pulley problem.

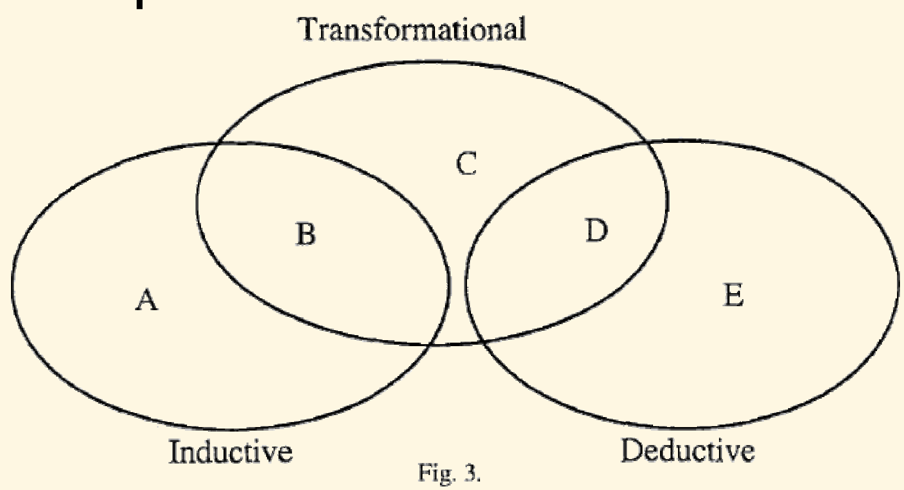
A diagrammatic representation of a pulley problem as described in:

'Why a diagram is (sometimes) worth ten thousand words"

Larkin and Simon (1987). Cognitive Science 11, 65-99.

Transformational reasoning through diagrams

- Diagrams use space to convey abstract concepts
  - External referential meaning (complex reality)
  - Internal meaning (inscription)
  - Rules for transformation are simplified
  - A series of abductive leaps
  - Warrant for belief



Simon, 1996

- In technology education: exploratory sketches→ procedural map→construction

Studies of visual thinking in the learning of science

Early studies are motivated by computer visualisations for pedagogy (Gilbert, Ed., 2006)

Need to take account of:

- Science and its pedagogy
- Developmental factors
- Social context of learning
  - Styles and tools of discourse

The issues:

- Conception, representation, transformation, communication
- Model-based transformational reasoning, manifested in ways characteristic of the domain

Some observations

- Visual-spatial images are easily susceptible to transformations: in the mind, or externally via concrete models, or on paper.
- Images can hold powerful metaphorical connotations which suggest relations and concepts extending beyond their concrete physical form (Arnheim, 1969; Tversky, 2005)
- Mental manipulations and transformations of images are a recurrent theme in the history of science (Shepard, 1978, 1988; Miller, 1984; Nersessian, 1995; Topper, 1996)

Transformational reasoning in science / learning

Physical world ⟷ Mental world

activity

social context

Observation

Description

Prediction

Explanation

Real situation

(Model-based) visual representation

Schematisation

Model-based visual representation

External representation

Restructuring

Drawings in the learning of science

Some prerequisites

- Familiarity with the medium
- Picture-text linkages
- Unit of comprehension
- Cultural priorities

Drawings in the learning of science

Some prerequisites

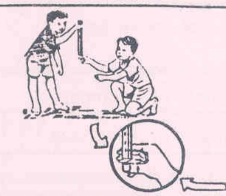
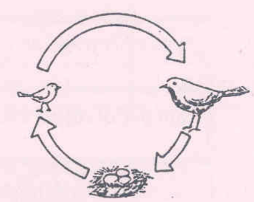
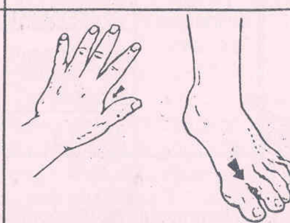
Type of Arrow	Name of the folder	Picture
Spatial Connection	खेळ खेळूया	
Transfer of material	पिण्याचे पाणी	
Direction of movement	दातांची निगा	
Sequence of Events	अंडी	
Drawing attention	खरूज	

Figure 5.5 : Types of arrows

Transformational reasoning in the learning of science

Diagrams integrate the visual with the semantic

- Transition from descriptive to explanatory

  - Drawings as descriptions

  - Use of contextual clues

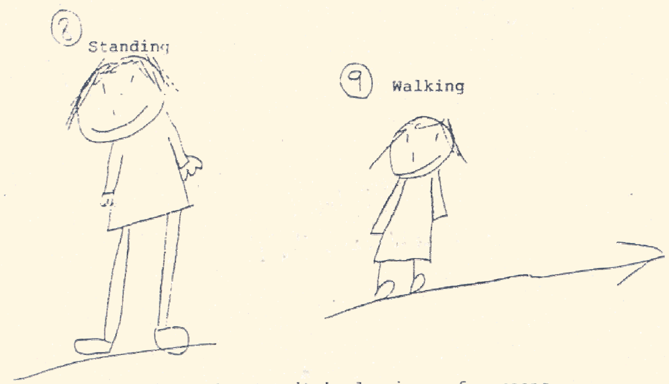


Figure 9 : Juanita's drawings of persons

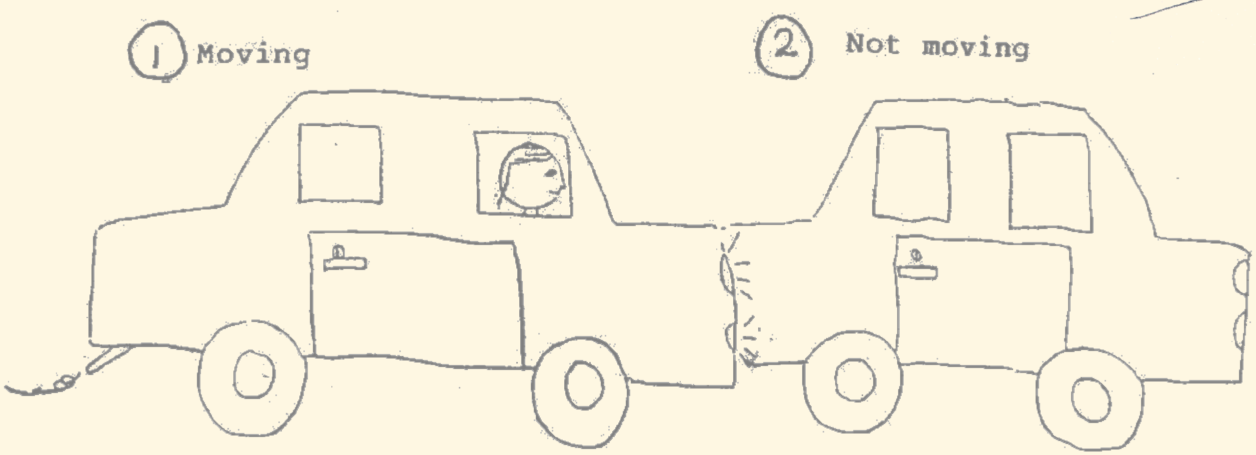


Figure 3 : Susan's drawing of cars

Transformational reasoning in the learning of science

- From descriptive to explanatory
  - Through contextual clues

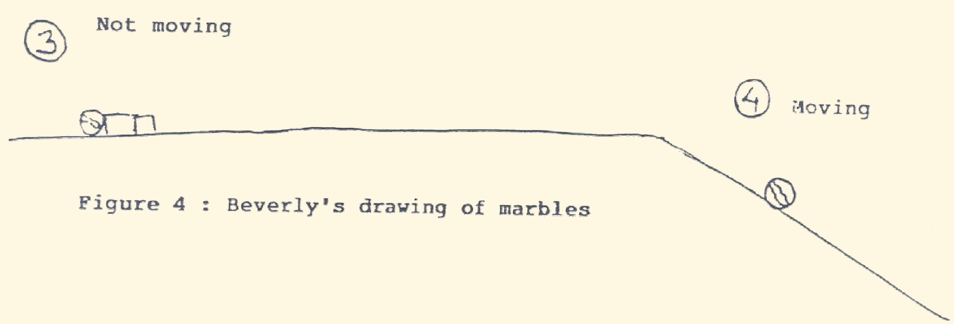


Figure 4 : Beverly's drawing of marbles

- Through schematization - use of conventions

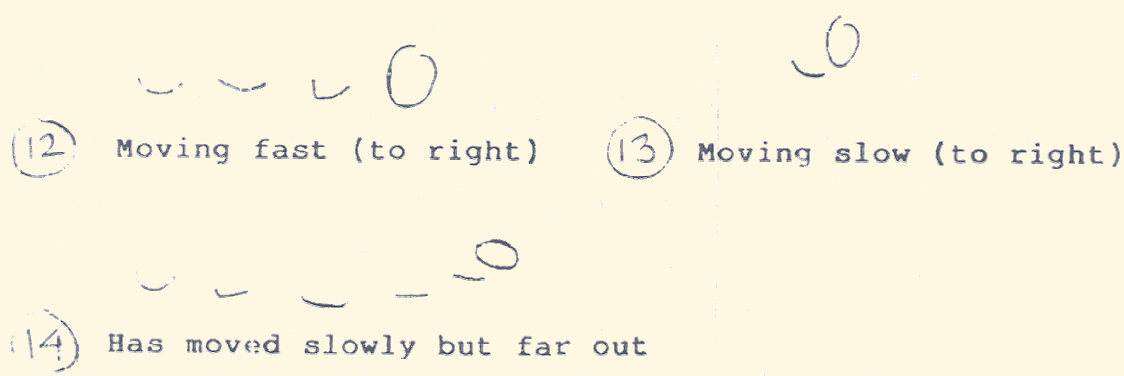
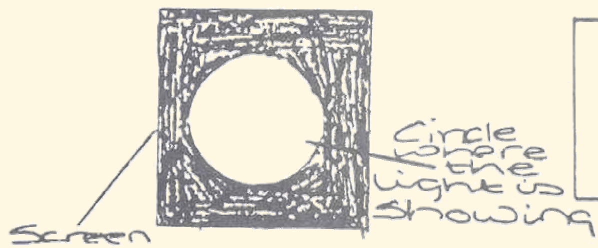


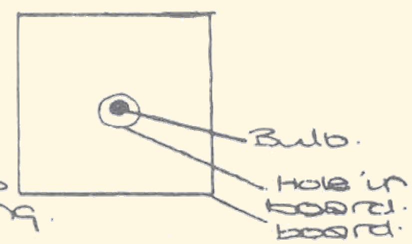
Figure 24 : Heather's drawings of fast & slow marbles

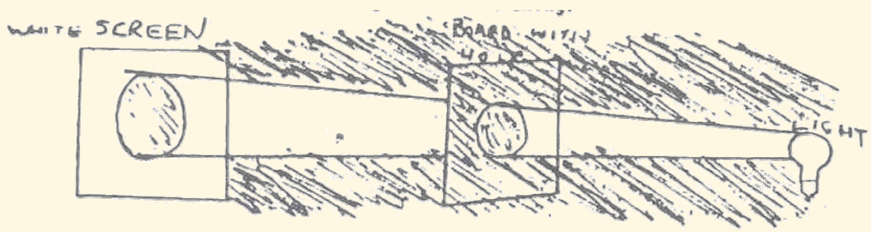
Transformational reasoning in the learning of science

Diagrams as opposed to verbal descriptions enable working within an abstracted context consisting of light sources, rays and geometrical projections

Transformation into a diagram allows conceptual elements into a perceptual description







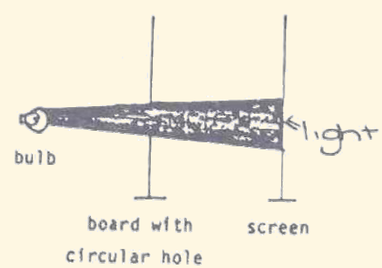


Figure a)
Side view of apparatus

Human physiology: structure and function

- Structure (static) - Function (dynamic)
- Diagrams – Text
- Mental manipulation

  “Suppose the stomach was in the shape of a pipe. What difference would it make? Would it affect digestion of food? If so, how?”

- Manipulation through diagrams

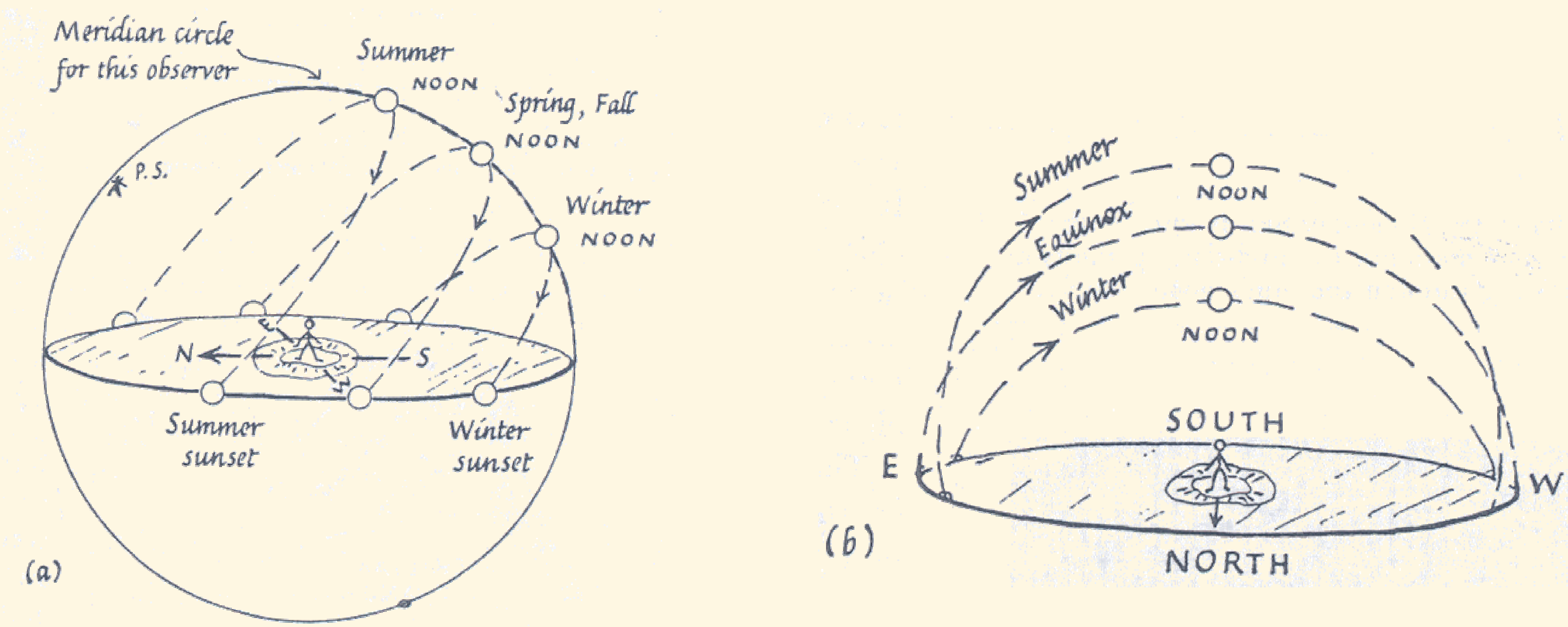
“The diagram below shows the trachea (wind-pipe) and the oesophagus (food-pipe) …

This is a cross-section of the trachea and oesophagus together. It shows us that the trachea is a hard, rigid tube compared to the oesophagus which is a softer and less-rigid tube …

Draw diagrams to show how the trachea, oesophagus and epiglottis might look when:
a) you inhale air normally
b) you swallow food normally
c) you get choked while eating”

Elementary astronomy

- Integration of
  - own observations
  - reports of earth-based perceptual data



Elementary astronomy

- allocentric models learnt in school

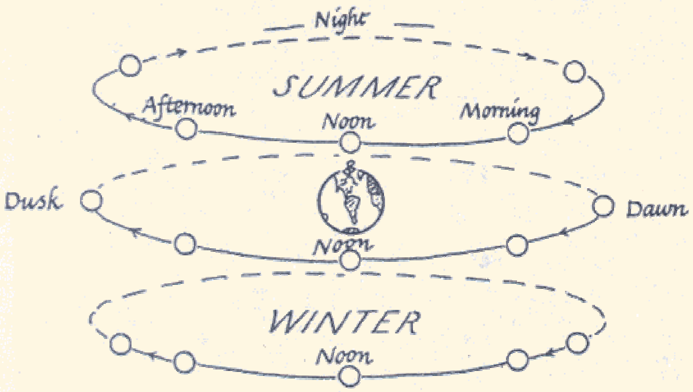


FIG. 13-6b. PATH OF SUN.
Viewed from stationary Earth, at various seasons. The Sun-positions are labeled noon, afternoon, etc., for observers in the longitude of New York. If such an observer could watch continuously, *unobstructed by the Earth*, he would see the Sun perform the "spiral of circles" sketched in FIG. 13-6c, during the course of 6 months from summer to winter; then he would see the Sun spiral upwards, revolving the same way, from winter to summer.

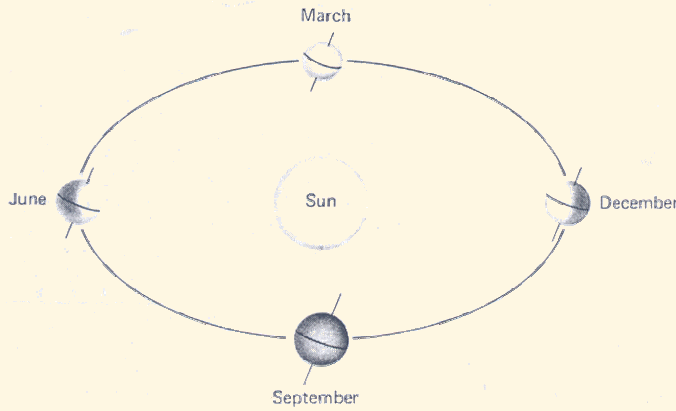


Figure 2–4. ***The Inclination of the Earth's Axis.*** The earth's axis of rotation is *not* perpendicular to the earth's orbit. The axis is tilted at an angle of $23\frac{1}{2}°$ and therefore the sun appears south of the celestial equator for six months of the year and north of the celestial equator for the remaining six months.

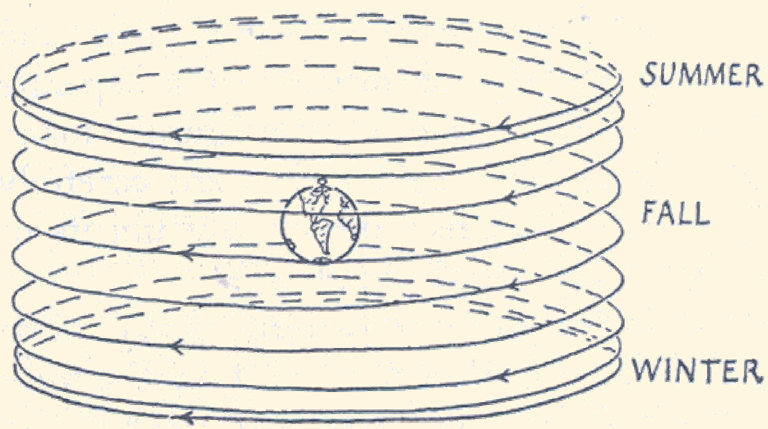
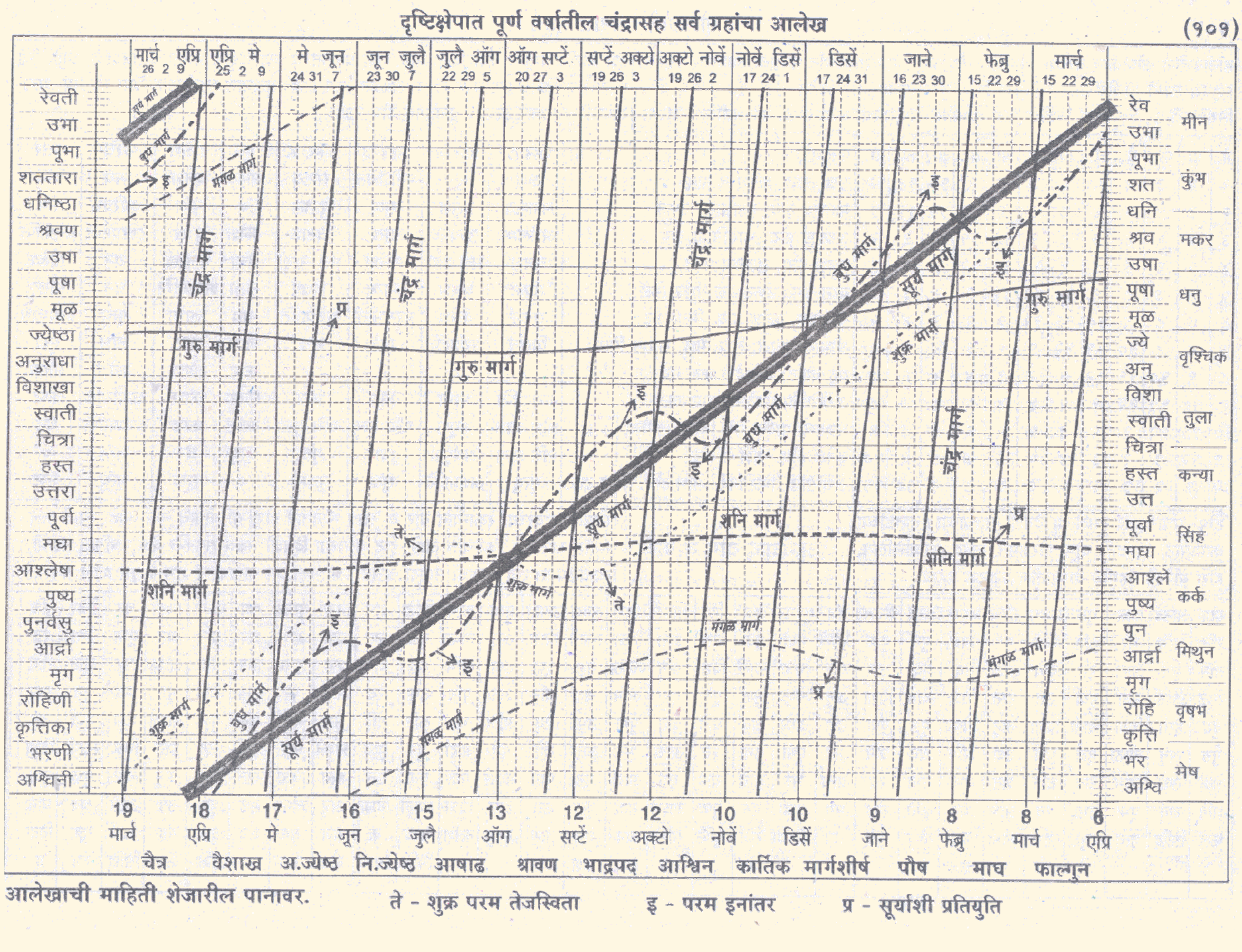


FIG. 13-6c. THE SUN'S SPIRAL OF CIRCLES, in course of half a year of seasons.

Elementary astronomy

- indigenous knowledge and practices



Elementary astronomy

- Tools

  - Gestures, role-play, kinesthetic feedback
  - Diagrams
  - Communication and collaboration

THANKS

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K. Subramaniam
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