VISUAL DEPICTIONS AND MENTAL VISUALISATION OF HUMAN BODY SYSTEMS IN MIDDLE SCHOOL STUDENTS

Ph.D. Synopsis

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1. Motivation for the thesis

Science is rich in visual images. The practice as well as pedagogy of science depends critically on the use of drawings and other visual elements. However, visual thinking, visual learning and visual communication (the three components of 'visual literacy') are relatively less popular as forms of learning, teaching and communication in Indian schools. Visual thinking refers to the incorporation of visual images as part of conscious or pre-conscious thought, and how we organize mental images meaningfully. Visual learning refers to the development of visual images for instructional purposes and the use of visual information to learn. Visual communication is the use of visual symbols to express ideas and convey meaning to others (Randhawa, 1978). Though textbooks and popular media make use of different kinds of visuals, expression of understanding through visuals and their comprehension is not given explicit focus within instruction. Biology is an inherently visual discipline and human physiology requires making linkages between structure and function: both of which are often not directly visible.

Hence the role played by visual literacy is crucial. Visual and verbal are two complementary modes of encoding and expression of ideas. Learning about biological systems requires the use of both of these modes. We explore in this thesis how students use visual and verbal forms of encoding and expression for their understanding of the human body.

2. Organisation of the thesis

This thesis is organised chapter-wise as described below.

Chapter 1: Introduction

Chapter 1 introduces our empirical work and the motivation behind it through a few broad themes and delineates the framework for the study.

The history of biology has numerous examples of the central role of visuals in the discovery of form and function in living systems. In the history of development of taxonomy, each specific instance of discovery consists of an iterative cycle moving from observations to initial theory formation to further observations, refinement of the theory and so on. In each case, observations are accompanied by diagrammatic records. From a cognitive and pedagogical perspective it is natural to ask how these visual observations, and their diagrammatic representations, are related to the mental visualisation that surely must have accompanied them. We have proposed in this thesis that analogical thinking and transformational reasoning are involved in mental visualisation, and that these processes underlie one's understanding of structure-function relationships in biology. We have used these ideas to develop tasks to assess mental visualisation of human body systems.

It is useful to distinguish between external and internal visual representations. External representations or 'visuals' are representations (e.g. diagrams) external to an individual - on a paper, computer monitor, etc.. Internal representations are formed in the mind of an individual. The activity of working with internal representations entails mental 'visualisation'. Both 'visuals' and 'visualisation' are important in the processes of thinking and reasoning.

Multiple external representations (MER) refer to a variety of representations possible besides the verbal in the processes of teaching and learning. Such representations include but are not limited to: spreadsheets, graphs, equations, tables, specialised software, blocks in the virtual world analogous to 3D blocks, symbolic representations, etc. (Ainsworth, 1999). In this thesis we have used line drawings as an instance of the visual mode and included the verbal mode too in our category of multiple external representations. These two modes occur all through the study from the formulation of questionnaires, development of the coding system, and observations and analysis of students' responses.

We have drawn inspiration from ideas of 'systems biology' to assess and interpret students' verbal and drawn responses. Systems ideas, though proposed about half a century ago, have re-emerged as a new prism which can help us understand, explain and describe complex systems such as life.

The systems biology paradigm suggests that we probe students' understanding of systems (as much as individual parts), their basic structural attributes, function and most importantly, the structure-function relationships. These criteria underlie our coding scheme for both verbal and drawn responses. The assessment also consists of correlations among structure-function (and text-diagram variables) to see their inter-connectedness. We studied students' understanding of the systems at two different levels of organisation (macro and micro) and also their reasoning about emergent consequences of structure-function relationships.

Chapter 2: A review of literature

Chapter 2 presents a review of literature focussing on the different uses of the term 'visual' and 'visualisation' and research which has studied external depictions or 'visuals' and internal mental 'visualisation'. The terminology is clarified. Visuals lie along a continuum from more depictive to more schematic representations. Visual information processing is simultaneous and holistic occurring through mechanisms of vision, whereas verbal processing is sequential or step by step (Farah, 1989). There are also differences in the understanding of the 'visual' in the sciences and in the arts. In the arts, “the image is the statement”. However in science, appearances point to something beyond, which is connected to the subject that is depicted (Arnheim, 1969).

Kearsay and Turner (1999) use the term 'visual literacy' in a more restricted and perhaps in a more operationalisable way than Randhawa (cited earlier). They refer to students' ability to 'read' pictures as 'visual literacy'. They also mention the complementary concept of 'graphical literacy' which could be applied to flowcharts, scientific diagrams, pictures and photographs. Roth et al. (2005) attempt to articulate what it takes to engage inscriptions in a critical and meaningful manner, calling this knowledge and ability 'critical graphicacy'. There are several factors which affect the interpretation of pictures such as cognitive and emotional interest, pictorial conventions, training and prior knowledge of the learner, picture-text-learner interactions and the type of representation.

Over the last forty years, the concept of mental visualisation has gained increasing acceptance in cognitive science. Alan Paivio proposed in his dual coding theory that cognitive information processing occurs through two distinct but interconnected systems: one for visual and the other for verbal information (Paivio, 1980). Information is much easier to retain and retrieve when dual-coded because of the availability of two interconnected mental representations. Furthermore, pictures rather than words are more likely to activate both coding systems. Guèrin at al (1999) have formulated a model which explains the role of mental visualisation in the production of drawings. They postulated a 'visual' pathway that is used to process unfamiliar drawings and a 'non-visual' pathway used to process routine drawings.

External representations are tightly bound to the domain, context (culture and situation) and learner (learning styles and background). Liddell (1997) documented some interesting differences in the use of pictures for comprehension of text in South African and British children. Studies carried out in the Western context suggest that a depictive representation makes text interpretation easier and richer. However this was not validated by results obtained with South African children who used pictures in a passive form or for expository purposes, a practice that children appear to bring from home.

There is documented evidence that some children are predominantly visual learners, or at least they respond more positively to visual stimuli. Alcock and Simpson (2004) have documented some interesting differences in the styles of thinking and reasoning of visual and verbal thinkers.

The role of visuals and visualisation in the history of science and in the practice of science is well-documented. Barbara McClintock, the Nobel-prize winning cytogeneticist used photographs as both her evidence and the key to her explanations, quite opposed to the prevailing trend at that time of using schematic representations. Visuals are used during the process of teaching and learning in a variety of ways. They may be used to depict an object or event as it exists (taxonomical diagrams in biology depict detailed structural observations), to elucidate a problem situation or structural aspects such as Punnett square used by geneticists which also helps to predict the outcome of a cross or breeding experiment, and as a summary or final stage of the reasoning process such as a flow chart, a concept map, or any summary which is graphical in nature.

Human body systems have been documented in the Indian and Western context. In the Indian context, the treatises *Charaka Samhita* and *Sushruta Samhita* are representative precursors of the medical and surgical schools which rely entirely on text descriptions. Vesalius's monumental work “The Fabric of the Human Body” (published in 1543) was considered for several centuries to the best illustrated atlas of the human body. Children's ideas about human body systems have also been documented for several decades. Significant work in this area has been reviewed.

Chapter 3: Rationale underlying the thesis

Chapter 3 describes the rationale underlying the thesis. We address the question of how to assess visuals and visualisation through students' verbal and drawn responses. Can we use students' verbal and diagrammatic responses to draw inferences about mental visualisation? Two possibilities are suggested from previous research, one deriving from analogical thinking and the other from transformational reasoning.

The use of analogies and analogical thinking in the history of science as well as in pedagogical practice shows the close connection between mental visualisation, model-based reasoning and analogical thinking. Analogical thinking is inherently visual in nature because of the pattern-matching that occurs between the source and target. In the study of human body systems we have used the term 'analogy' broadly to cover all explicit comparisons related to both structure and function. Analogies help students bridge the gap between their real world knowledge and abstract concepts thereby increasing their motivation too.

Ramadas (2009) reviewed research on ‘transformational reasoning’ as an aspect of visual thinking, as seen in science, and in children’s learning, specifically in the learning of science. This review makes the argument that transformational reasoning offers a promising method to study mental visualisation. The term 'transformational reasoning' first proposed by Simon (1996), refers to a reasoning process that is neither inductive nor deductive, but draws on the characteristics of both forms. This reasoning process is set in motion when learners actively search for or try to get a sense of “how things work”. It exploits an ability to understand the workings of a system and translate it into a mental or physical representation that can be “run”. The result is a dynamic process by which a new state or continuum of states are generated. Such reasoning, Simon points out, has been implicated in the process of creative discovery as seen from reports of scientists, popularly called “thinking out of the box”.

In developing our assessment methods as well as some of our comprehension passages explained in Chapter 5, we have drawn from the studies of Heiser and Tversky (2006) on mechanical systems. Whether one considers biological systems or mechanical ones, a common conceptual framework encompassing structure and function underlies expression through both text and diagrams. Three very general aspects of this common framework are: (1) Segmentation, (2) Order, and (3) Hierarchy (Tversky, 1999). These aspects enable us to assess both descriptions and depictions using a common set of criteria, and thus to translate between verbal and visual modes of expression. With this rationale we conducted an empirical study which was exploratory in nature. Through this study we formulated a coding scheme for students' text and diagram responses.

To characterise mental visualisation, we have employed unfamiliar problem situations which might necessitate generating and manipulating visual images or transformational reasoning. Visualisation questions could be categorised into five different kinds: 1) describing or drawing a diagram from a novel viewer / object orientation, 2) describing change in appearance of organs during regular function, 3) manipulating structure by change of size / dimension and anticipating its effect on function, 4) manipulating structure by making it appear like some other organ, or asking the student to imagine an alternative structure, and anticipating the effect on function and 5) describing the appearance of a system, an organ or substance following a transformation. Correlation of form with function is essential to understanding human physiology. Transformational reasoning on an image or a diagram helps to visualise structure and function and the relationships between them.

The empirical study was carried out in two phases. Phase I was an exploratory study conducted with thirteen students, which helped refine our methodology for testing on a larger sample in Phase II. Modifications were made to our methodology as an outcome of Phase I. We developed a coding scheme (explained in Chapter 4) which was validated in Phase I for use with the larger sample of Phase II.

The design of the study was 'Mixed Methods'. A mixed methods research design is a procedure for collecting both quantitative and qualitative data in a single study (Creswell, 2003). This design seemed appropriate to the nature and scope of the study and it allowed us to draw from the strengths of both methods of analysis, while addressing in some measure the weakness of each.

Chapter 4: Exploratory Phase (Phase I)

Chapter 4 moves on to the first phase of our empirical study, which was concerned with students' understanding of the digestive, respiratory and circulatory systems of the human body.

Research questions

The following research questions were formulated:

I/1. How can we assess students' expression of understanding of structure and function through verbal descriptions and diagrams?

I/2. How effectively do students express their understanding of structure and function through written and spoken (i.e. verbal) descriptions?

I/3. How effectively do students express their understanding of structure and function through diagrams?

I/4. Is there a correspondence between expression of understanding through verbal descriptions and diagrams?

I/5. What are some of the qualitative characteristics of students' diagrams?

I/6. What are students' preferences for written versus diagrammatic expression to communicate their understanding?

I/7. Can we use analogies to study the visual imagery involved in understanding of human body systems?

I/8. What are students' conceptual difficulties related to structure and function of human body systems?

Sample of students, curriculum, questionnaires and analysis

Thirteen students who had completed Classes 6, 7 and 8 were selected from an English medium school in Mumbai, India. The sample was mixed in terms of ability level. The students belonged to a school located on the campus of a well-known scientific establishment in the city. Their parents were either scientists or engineers. Students were asked to respond to three questionnaires on the digestive, respiratory and circulatory systems. They were also asked to express themselves spontaneously using diagrams and words as they wished. Every student was interviewed after the administration of each of the three questionnaires.

The questions were designed keeping in mind the content of the textbooks for Class 6. The type and sequence of questions was similar for the three systems, consisting of basic knowledge questions for the entire system, a comprehension passage and open-ended questions requiring the use of analogies. The data from the written questionnaires and interview transcripts were pooled for each student. Two forms of responses were distinguished: “Verbal” (Vr) and “Drawings” (D). A scheme of analysis was developed based on the rationale described in Chapter 3. This led to a coding scheme that could be used across text and diagrams and incorporating both structure and function aspects. The coding scheme is summarised in Table 1.

Table 1: The scheme of data analysis

Basic knowledge			
Text responses (Vr)		**Diagram responses (D)**	
Structure (VrS)	**Function (VrF)**	**Structure (DS)**	**Function (DF)**
Names of Organs	-	Segmentation (depiction of organs)	-
Order (described location of organs)	Order of action	Order (depicted location of organs)	Order of action
	Hierarchy (descriptions)		Hierarchy (depictions)

Since the sample of students in Phase I was small, it was possible to track their performance through scattergrams combined with case studies. Further, the scores were analysed statistically to compare and correlate students' understanding of structure with their understanding of function. Scores on verbal and drawn responses were combined to give a total structure score and a total function score. Pearson's correlation coefficient (ρ) was determined between verbal-drawing and structure-function scores across all the systems. The Fisher's transformation (z) was carried out in order to check for significant difference between the scores. Students' mean scores and scattergrams were analysed and the observations were summarised.

Observations and results

Research questions I/2 and I/3 dealt with students' understanding of structure and function concepts as expressed through text and diagrams. Question I/4 asked whether there is a correspondence between expression through text and diagrams. We found that mean scores were in general high for all the criteria (VrS, VrF, DS and DF shown in Table 1) across the three systems. Correlational analysis painted a different picture. In comparison with the other systems, the digestive system alone presented an anomalous result in not showing correlations for both structure-function and verbal-drawing scores. Structure and function scores were correlated only for the respiratory system, whereas verbal and drawing scores were correlated for the respiratory and circulatory systems. The correlations along with the accompanying scattergrams were interpreted qualitatively in terms of students' understanding and treatment of these topics in their textbooks.

Research questions I/5 and I/6 had to do with students' preferences for verbal or diagrammatic expression and qualitative characteristics of their diagrams. Although the majority of students drew textbook-like diagrams, some came up with diagrams which were quite different from what is given in their textbooks. All the diagrams could be classified into two kinds: those within the constraints of the human-body outline and diagrams drawn without the outline. Some students drew their own outlines of the human body to depict the organs within it. To depict a process, such as the process of digestion, the organs were shown as separate parts with descriptions of what goes on in each part.

Students were equally divided about their preferences for diagram or written expression. Positive aspects stated by them include: diagrams giving an overall view, evoking interest, etc.. Negative aspects were difficulty with drawing, and exactness required while communicating through diagrams.

In response to Research question I/7 regarding students' use of analogies, we found that students came up with a variety of analogies, both structural and functional. There were also many responses which did not present analogous examples, but were described in terms of the structure or process itself, (e.g. stomach reminds me of digestion). The structural analogies included those based on mere appearance like “the liver is like an upside down triangle” and those based on appearance but which also included more relational attributes like “the stomach is like a bag”. Here the stomach is not just visually like a bag, but it can also hold stuff just like a bag does. In some cases students made the functional attributes explicit, as in “the stomach is like a bag which keeps getting filled”, in which case it was classified as a functional analogy.

Examples of functional analogies conclude the heart being referred to as a water pump, the action of the lungs to a balloon contracting and expanding, and the stomach analogous to a grinder. These examples illustrate the fact that there is an overlap between structural and functional analogies.

Students' responses to the analogy question were not scored quantitatively. Rather, at this stage we were interested in looking at the qualitative characteristics of the responses.

Research question I/8 had to do with common conceptual difficulties present among students. Macro level processes such as the role of the mouth, food-pipe and to some extent the stomach were better understood compared to the role of the liver and pancreas, and therefore the process of chemical digestion (micro-level processes). Likewise for the respiratory system, the role of the nasal passage and trachea were easier compared to cellular respiration and the connection between the respiratory and circulatory systems.

Though there were no clear-cut 'visualisers' or 'verbalisers' in this sample, we were able to identify two students whose styles of communication were predominantly diagrammatic or schematic / verbal. Case studies of these two students: TT and GP, are explained in the thesis with examples of their diagrams.

There were some methodological outcomes of Phase I. We modified our analogy questions in Phase II by introducing some task constraints. Also, the coding scheme for analysis of diagrams and text was used with some modifications in Phase II.

Chapter 5: Phase II - Basic knowledge, visualisation and comprehension of text and diagrams

Chapter 5 describes Phase II of the study where we tried our revised questionnaires and scheme of analysis with a larger sample of students to understand their written and drawn responses as well as responses to 'visualisation' questions. Part 1 of Phase II dealt with basic knowledge and visualisation. Part 2 dealt with comprehension and inference from text, while Part 3 dealt with comprehension and inference from diagrams.

Research questions

The research questions which were formulated for the three Parts of Phase II are given below.

Part 1

II/1. How effectively do students express basic understanding (i.e. structure and function) of the digestive and respiratory systems through text?

II/2. How effectively do students express basic understanding (i.e. structure and function) of the digestive and respiratory systems through diagrams?

II/3. Is there a correspondence between expression of understanding through text descriptions and diagrams?

II/4. What are students' conceptual difficulties related to the structure and function of human body systems?

II/5. How do we characterise mental visualisation?

II/6. How is mental visualisation (characterised in terms of transformational reasoning) related to students' understanding of structure and function through text and diagrams?

Part 2

II/7. How well do students comprehend and infer structure-function relationships through text describing structure or function?

Part 3

II/8. How well do students comprehend and make inferences from diagrams conveying predominantly structure or function?

II/9. How can pedagogical practices be informed by our understanding of visual literacy?

Research questions leading from Phase I:

II/10. Do structure and function scores for the respiratory system show more correlation compared to the digestive system?

II/11. Are the alternative conceptions for the digestive and respiratory systems found in Phase I of this study found in the larger sample of Phase II as well?

II/12. Are 'visualisers' and 'verbalisers' distinguishable?

Questionnaires and analysis

Phases I and II differed with respect to the sample, questionnaires, data and coding scheme. The differences are elaborated in Table 2.

Table 2: Differences between the two Phases

Criterion	Phase I	Phase II
Sample	• 13 students • 6 girls, 7 boys • drawn from one school • from scientists' families	• 87 students • 46 girls, 41 boys • drawn from four other schools on the same campus • from mixed socio-economic backgrounds
Questions	• Students were questioned on three systems: digestive, respiratory and circulatory • Tested mainly for basic knowledge with one questionnaire for each system • Outlines of the human body given for drawing diagrams • Comprehension passages taken verbatim from the textbook • Questions on the system as a whole • Open-ended questions on analogies	• Students were questioned on two systems: digestive and respiratory • Tested through three parts: basic knowledge and visualisation (Part1), comprehension of text (Part 2) and comprehension of diagrams (Part 3) • No outlines were provided • No comprehension passages in Part 1. Included as separate questionnaires in Part 2. • Questions on individual organs in Part 1 • A few questions on analogies with some constraints; transformational thinking assessed through questions on manipulating s-f related to understanding (visualisation in Part 1)
Data	• Verbal (written + oral) and drawn responses	• Written and drawn responses
Coding scheme	Structure criteria: Segmentation / Organs and Order Function criteria: Order and Hierarchy calculated separately and then added to	Structure criteria: Same as Phase I Function criteria: Order and Hierarchy combined during calculation to obtain the F score

	obtain the F score.	

Part 1: the digestive and respiratory systems through text and diagrams

The questionnaires for Phase II Part 1 incorporated questions on basic knowledge (structure and function) and mental visualisation (using the notion of transformational reasoning). 'Visualisation' questions for both the digestive and respiratory systems were of five different types as mentioned in Chapter 3. Examples illustrating these types of questions are given below:

1. *Describing or drawing a diagram from a novel viewer / object orientation*

- Suppose you ask your friend to open wide his mouth. You then look inside it. What organs do you see inside the mouth? Describe their shape. How do these organs help in digestion of food?

- Draw the inside of your friend’s mouth as it might have appeared to you.

An example from the respiratory system is:

- How do you think the inside of your nose looks like? Make a drawing of how it looks like when:

  a) you breathe in air containing dust particles

  b) you breathe out

2. *Describing change in appearance of organs during regular function*

Questions in this category are in the questionnaire for the respiratory system alone. Examples of such questions are:

- Draw and explain the changes that take place to the lungs and diaphragm while:

a) you breathe in and b) you breathe out

- What do you think is the difference between a sneeze and a cough?

3. *Manipulating structure by change of size or dimension, and anticipating the effect on function*

   Questions in this category are in the questionnaire for the digestive system alone.

- Suppose the food pipe was longer or shorter, what difference would it make? Would it affect digestion of food? If so, how?

4. *Manipulating structure by making it appear like some other organ, or asking the student to imagine an alternative structure, and anticipating the effect on function*

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

- The trachea is quite strong and rigid compared to the oesophagus or foodpipe. Why is it that way?

5. *Describing the appearance or function of a system or organ or substance following a transformation*

- Draw and describe the appearance of a piece of toast at each step of the process of digestion.

- Do you think air taken into the body could serve any other function besides its role in respiration?

Responses to questions on basic knowledge were coded using the segmentation, order and hierarchy framework outlined in Chapter 3. Responses to Visualisation questions were coded separately using a four-point coding scheme which checked for generation and manipulation of images. Analysis was carried out on the five variables: Text Structure (TS), Text Function (TF), Diagram Structure (DS), Diagram Function (DF) and Visualisation (V).

The coding of all responses was done by the author. An independent coder was then trained by the author, using about 36 – 63 coding instances. This trained coder then coded a random set of 10 answer sheets for each system. Scores were calculated as per our scheme of analysis. Finally the Spearman's correlation coefficient (ρ) was determined between scores. The correlations were significant at $p<0.01$ level for all the variables of the digestive system. For the respiratory system the correlations between scores assigned by the two coders were high ($p<0.01$) for all the variables except TS, for which the correlation was significant only at $p<0.05$.

Statistical analyses included frequency distributions which were plotted along with descriptive statistics for all variables. To check for differences in mean scores between the variables, t tests were done. Spearman's correlation coefficient (ρ) was used to check for significant correlations between scores on the variables.

Observations and results for Part 1

Research questions II/1, II/2 and II/3 had to do with students' basic knowledge of the digestive and respiratory systems and its expression through text and diagrams. The results indicate that structure concepts were understood better than function concepts. Also students expressed both structure and function concepts better through text than through diagrams. They also showed a preference towards expression through text: more than a third responded exclusively through text. Among students who drew diagrams, text scores were significantly higher than diagram scores. Most student diagrams were stereotypical but imperfect copies of textbook diagrams.

Diagrams of the digestive system presented an anomaly: function was better expressed compared to structure. The anomaly was probably due to the high level of structural complexity in the digestive system, with a larger number (12) of organs to be depicted in the correct shape and relative spatial configurations. Correlational analysis indicated a consistency between TS and TF and between DS and DF for both digestive and respiratory systems. For the digestive system, there were higher correlations of visualisation with text scores than with diagram scores, but this was not so for the respiratory system.

Frequency distributions showed a high incidence of students not drawing diagrams at all. The other striking aspect of the distributions for the digestive system is their bimodal nature, with a disproportionately large number of students in the middle. Using Low, Medium and High categories to sort the original responses, we identified discriminating factors between the medium and high-scoring students to be their understanding of the small intestine and accessory organs, namely, the liver and pancreas, and the small intestines.

Scores for the respiratory system were lower than those for the digestive system. The distributions of scores showed that they were skewed towards the lower scores but not bimodal (as was the case of the digestive system) leaving aside the large incidence of students not drawing diagrams at all.

Research question No. II/4 asked about the conceptual difficulties students had with respect to the two systems. The most common error was to consider the food to go into the liver and pancreas during digestion. The other common error had to with the connections between the stomach / duodenum and the small and large intestines. Difficulties in understanding for the respiratory system were common across the range of students unlike the case of the digestive system. Conceptual misunderstandings about respiration, involving the pharynx, bronchioles, alveoli and diaphragm, were uniformly present across low and medium scoring students.

Research question II/5 and II/6 had to do with characterising mental visualisation in the context of our study. In parallel with scores on basic knowledge, visualisation scores too were significantly higher for the digestive system compared to the respiratory system.

For the digestive system, of the 25 students with high visualisation scores, 18 had high text scores while 9 had high diagram scores. This was not as surprising as it might seem, since most of the visualisation responses could be given in the verbal mode, and most students preferred to do so. Students who could describe the system effectively could also articulate what would happen if structure of the system was different or it was viewed in a different way. Their difficulty lay more in exact depictions on paper than in mental visualisation. Thus we could conjecture that good visualisers were also good verbalisers, but that drawing skills did not necessarily accompany mental visualisation. For the respiratory system however we found that the correlations were all comparable, so these results are still not conclusive.

Research question II/9, following from Phase I had to do with structure and function scores for the respiratory system being more correlated than those for the digestive system. We found that in Phase II, structure and function scores for both systems were significantly correlated. Since the questions on structure and function were ordered as per the order of each individual organ of the system, students may have found it easier to correlate structure with function.

Research question II/11 had to do with a comparison of the conceptual difficulties from Phase I to II for both the digestive and respiratory systems. It was found that for the respiratory system also, similar alternative conceptions were found. In both systems, an understanding of processes at a macro level, the passage of food or air, was attained by most students, while difficulties arose at the microscopic or chemical level, the action of the liver and pancreas, alveolar action and cellular respiration.

Research question II/12 (which was also a question leading from results of Phase I) asked if visualisers and verbalisers were distinguishable. We tried to check this from the students' mean scores. The scores were recoded into three categories: Low (0-0.33), Medium (0.34-0.66) and High (0.67-1.00). After recoding the scores as low, medium and high we found that a group of high-scoring students were good in both visual and verbal modes, while another group of pure 'verbalisers' had minimal facility with diagrams. There were no students who were good with diagrams but not with text. Thus, a few verbalisers could be distinguished but not visualisers.

Part 2: Comprehension of structure-function relationships from text

In our analyses of students' responses to questions in Parts 2 and 3 we have classified certain questions probing for certain aspects of content as more 'easy' or 'difficult' based on the mean scores. The results are qualitatively substantiated with reference to the nature of the questions and their content.

Research question II/7 had to do with students' comprehension of structure-function relationships from text. Structure and function tasks were designed to probe these aspects. This was easier to do for the digestive system, but not for the respiratory system where a clear separation into structure and function was difficult. For the digestive system, two passages were prepared, each in two different versions: a 'structure' version (Part 2A) and a 'function' version (Part 2B) to be administered to two sub-samples of students.

Not surprisingly, students were more competent at answering questions calling for prior knowledge from the textbook than those which were outside of the textbook. Mean scores on questions pertaining to Passage 1 pertaining to the teeth and saliva were higher than those pertaining to Passage 2 on the oesophagus and stomach. Within the first passage, questions pertaining to the teeth were easier in both structure and function versions of the passages, than those relating to action of the saliva.

In general, students found it difficult to answer questions requiring transformational reasoning, particularly those related to the epiglottis, mucus and glands - parts of the system that were relatively unfamiliar to students. The question on 'glands' was the most difficult one in both versions of the passages.

Questions calling for drawing inferences regarding structure-function relationships (which were in the majority) were used for further quantitative analysis. From the scores on these questions, mean s-f scores were calculated for Passage 1 and Passage 2. Wilcoxon's signed ranks test was used to check for significant differences between the mean scores on Passage 1 and Passage 2 in Parts 2A and 2B. The Mann Whitney U test was used to check for differences between the mean score for each passage in its two versions in Parts 2A and 2B.

Scores on Passage 2 in both versions were lower than the corresponding scores on Passage 1, a difference that might be attributable to prior knowledge. Passage 1 concerned chewing of food in the mouth, a phenomenon that is familiar from prior experience as well as school learning. Passage 2 concerned the mechanical action of the epiglottis, oesophagus and trachea, situations that are further removed from experience, structurally more complex, and also passed over quickly in middle school.

Interestingly, though scores on Passage 1 in the structure and function versions were not significantly different, in Passage 2 scores on the function version were higher. Thus the 'function' version of Passage 2 enabled students to understand the role of the epiglottis and of mucus and to better depict how the food is pushed from the mouth to the stomach. Overall these results indicate that the content of the passages affected the results, more than the fact of it being a predominantly structure or function description.

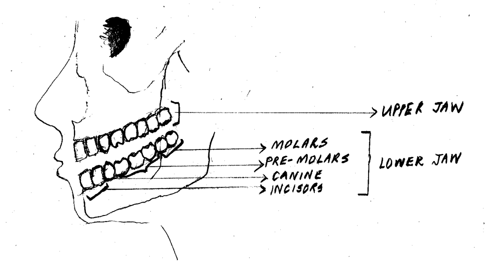
For the respiratory system, there were three passages, the first describing predominantly structure and the next two describing predominantly function. Equivalent structure and function passages were not prepared because of the difficulty in clearly separating structure from function and also because of limitations of possible level of detail, considering the grade level of the sample. Chemical aspects of respiration could not be probed in detail, so mainly mechanical action was considered. All students answered a single version of the test.

For the three passages on the respiratory system we found generally lower scores than for the digestive system. As for the digestive system, questions requiring inference-making and drawing new diagrams were found to be difficult. Except for question 1a which required drawing of the respiratory organs mentioned in the school textbooks, the other 'diagram' questions were difficult for students. Three questions requiring transformational reasoning dealing with the larynx, pharynx and diaphragm were relatively easier though this was not a clear pattern. As for content, Passage 1 about the organs of the system was easier for students compared to Passages 2 and 3 about functional aspects. Ciliary action was difficult for students to comprehend followed by the mechanics of breathing. In general, students did not have a clear conception about the bronchioles, alveoli and capillaries.

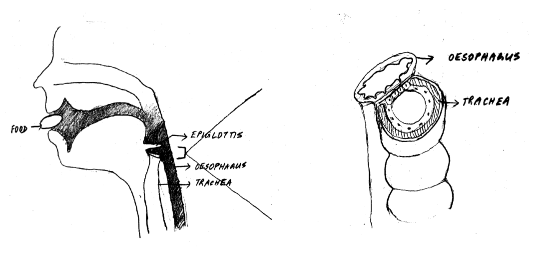
Part 3: Comprehension of diagrams conveying predominantly structure or function

Having found that students have a low preference and low competence in expressing themselves through diagrams, and having identified their problems in understanding the micro-level aspects of function, we went about generating and adapting diagrams that might encourage visualisation through connecting of structure with function at the macro and micro levels. This final part of the study has a direct bearing on pedagogic practice.

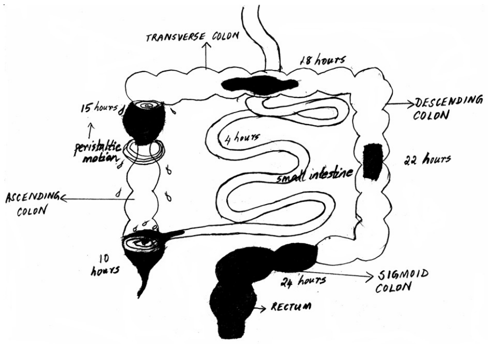
This part of the study addressed Research questions II/8 and II/9 on students' understanding of structure-function relationships through diagrams, and the direct implications that can be drawn for pedagogic practice. The diagrams used for the comprehension tasks are given below.



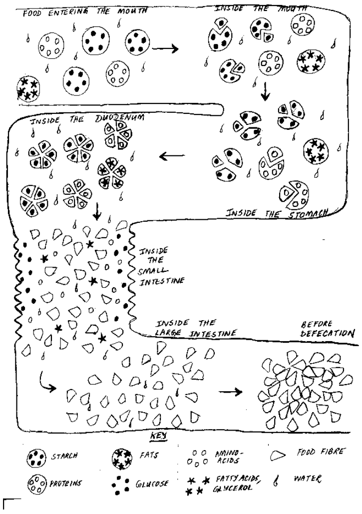
Task 1



Task 3



Task 6



Task 7

There were two questionnaires for the digestive system: Parts 3A and 3B which were administered to all the students. Part 3A consisted of four tasks of which Tasks 1 and 3 involved comprehension of structure diagrams concerning placement of teeth in the jaw, and positioning and cross-sections of the oesophagus and trachea. Task 2 required examining and answering questions on the cross-section of an electric cable. Task 4 required students to draw a diagram of the small intestine based on a description. Part 3B had three tasks (Tasks 5, 6 and 7) of which Task 5 was a precursor question. Task 6 required students to pay attention to structural and functional details of the large intestine. Task 7 presented a predominantly function diagram of the entire digestive system. The diagrams in all the tasks were adapted from the Time Life series (Broderick, 1994).

Observations and results for Part 3 of the digestive system

The mean scores for each task indicated the difficulties students may have encountered in diagram comprehension. The most difficult of the tasks was no. 3 involving comprehension of a magnified view. Tasks 1, 2, 4 and 5 turned out to be of moderate difficulty. Part of the problem with Task 3 may have been in understanding the idea of cross-section, which was tested separately in Task 2. Finally the content may have posed a challenge: the situation of the trachea, oesophagus and epiglottis was found difficult in the text comprehension tasks too.

Task 6 was understood fairly well in terms of passage of waste material, but the time labels were less well understood, and labels for the ascending, transverse and descending colons were found uninterpretable by the majority of students. Thus, though structure and sequence were clear to students, the detailed spatial and temporal aspects of the diagram were difficult to comprehend. The reasons may lie in diagrammatic conventions, in language (terminology) or in conceptual understanding.

Task 7 was a schematic function diagram with symbols for the various components of food. Many students had trouble in understanding the use of the key, but more striking was the observation that portions near the beginning and the end of the digestive tract were comprehended better than the portions in the middle. Relatively simple mechanical processes were depicted in the beginning and end of the entire process, whereas more complex and simultaneous chemical action were depicted in the middle sections. It is in the middle stages that there are several simultaneous reactions happening, resulting in more information to be processed by students.

Overall, difficulties in comprehending diagrams related to understanding of cross-sections, microscopic or chemical processes and structure-function relationships. These difficulties were partly related to specific biology knowledge, as also to general aspects of diagrams like conventions, viewpoints and amount of information to be processed.

Observations and results for Part 3 of the respiratory system

For the respiratory system too, detailed diagrammatic representations were prepared dealing with both structure and function in the same questionnaire. The first dealt with the structure of the respiratory system, and gas exchange in an alveolus. This task was composed of three diagrams with details of the organs of the respiratory system, gas exchange in an alveolus showing the point of contact between the oxygenated and deoxygenated blood in the capillaries and an enlarged bronchiole with details of the alveolus. The second diagram was regarding the changes which take place to the diaphragm and lungs during the processes of inspiration and expiration

The tasks were scored as mentioned for the digestive system. Questions testing for the structure of the respiratory system were easier than chemical action and mechanics of respiration. Tasks involving cross-sections were relatively difficult. Also basic difficulties such as understanding the role of each organ involved in respiration interfered with comprehension of diagrams dealing with them.

Statistical analysis showed that scores for the first task were much higher perhaps because of the range of content-related questions it tested for. The second task on the other hand dealt with the mechanism of inspiration and expiration alone.

Compared to students who participated in Phase I, students who were part of Phase II, had minimal facility with diagrams and several did not draw any diagrams. However, as in Phase I, diagrams proved to be a useful tool in bringing out their alternative conceptions.

Chapter 6: Conclusions and discussion

Our findings should be placed within the context of the overall socio-cultural context in India. India had an ancient and highly exclusive tradition of oral learning. That exclusivity finds reflection in an acute shortage of resources for mass education, even as outdated practices of oral and text-based instruction persist in the vast majority of schools. Specifically this means that even pictures are rare in many State textbooks, let alone availability of videos and animations. The highly competitive nature of the Indian educational system means that classroom discourse is often driven by requirements of examinations which are predominantly verbal in nature. These factors contribute to the de-emphasis of visual forms of teaching, learning and communication in the classroom.

In Phase I, our sample consisted of students belonging to relatively more privileged backgrounds, all being children of scientists. Typically they would have access to illustrated books, TV and computers. In Phase II we had a larger sample that was mixed in terms of educational background at home and socio-economic status. This difference may have had a bearing on the differences in results between the two Phases.

A contribution of the thesis, in terms of methodological aspects, is the use of transformational reasoning and analogical thinking as research tools to study students' visualisation of body systems. Another contribution is the development of a coding scheme keeping in mind an underlying theoretical framework and systems criteria. This coding scheme was particularly useful since we did not find previous literature on assessment of drawing taking into account their content-specific features while also being generalisable to other biological systems and quantifiable. Another methodological outcome was the use of a combination of qualitative and quantitative analysis to arrive at our conclusions. Interweaving flexibly between the two helped us use the strengths of both methods.

We used line drawings in this study for the advantage of these being easy to produce by students, and ease of reproduction through printing. They are therefore the most widely used in school learning. However their potential has not been explored adequately.

Though most students' diagrams tended to follow textbook diagrams, there were a few students who came up with alternative diagrams. These responses resulted in a variety of representations in Phase I tending to lie along a continuum from very depictive representations using colours to distinguish organs, to schematic representations making use of annotations such as arrows, boxes and lines, etc.. In Phase

II however we did not see such variety, perhaps because of the difference in the sample.

Though the exercise of generating analogies helped students connect new concepts with real world knowledge, the pattern-matching which helped them arrive at these analogies led to several erroneous and often irrelevant responses which could have led students away from a correct understanding. Greater teacher intervention and task constraints need to be imposed for analogy to be an effective pedagogical tool.

Prior content knowledge was a predominant factor which shaped students' responses. Our visualisation tasks were embedded in content and it was not surprising that students needed to have a good basic understanding to perform manipulations. The four point scoring used for these questions emphasised generation and manipulation of images, and doing it correctly. Most students were able to generate an image. However correct manipulation proved to be a challenge since its interpretation probably depended on prior content knowledge. Another striking observation was the prevalence of similar alternative conceptions in Phases I and II. Our analysis also showed up the places where students' content knowledge was affecting their performance.

Tasks which required analogical thinking and transformational reasoning not only served as research tools to probe students' visualisation but also in Parts 2 and 3 gave us an understanding of students' conceptions of the human body.

We have placed students' difficulties in understanding in the context of the treatment of these topics in the textbooks of Classes 6, 7 and 8. The work ends with pedagogical implications for the study of biology and development of visualisation abilities in school students.

Some special features of the thesis

This thesis has contributed to our understanding of visuals and visualisation in the context of human body systems in the following ways:

- Unlike in previous research on body systems, our emphasis was not on probing alternative conceptions alone, but on looking at students' use of 'visuals' (diagrams) and mental visualisation relating to human body systems.

- Use of systems criteria in assessing basic knowledge and visualisation: an outcome of this was the development of a common and generalisable scheme of analysis to assess text responses, visual depictions and mental visualisations.

- We proposed a correspondence between mental visualisation and the structure-function relationship and used specific visualisation questions calling for transformations of structure and the effect on function.

- Use of questions probing analogical thinking, which we conjectured might require the use of visual thinking: its possibilities merit further study.

Some limitations of the thesis

Though the sample was mixed in terms of ability, the students came from schools on the same campus. Thus generalising of our results may require replication of the study in diverse contexts.

A rather ambitious aim of this thesis has been to elicit and assess mental visualisation. Tasks related to mental visualisation were framed based on our reading and interpretation of the cognitive science literature, our understanding of the discipline of biology, and our intuition about what constitutes visualisation of biological systems. Through this study we got some insights into students' understanding and the pedagogical aspects related to learning of biological systems through text and diagrams. However we found that prior content knowledge was a predominant factor shaping students' responses, and thus we were not able to validate our conjecture regarding what constitutes visualisation, even specifically in the context of human body systems. Research for this purpose would need the collaboration of cognitive psychologists. Notwithstanding the limitations, we believe that this thesis points the way towards a practicable yet more productive use of visuals and visualisation in science education.

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4. List of publications

Relevant chapter numbers in the thesis are indicated within brackets

Mathai, S. and Ramadas, J. (2009). Visuals and Visualisation of Human Body Systems. *International Journal of Science Education*, Visual and Spatial Modes in Science Learning, 31 (3), pp: 431-458. (Chapters 3 and 5)

Ramadas, J. and Mathai, S. (2008). Book Review. Visualization in Science Education. John K. Gilbert (Ed.), 2005 Dodrecht: Springer. *International Journal of Science Education* 30 (15), pp: 2091-2096. (Chapter 2)

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Mathai, S. (2007). *Visual Thinking in the Classroom: Insights from the research literature*. In Natarajan, C. and Choksi, B. (Eds.) Proceedings of the Conference epiSTEME-2, Homi Bhabha Centre for Science Education, Mumbai: Macmillan. (Chapter 2)

Mathai, S. and Ramadas, J. (2006). The visual and verbal as modes to express understanding of the human body, In Barker-Plummer, D, Cox, R. and Swoboda N. (Eds.) *Diagrammatic Representation and Inference*, *Diagrams 2006, LNAI 4045*, pp: 173-175. Berlin: Springer-Verlag. (Chapter 4)

Mathai, S. and Ramadas, J. (2004). *Putting Imagery back into Learning: The Case of Drawings in Human Physiology*, Proceedings of the Conference epiSTEME-1, Homi Bhabha Centre for Science Education, Mumbai. (Chapter 4)

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