Declaration

This thesis is a presentation of my original research work. Wherever contributions of others are involved, every effort has been made to indicate this clearly with due reference to the literature. Acknowledgement of collaborative research is indicated in the list of publications.

This work was done under the guidance of Prof. Jayashree Ramadas at the Homi Bhabha Centre for Science Education, Tata Institute of Fundamental Research, Mumbai.

Sindhu Mathai

In my capacity as supervisor of the candidate's thesis, I certify that the above statements are true to the best of my knowledge.

Prof. Jayashree Ramadas

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List of publications

Relevant chapter numbers in this thesis are indicated within brackets.

Mathai, S. and Ramadas, J. (2009). Visuals and Visualisation of Human Body Systems. In *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***)

Mathai, S. and Ramadas, J. (2007). *Visualising structure and function of the digestive system*. Abstract for Gordon Research Conference on Visualization in Science and Education, Bryant University, RI, USA. (***Chapter 5***)

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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Abstract

We investigated how middle school students use visual and verbal forms of thinking, reasoning and communication to express understanding of the human body. We probed students' understanding of structure, function and the relationships between them in the context of three human body systems: the digestive, the respiratory and the circulatory. Students were asked to respond to questions which tested for basic knowledge, visualisation, and comprehension of text and diagrams. They were required to translate between visual and verbal modes and across macro and micro levels of organisation of the system. We assessed their basic knowledge using a scheme, based on a common conceptual framework encompassing structure and function, which we used to code both text and diagrams. Transformational reasoning and analogical thinking were used as research tools in the form of tasks to probe visualisation of body systems.

The empirical study was carried out in two Phases. Phase I was an exploratory phase, in which we studied a small number of students in detail. The methodology was then refined for testing on a larger sample in Phase II.

Overall, the results showed that students were more comfortable expressing their understanding through text rather than through diagrams. Structure concepts were understood better than function. Common alternative conceptions relating to the body systems were identified. Prior content knowledge was an important pre-requisite to help students use transformational reasoning. The exercise of generating structural and functional analogies helped students connect prior knowledge with new concepts. The results have led us to draw certain implications for visual literacy and pedagogical practices in biology.

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

Ph.D. Synopsis

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. Guérin 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 the 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: Theoretical rationale and framework

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 and analogical thinking. Analogical thinking in the history of biology Analogical thinking is inherently visual in nature because of the pattern-matching that occurs between the source and target. In the context of science teaching and learning, the target (unfamiliar domain) relates to a scientific concept (Treagust, 1993). 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 for Phase I

The following research questions were formulated for Phase I:

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. Our open-ended questions on analogies were modified 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 conceptual difficulties 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 • Classes 6, 7 and 8 • 6 girls, 7 boys • drawn from one school • from scientists' families	• 87 students • completed Class 6 • 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	• Students were questioned on two systems: digestive and respiratory • Tested through three parts: basic knowledge and visualisation (Part1),

Criterion	Phase I	Phase II
	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	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 obtain the F score.	Structure criteria: Same as Phase I Function criteria: Order and Hierarchy combined during calculation to 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.

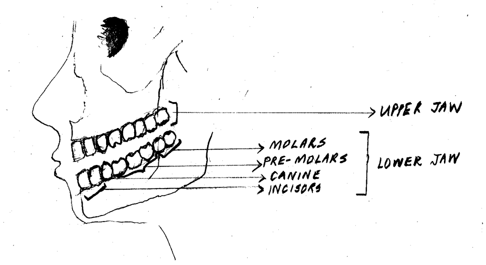
For the respiratory system, there were three passages, the first describing predominantly structure and the next two describing predominantly function. Equivalent structure and function passages were not prepared because of the difficulty in clearly separating structure from function and also because 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.

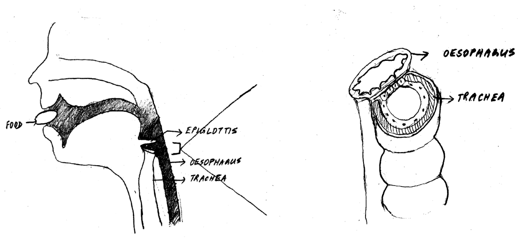
Part 3: Comprehension of diagrams conveying predominantly structure or function

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.

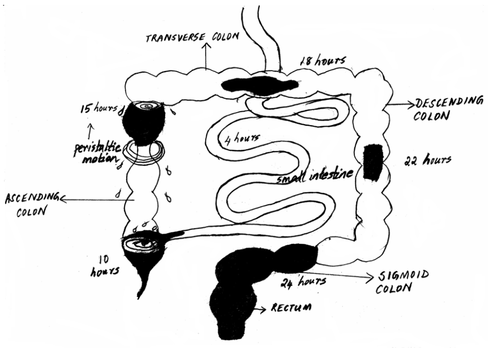
This part of the study addressed Research questions II/8 and II/9 on students' understanding of structure-function relationships through diagrams, and the direct implications that can be drawn for pedagogic practice. The diagrams used for the comprehension tasks are given below.



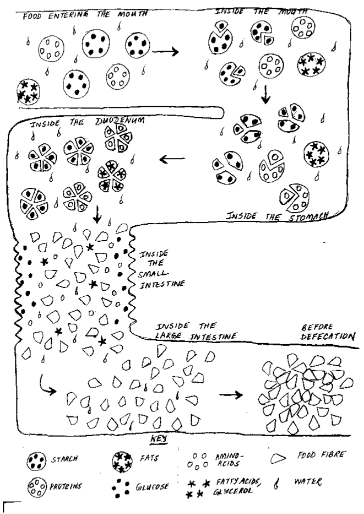
Task 1



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. Scores for the first task were much higher perhaps because of the range of content-related questions it tested for. The role of the capillaries, though mentioned clearly in the textbooks, was found to be difficult for students. This was a consistent result from Phase I too. The second task dealt with the mechanism of inspiration and expiration. There were only two questions in this task of which a question about the mechanics of respiration was easier than one about the position of the heart. Across the tasks, basic difficulties such as understanding the role of each organ involved in respiration interfered with comprehension of diagrams dealing with them.

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 methodological contribution is the development of a coding scheme keeping in mind an underlying theoretical framework based on 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.

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. 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.

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 (as discussed earlier) we did not see such variety.

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 and research tool.

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:

- We studied students' use of 'visuals' (diagrams) and mental 'visualisation' relating to human body systems, unlike previous research where the emphasis was on probing alternative conceptions alone .

- 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)

Mathai, S. and Ramadas, J. (2007). *Visualising structure and function of the digestive system*. Extended Abstract for the Gordon Research Conference on Visualization in Science and Education, Bryant University, RI, USA. (Chapter 5)

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)

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1 | *Chapter 1: Introduction*

Table of Contents

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. Yet visual thinking, learning and communication, the three aspects 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 in a context that is not necessarily instructional (Randhawa, 1978). Though textbooks and popular media make use of different kinds of visuals, expression of understanding through visuals and comprehension is not given explicit focus within instruction. Biology is to a great extent a 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 to communicate their understanding of the human body.

1.1 *Biology as a visual discipline*

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.

Otto Brunfels' three volumes of "Living Illustrations of Plants" in the mid-sixteenth century contained accurate drawings and descriptions of 238 plants (Ronan, 1983). Rondelet's "The Complete History of Fish" also in roughly the same period included a detailed drawing of a sea urchin, perhaps the earliest surviving picture of the dissection of an invertebrate. Malpighi in the seventeenth century made extensive diagrams of tissues, capillary tubes and red blood corpuscles.

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 (more broadly called 'visual thinking') 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. These ideas are referred to in the present chapter in an intuitive way, in the same spirit that motivated our study. They are connected and explained further in Chapters 2 and 3. Here we consider the historical instances that provide a strong motivation for the arguments that are developed in this thesis.

William Harvey's discovery of the mechanism of circulation was made possible both by analogical thinking and transformational reasoning. Harvey justified his conclusions by drawing analogy from two Aristotelian tenets: perfection of circular motion, and parallelism between the macrocosm and the microcosm (Venville and Treagust, 1997).

Transformational reasoning (i.e. manipulation of images) was used in several instances. He observed the dilation of the arteries when the heart contracted, and concluded that it was because the heart was forcing in blood through them. By observing the action of the valves between the heart's upper and lower chambers he concluded that the flow of blood was continuously in one direction only. Also the amount of blood pumped by the body would be too voluminous to be handled by the veins alone. Therefore the valves in the veins, he reasoned, could be facilitating the one-way flow of blood.

In modern biology, the discovery of the structure of DNA by Watson and Crick in 1953 was facilitated by visualising the 3D structure helped by X-ray diffraction data. This conversion from 2D to 3D was possible because of transformational reasoning on the X-ray diffraction image. Proteins were found to be made of amino acids from records of their separation using chromatographic techniques. The use of visuals and techniques for visualisation at various levels of biological organisation necessitate the use of multiple representations both external and internal to facilitate conceptual understanding.

1.2 *Multiple representations in biology education*

It is useful to distinguish between external and internal representations. External representations or 'visuals' are representations (e.g. pictures, diagrams, etc.) external to an individual - on a paper, computer monitor, etc.. Internal mental representations are formed in the mind of an individual. The activity of working with internal representations may involve mental 'visualisation'. Both visuals and visualisation are crucial in the processes of thinking and reasoning. Multiple external representations (MER) refer to the variety of representations possible besides the verbal in the processes of teaching and learning. Such representations include but are not limited to: photographs, diagrams, spreadsheets, graphs, equations, tables, specialised software, blocks in the virtual world analogous to 3D blocks, symbolic representations, etc. 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.

MERs in general are known to have significant pedagogical functions. When two external representations are used in the process of teaching and learning, they complement each other either in terms of information or processes that each supports, they help in the understanding of a second representation by using a familiar representation or exploiting the inherent properties of the first representation, and to construct a deeper understanding (through internal or mental representations) of complex ideas (Ainsworth, 1999).

Schönborn and Bögeholz (2009), report some interesting observations made by nine experts in biology content knowledge about the role of transfer and translation processes in understanding biology. They note: "Biology pupils are expected to acquire knowledge and understanding that is diverse and embedded at different levels of complexity and abstraction; flexibly transfer knowledge during problem-solving; and interpret and translate across multiple external representations." To construct a deep understanding of the topic, students need to transfer their learnt knowledge from a familiar situation to a new one, and from one level of organisation to another. For this to happen students need to translate across various external representations, since external representations in biology are at various levels of familiarity, complexity and organisation. Experts in this study felt that to achieve a comprehensive understanding, one should be able to process and interpret the features of an external representation, translate across external representations that deal with the same biological idea, and translate across representations conveying different biological ideas.

Verbal representations are part of multiple external representations. However, since the verbal is a well-established and well researched mode of thinking, reasoning and communication, the emphasis while describing multiple external representations in the literature has been in the use of 'visuals'. In this thesis too, we have emphasised the role of visuals as well as their relationship with mental visualisation, while keeping in mind also the verbal mode of understanding and expression.

1.3 *Systems biology and students' understanding*

Szent Györgi (1969) made the important point that each level of biological organisation is important for what it is. Each level of organisation as well as the interdependence between different levels should be understood without giving more importance to one over the other. Szent Györgi's observations resonate with the current interest worldwide in the field of 'systems biology'.

We have drawn inspiration from ideas of 'systems biology' (Vidal, 2009) 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. Intuitively as well as through firm theoretical grounding, it is clear that no life form can exist without complex interactions between macromolecules leading to their emergent properties. As aptly put by Vidal (2009), "Gene products do not act alone, individual cells separated from their neighbours lose many of their functional and structural attributes, macromolecules and metabolites are intimately linked to each other. Importantly, evolution rarely acts on separate biochemical reactions, individual cells or distinct species, but rather, impinges upon complex multi-scale systems in which these components are intricately interconnected."

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. Our coding scheme for verbal and drawn responses is based on criteria that can be generalised across systems, based on their basic attributes of structure, function and structure-function relationships. The assessment also consists of correlations between variables to see their inter-connectedness.

1.4 *Organisation of the thesis*

This thesis is organised chapter-wise as follows:

Chapter 1 has introduced our empirical work and the motivation behind it through a few broad themes. It concludes with the organisation of the thesis.

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. The visual-verbal continuum as well as distinction, visuals and visualisation in the history of science, its role in conceptual development and understanding human body systems have also been discussed. A few studies dealing with pedagogical implications are reviewed.

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. Literature in this area leading to our empirical study is reviewed. The framework for the empirical studies to be described in successive chapters is represented through a concept map.

Chapter 4 moves on to the first phase of our empirical study, which concerned students' understanding of the digestive, respiratory and circulatory systems of the human body carried out on a small sample of students. The outcomes allowed us to modify our methodology for testing on a larger sample for Phase II.

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.

Chapter 6 summarises the results and conclusions of this work and discusses them in the light of text-book content on the human body. Some implications for pedagogical practice have also been discussed.

2 | *Chapter 2: Literature Review*

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In this literature review, we delineate some of the relevant contexts in which ‘the visual’ has been researched and understood, its historical significance and role in the process of teaching and learning particularly in the context of human body systems. There exists a host of studies investigating the role of visuals of different kinds in understanding content in various disciplines. This Chapter presents only a representative set mainly to elucidate the issues that are relevant to our research. In Chapter 3 we review some further research that directly contributed to the design of our research.

2.1 *Visuals and visualisation*

Systematising and characterising the “visual” presents unique challenges because of the diversity of visual representations known to us and the various contexts in which visuals and visualisations are studied. In psychology and cognitive science the terms 'visual’ and 'visualisation' / ‘visualization’ are used to refer to internal mental processes and constructs. Shepard (1978; 1988) used the terms ‘mental imagery’ and ‘visualisation’, in the context of scientific imagination and also in empirical studies of mental rotation (Shepard and Metzler, 1971). Kosslyn (1990) further investigated the phenomenon of “mental imagery” to emphasise the brain activity associated with visualisation (more details in Section 2.7 - 2.8: Mental Visualisation). Tufte (2001) used the word ‘visualization’ to mean the representation of visual information in the form of tables, diagrams and graphs.

In the last decade of research and development in this field, the term ‘visualisation’ has come to refer to mental processes as well as external artifacts such as drawings and computer simulations. Hegarty (2004) tried to distinguish between the two meanings by referring to an ‘external visualization’ as an artifact printed on paper or shown on a computer monitor, that can be viewed by an individual. An ‘internal visualization’ according to Hegarty (2004) is a representation in the mind of an individual. Gilbert (2005) after reviewing the relevant terminology has suggested that this distinction may be of lesser importance in the practice of science and in science education. He therefore recommended for convenience the use of the term ‘visualization’ to cover both internal and external types. However, in this thesis we are concerned with external representations (students' diagrams and pedagogical diagrams) as well as students' internal mental visual representations. Thus we have found the need to clarify these two contexts and further to examine the relationship between them. We therefore consistently use the term “visuals” for external representations and “visualisation” for internal, mental representations.

2.2 *The visual-verbal comparison*

Visuals lie along a range from more depictive representations such as photographs, realistic sketches, videos, 3D representations such as models and sculptures, to more simplified and abstracted line drawings, cartoons, children's expressive drawings, and also transient visual referents such as gestures. Scientific drawings always involve an abstraction from a real situation. The drawing may be as close to an object as a labelled diagram showing parts of a plant, it may be further schematised as in say, light rays which in reality are invisible, or it may simply depict conceptual relationships, as in the working of the immune system. Visual languages have been developed which use highly sophisticated conventions, in domains such as chemistry, astronomy, geology, design, etc.. The more formal and well-developed symbol systems such as flow charts, networks, Venn diagrams, Euler circles, cladograms in evolutionary biology, etc., employ symbols which do not resemble their visual referents; they have a vocabulary as well as grammar of their own.

Roth et al. (2005) have tried to come to an understanding of the different practices involved in reading and understanding the entire range of visual materials which, following Bruno Latour, they call 'inscriptions'. In their analysis, Roth et al. argue that in moving from the particularity of one observation to the generality of a scientific claim, one is grappling with a range of visuals beginning from complex photographs to naturalistic drawings, maps, diagrams, graphs, tables and finally equations, which are more language-like. Between any two of these types of visuals there is a gap in kind which in use has to be bridged by graphicacy practices in the classroom.

Biology as we argued in Section 1.1, is an inherently visual discipline. It is pertinent to recall Fox-Keller's (2004) question in the context of validation of biological knowledge: "And are there not circumstances in contemporary scientific practice when the mere observation of a phenomenon is so satisfying and compelling that no further explanation is required?" She further adds, "Is clarity in thinking always and necessarily of higher epistemological value than clarity in seeing?" Today in the biological sciences, an increased understanding of processes at the molecular level has led to the use of more schematised representations in communication. However the demands of disciplines like taxonomy and physiology still necessitate the use of more depictive and realistic diagrams, photographs, videos, etc..

One sees in the analyses of Roth and Fox Keller a tension, but also a continuity, between the depictive visual on the one hand and analytic text on the other. Visuals have sometimes been perceived as a form of language that is prior to conventional written language. However, unlike language, visual information cannot be easily simplified and analysed and therefore a visual language analogous to or comparable with natural language may not be a possibility (Dondis, 1973). Dondis however claimed that “The symbol systems we call language are inventions or refinements of what was once object perceptions in picture strip mentality” (Dondis, 1973). Although there are conflicting views on this point, Karmiloff Smith cites research on art history to make the argument that precedence need not imply derivation, that systems of written language and number are not mere extensions of drawing (Karmiloff Smith, 1995).

C. S. Peirce classified diagrams in Biology into three types depending on their level of complexity- the simplest being the one-part type and the most complex being the three-part type. Pierce's classification of diagrams included verbal descriptions also, based on their logical validity (Moxley, 1983).

‘Visual’ understanding requires simultaneous, holistic processing of information in the environment by the brain through mechanisms of vision. This can be contrasted with understanding of verbal information, which is processed sequentially or step by step. In the artificial intelligence paradigm Shimojima (1999) has contrasted linguistic and graphic representations as, respectively, digital versus analog systems of representation; sequential versus non-sequential; use of relation symbols versus object symbols; less homomorphic and more homomorphic (corresponding to shapes and sizes of the represented entities) systems of representations; representations with no limitations on expressivity and ones with limitations; representations obeying constraints extrinsic to the world versus those obeying both extrinsic and intrinsic constraints (i.e. constraints deriving from the structure of the represented world); and representations that do have phonetic constraints versus those that do not. Shimojima's distinctions are general enough to be applied across content areas. In this review however we look at properties of visuals that apply to science and more specifically to systems in biology.

2.3 *Visuals in science and art*

Visuals are understood differently in the sciences and in the arts. In the Arts the "Image is the Statement", and a variety of appearances are possible for a given theme or object- each of which may reflect an individual outlook and is open to individual interpretation and invention (Arnheim, 1969). However, in the Sciences, appearances point to something beyond, which is more definite or specific, and discernible only by a trained and prepared mind. In a scientific picture some aspects of the situation may be of no consequence such as the colour of containers in an experiment, the clothes a person is wearing, etc.. Such aspects may be integral to a work of art. Yet there are similarities too, for both Art and Science consider the sensory world to be the signature of things, and in both the interpretation of visuals is influenced by the socio-cultural and historical context (Arnheim, 1969; Mishra, 1999).

Gombrich (1960) and Gregory (1970) argue that progress in science led to new developments in Art. On the other hand, Baldasso (2006) quotes historians of science to argue that the scientific revolution drew from developments in 15th century art. He states that "a visual turn" during the Renaissance was a prerequisite for progress in the life sciences and also in the achievements of Copernicus, Galileo and Newton. Leonardo da Vinci's detailed drawings of the human form and physiology as well as his technical drawings of machines were made during this period.

According to Arnheim (1969), making a pictorial representation of an object, event or process, involves an overall understanding of the skeleton or structure of the subject of the picture. Understanding this structure is a perceptual challenge and several children turn away from art at an early age because of a lack of appropriate guidance. Pestalozzi working in the nineteenth century made use of geometrical figures- circle, line, triangle, etc. to construct 'structured skeletons' of the subject to be drawn (Arnheim, 1969). Working with a geometrical perspective is indispensable to portray a three-dimensional world on a two- dimensional surface.

As in science, pictorial representations in art too are not necessarily concerned with depiction of concrete objects in the physical world. Abstraction in art has been with us, from the patterns and symbolisms of ancient times to the more recent works of expressionist, postmodern and contemporary artists. Perhaps the abstraction of visuals in science is more rule-based, related to content and therefore accessible to students in its simple forms. The research of Roth et al. (2005), cited in the previous section is relevant in this context.

2.4 *Visual literacy*

The question of whether and how visuals help in learning is tied up with the question of developing “visual literacy” (Randhawa, 1978; Trumbo, 1999). Visual literacy is a holistic construct composed of visual thinking, visual learning and visual communication (referred to in Chapter 1). 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 in a context that is not necessarily instructional (Randhawa, 1978) . Interest in teaching visual literacy grew with increasing concern about the ubiquity of scientific images in the media. Today there is an ever evolving collection of new technologies which use visuals but without providing the requisite training to comprehend them. Trumbo subscribes to Randhawa's understanding of the components of visual literacy mentioning that it places emphasis on the learning requirements of visual literacy rather than the communication process alone (Trumbo, 1999). Attempts are also being made to incorporate visuals and visual thinking into the science classroom.

Kearsay and Turner (1999) use the term visual literacy in a more restricted and thus perhaps a more operationalisable way. 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'.

2.5 *Pedagogical functions of visuals*

Challenges in characterizing and systematizing visual information have led to difficulty in implementing a concise set of visual skills to be used by the child at various stages of the curriculum. ‘Gifted’ children often abstract this understanding from tasks required to be done in various contexts for which they have an inclination. These skills are further refined “on the job” by students who choose to take up careers in design, computer graphics, etc.. One consequence is that the use of diagrams and visual tools are therefore considered the privilege of a talented few rather than an essential part of the curriculum for all students.

Parrish, P in an online presentation (http://www.comet.ucar.edu/presentations/illustra/) talks about the three important functions associated with pictures: they can attract attention, aid retention, enhance understanding and create context. Also illustrations because of their complexity can display various inter-relationships of lines, shapes, colours, spaces and text. Therefore they stand out to the learner and introduce a visual variety. Illustrations can facilitate memory for abstract pictures by providing images that learners may not be able to generate on their own. This is analogous to Paivio’s dual coding theory. Abstract information is stored using well-structured schemas. Complex schemas which are organized and structured efficiently facilitate recall by providing many efficient paths to reach information.

Drawings have been popularly viewed as serving primarily an aesthetic purpose. Drawings are also often seen to be the privilege of a talented few. Historically however, drawings were used to record personal or culturally significant images for domestic and religious purposes (Anning, 1997). Randhawa points out that the development of the visual cortex enabled early hominids to use visual cues for social communication, develop mental maps of their territories, and learn to make and use tools through observation. These functions eventually paved way for the emergence of conceptual thinking. (Randhawa, 1978.)

Alesandrini (1984) classified pictures into: 1) Representational pictures: these are realistic pictures- which bear resemblance to the objects or processes they represent (for e.g. structural diagrams in biology). Representational portrayal can also be effected for tangible and abstract concepts. 2) Analogical pictures: these pictures point to familiar, analogous examples to illustrate their point. These pictures function on the premise that new information is better remembered if related to prior knowledge (for e.g. analogy of the lungs with a pair of balloons). 3) Arbitrary pictures: these pictures are highly schematised visuals- they do not look like the things that they represent. They are however logical or conceptual in nature (for e.g. using symbols to denote objects or processes; an example of this is referred to in Phase II Part 3 of our empirical study as Task 7)

Brody (1984) has suggested that pictorial research should pay greater attention to the instructional role or functions served by pictures. These functions should be applicable to a wide variety of objectives, strategies and procedures. Brody classified the functions served by pictures into three types: 1) Attentional: they help to gain the student's attention; 2) Explicative: they help explain or elaborate information present in the text. They can also help the student explicate his or her understanding of a particular topic through diagrams and 3) Retentional: they help the student remember and retain what has been taught more effectively and meaningfully.

Carney and Levin (2002) summarised five functions of text illustrations proposed by Levin in 1981: 1) Decorational: by making the material more attractive, though not of relevance to the text, and thereby helping the reader enjoy the textbook, 2) Representational: illustrations can help the reader visualise a particular event, person, place or thing, 3) Organizational: helps the reader organise information into a coherent framework, 4) Interpretational: helps the reader understand the text particularly by clarifying difficult text and 5) Transformational: serves a mnemonic function and transforms the organisation of textual information by helping the reader retain key information.

Drawings also assume the status of a non-verbal language especially in early childhood by helping children externalise conceptions as well as feelings about certain objects or events. Carvalho (2004) points to the use of drawings as an alternative vehicle of communication, a medium in which children feel free to express themselves without being afraid to give an erroneous answer.

Literature related to visuals and visualisation in science education is reviewed in Sections 2.5 and 2.13.

2.6 *Factors affecting interpretation of visuals*

2.6.1 *Cognitive and emotional interest*

Peeck (1987) points to the affective-motivational roles with respect to the function of pictures in text. Pictures have been said to arouse interest, set mood, arouse curiosity, make reading more enjoyable, and to create positive attitudes towards the subject content and towards reading itself. Harp and Mayer (1997) distinguish between emotional interest and cognitive interest through experiments with college students. College students (who were skilled readers) were given instructional material on lightning which had pictures and text intending to arouse emotional interest. These students were found to be distracted by the additional material and performed worse on post-tests on retention. In another experiment, students were asked to rate how interesting a passage is by rating both emotional interest and cognitive interest in the same passage. Harp and Mayer found that as per their predictions, entertaining text and illustrations were rated low on cognitive interest and high on emotional interest, as opposed to summary text and illustrations which were rated high on cognitive interest and low on emotional interest. The authors suggest a greater role for cognitive interest over emotional interest in helping students comprehend scientific explanations.

2.6.2 *Pictorial conventions*

Progress in understanding or grasping the inherent meaning of pictures is a result of a growing vocabulary of pictorial symbols and conventions (Mishra, 1997). This is especially true in the case of science diagrams. Only a trained mind would be able to understand the various symbol systems used in science. A picture has this unique property of denoting things which are absent. To understand a science diagram one needs to have some prior knowledge about the things to look for in it. Inadequate or no prior knowledge about what to look for would lead to an incorrect understanding. In this context there has been research on the conventions that children and older students use in their own drawings in the science context.

Ehrlen (2009) used dynamic interview situations to study children's drawings of the earth. Audio recorded interviews, drawings and notes were analysed. It was found that some children followed culturally accepted conventions in their drawings but held on to alternative conceptions, while others had a consistent explanation for why they drew the earth 'flat' without it actually being so.

Ramadas studied pictorial conventions used by children in depicting light (Ramadas, 1982; Ramadas and Driver, 1989; Ramadas and Shayer, 1993) and motion (Ramadas, 1990). These conventions were found to be dependent on conceptual understanding as well as on the demands of the problem situation. Younger students tended to use contextual cues while older students used abstract conventions. Partial schematisation of a problem or presenting a more advanced problem (e.g. depict 'speed' rather than simply 'motion') encouraged students to use abstract pictorial conventions (Ramadas, 1990).

Working with out-of-school neo-literate children and adolescents, Kulkarni et. al. (1991) found that drawings depicting social interactions were comprehended more easily than drawings of objects. In schematic drawings using arrows, relationships between objects were easier to understand than arrows depicting a sequence of events.

2.6.3 *Ability, training and prior knowledge*

An important finding from previous research has been the positive effect of training on improving visual skills (Newcombe, 2006, Sorby, 2009). Trained females do better than untrained males on certain tasks, even those with otherwise clear male advantages. There is therefore emerging emphasis on the role of interest, familiarity and practice on visualisation ability.

Mayer and Gallini (1990) found that explanative illustrations on how scientific devices work were more useful to inexperienced learners, than to high ability participants who were found to spontaneously engage in forming mental models. Heiser and Tversky (2006) found that use of line diagrams depicting functional information of mechanical systems are effective for college students with high mechanical ability/expertise but difficult for those with low ability/expertise. High ability students are able to form mental models integrating structure and function information. Those with low ability/expertise form mental models of structure which is separate from knowledge of function.

The importance of prior knowledge in developing dynamic mental models in students and experts was highlighted by Clement et al. (2005). Such models include runnable intuition schemas which generate dynamic imagery. Reid (1990 a and b) found that low ability students took a longer time looking and trying to comprehend pictures as compared to high ability students who accessed them less often and were also able to comprehend them effectively.

2.6.4 *Picture-text (-learner) interactions*

Reid (1990 a, b) defined what is now known as the 'picture superiority effect': the phenomenon by which, under certain circumstances, learning is enhanced in the presence of pictures. It was found that in studying the role of pictures in learning of biology, there was no clear-cut 'picture superiority effect'. (Reid, 1990b). Reid (1990 a) tried to answer the question: “What does the learner perceive from the picture?” He or she experiences two different forces: within the picture itself (in the construction of the picture) and outside the picture but within the learner. Within – picture variables comprise of figure-ground differentiation and component manipulation, including form (shape), colour and depth of field (location). The variables within the learner, which need to be taken into account while processing pictures, are: ability level, interest, etc..

Carney and Levin (2002) elucidated some suggestions to enable picture-text facilitation, which include picture-text overlap, prerequisite basic reading skills, getting students to work with illustrations so as to yield controllable products, taking into account students' individual learning styles, etc..

Mayer (1989) conducted two experiments with college students presenting them with information on car brakes that contained labeled illustrations of systems, illustrations without labels, labels without illustrations or no labeled illustrations. He found that students who received illustrations with labels performed better on post-tests which tested for recall of explanative information rather than non-explanative information. Also they tended to perform well on questions requiring transfer of knowledge but not on verbatim content. Mayer has suggested four conditions for meaningful instructions, particularly, meaningful illustrations:

a) Potential meaningfulness of the material: learners should be able to construct meaningful mental models based on it. Mayer has therefore focused on explanative text: text that explains, particularly explanations of systems such as vehicle braking systems.

b) Novice status of the learner: meaningful instructional methods are most useful for less skilled learners, i.e. those who do not spontaneously engage in creation of mental models or any kind of meaningful learning.

c) Effectiveness of instructional manipulation: the instructional material should also direct the learner to explanative information and helps to build connections.

d) Appropriateness of text: the instructional material should focus on meaningful learning depending on the context such as creative use of information to answer transfer questions.

Mayer and Gallini (1990) conducted three experiments on college students, who were asked to read expository passages on how scientific devices work. These illustrations had either no illustrations (control), static illustrations with labels for each part (parts), static illustrations with labels for each part and major action (parts and steps). Mayer and Gallini suggest that parts and steps illustrations serve as runnable mental models, particularly for inexperienced learners. Also, analogous to Mayer (1989), the illustrations improved performance on recall of conceptual information and also creative problem solving, but not non-conceptual information or verbatim recall. Reid and Beveridge (1990) studied computer based science texts and found that a) more difficult topics were associated with more time looking at the pictures and b) less successful students spent more time looking at the pictures than their more successful counterparts.

2.6.5 *Type of representation*

Previous research has indicated that line drawings are the most useful diagrammatic representations (Alesandrini, 1984; Kearsay and Turner, 1999). This usefulness follows from the economy, simplicity and varying levels of complexity that line diagrams facilitate, causing it to be the most effective type of diagram.

Kearsay and Turner (1999) questioned 14 – 15 year old students using the biology textbooks of the Nuffield curriculum. They found that students' preferences differed from those of teachers with respect to a biology illustration. Students preferred clear, line drawings to complex photographs. Their approach was more pragmatic compared to teachers who seemed to value realistic depictions. Kearsay and Turner found that line drawings are most useful to students who are less skilled in understanding verbal descriptions. The realism depicted by photos makes them attractive, but does not serve much of an instructional function for less able students. Realism however facilitates learning in more able students. A line drawing has the advantage of extracting relevant information and ordering it to draw attention to the intended information alone, but in the process greatly simplifies it. Based on this study, Kearsay and Turner put forth the following suggestions for effective pictorial representations in Biology:

a) There should be clear links between the figures and the text.

b) The diagrammatic representation should also have an accompanying verbal equivalent.

c) Extra information and numerous details in diagrams stretch a student's cognitive capacity. But this advantage depends on the type of learner, teacher and the environment during learning. Line drawings are the most useful irrespective of the level of ability of the students.

Alesandrini (1984) from his review on the effect of type of representation on learning, and his classification of kinds of pictures(outlined in Section 2.5), concluded the following on the effect of type of representation in learning concepts

- Representational line drawings were found to be useful in rendering abstract concepts concrete in subjects such as Chemistry and Geometry but not Mathematics. Realistic models were also found to be effective if students could manipulate them rather than merely watch teachers using them. Learner drawn realistic pictures illustrating a prose passage were also found to aid learning.
- Analogical pictures aided retention of information in areas as diverse as heat flow and programming.
- Arbitrary pictures are commonly used as graphic organisers serving to illustrate or organise text-based content and are of different kinds such as: structured overviews, hierarchical mapping, networks, structural outlines, tree diagrams, etc..

2.7 *Mental visualisation*

The literature on visuals that is reviewed in the preceding sections had implicitly assumed, and often empirically found a link between these external visuals and internal processes of understanding. But does there really exist a phenomenon that we might call internal mental visualisation? And if there is one, how is it related to the external visuals or drawings, that we have discussed so far? Over the last forty years, the concept of mental visualisation has gained increasing acceptance in cognitive science. In the 1970s 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 (Paivio, 1991). Furthermore, pictures rather than words are more likely to activate both coding systems.

The notion of mental visualisation is supported by research on brain function. Neuropsychological evidence was found for two separate pathways in the brain to process incoming information: the visual and verbal (Farah, 1989). Correspondence between visual perception and visual imagery (explained below) hinges on two facts: the occipital lobe of the brain contains numerous topographically mapped regions that support visual representations and secondly, most cortical areas involved in visual perception are also involved in visual imagery. Further, visual processing was found to code for two kinds of information: 'visual' properties such as shape and colour, and 'spatial' relations such as distance and motion (Kosslyn, 1990). Some common intuitive examples of visual processing are: face recognition, biomotion (http://www.biomotionlab.ca/Demos/BMLwalker.html) and stereograms.

Tversky (2005) has classified research programs on visual imagery into two kinds: the bottom-up and top-down approach. The bottom-up approach aims to understand the elementary units or building blocks of more formal, complex visuospatial reasoning. The major research program using a bottom-up approach was pioneered by Shepard (1971) and Kosslyn (Kosslyn, 1994). These researchers viewed imagery as 'internalised perception' and established its similarity to properties and characteristics of percepts (Tversky, 2005). Further, this approach connected mental transformations on images with observable changes in objects, as in mental rotation. Perceptual processes like mental scanning were found to parallel physical scanning of objects.

Thus, in attempting to demonstrate the similarities between imagery and perception, the imagery program focused both on properties of objects and on characteristics of transformations on objects. Tversky points out that "The thrust of the research programs has been to demonstrate that images are like internalized perceptions and transformations of images like transformations of things in the world" (Tversky, 2005).

In contrast the top-down approach considers the schematic representation of entities. Unlike classic images, they are not likenesses but 'tokens'. Spatial relations are more qualitative and approximate. A proponent of this approach Johnson-Laird (1983) proposed that people form mental models with both depictive and propositional features and there is a dynamic relationship between its parts, which in turn helps reasoning and problem-solving. Visual imagery has also been studied in complex domains such as design (Tversky, 2005) using a top-down approach.

Documented evidence from historians of science as well as self-reports of scientists attest to the use of visuals and model-based reasoning in scientific discovery. Mental models, like external ones, often have structural analogies with the experienced world. But models too, like visuals, range from the depictive to the schematic. Increasing schematisation in a model calls for the incorporation of more propositional content in the visuals (occasionally making the visuals redundant, as happened in case of Maxwell's electromagnetic theory – see Nersessian, 1995).

2.8 *Role of mental visualisation in the production of drawings*

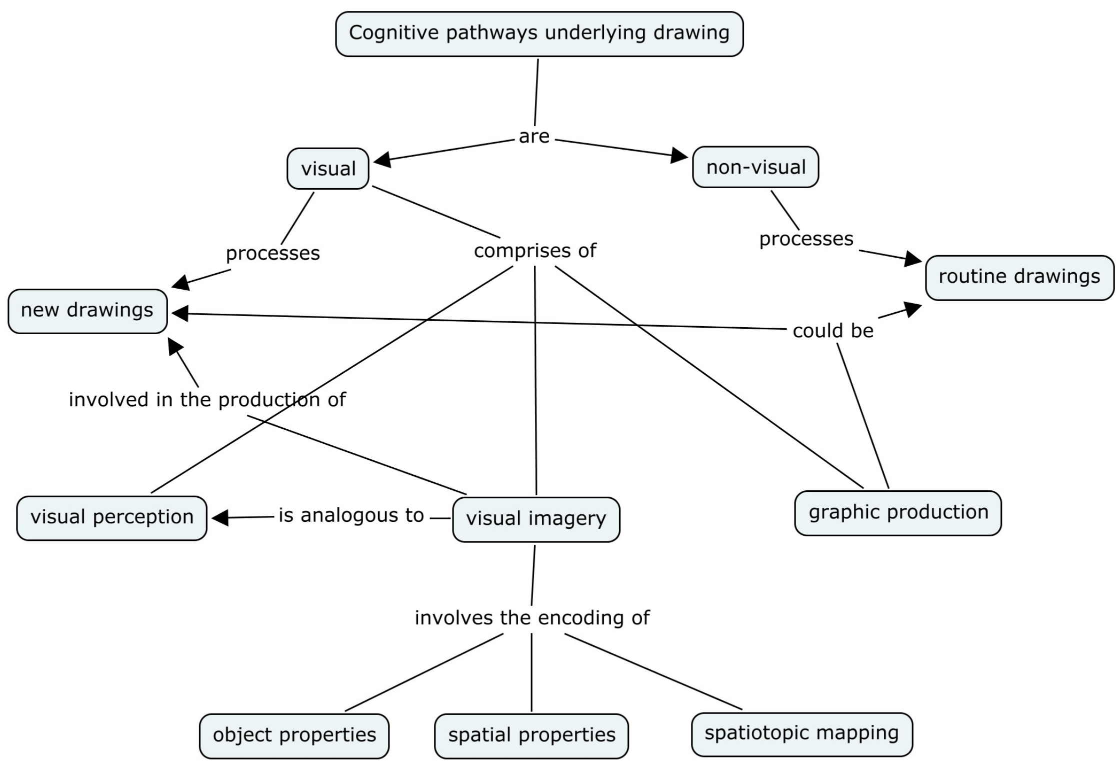
Drawings in science are embedded within an elaborate conceptual context. Children's use of drawings in science therefore, must be seen in relation to their mental visualisation as well as to their propositional understanding in the content area. To understand the role of visualisation in drawing, we used the model proposed by Guérin et al. (1999) which takes into consideration the models of Kosslyn and Koenig (1992) and van Sommers (1989). Kosslyn and Koenig describe top-down and bottom-up approaches involved in processing drawings. The 'bottom-up' and 'top-down' terminologies paralell those used by Tversky to classify research programs in cognitive science (Section 2.7). The bottom-up pathway identifies specialised regions in the brain which are activated in response to the perception of an object before the production of a drawing. The top-down pathway holistically verifies hypotheses of the properties of an object (properties look-up). The bottom-up pathway is explained in detail below.

Drawing using the bottom-up pathway begins with physical properties (or 'object properties' as termed by Kosslyn, 1994) and 'spatial' properties. Neurophysiological evidence suggests that cells in the ventral system of the brain respond to object properties. On the other hand specialised regions of the left hemisphere of the brain (dorsal system) responds to spatial properties. Spatial properties includes categorical relations and coordinate relations. There is further a third component from the dorsal sub-system which is involved in the function of spatiotopic mapping. Categorical relations are spatial relations between two objects (for e.g. to the left of, connected to), coordinate relations are metric relations (e.g. on the face, between eyes, nose) and spatiotopic mapping (locates objects in space within a unique reference frame). Guérin et al.'s model posits two kinds of cognitive pathways in the production of drawings: a visual pathway for the processing of novel and unfamiliar drawings, and a non-visual pathway for the processing of routine, familiar drawings.

The non-visual pathway can be physically located in the brain: it spans the region from the associative to procedural memory. The visual-imagery pathway spans the region from the associative memory to the visual buffer and includes two parallel processing systems. The first forms a single-part or global image (involving the associative memory, long-term visual memory, encoding of coordinate and categorical spatial relations, spatiotopic mapping and ends in the visual buffer). The second system is multipart and involves the addition of parts to the global image (involving long term visual memory, associative memory and the subsystems of top-down hypothesis testing). The second system is also involved in the inspection of the mental image formed in the visual buffer or working memory. A summary of the model of Guérin et al. in the form of a concept map is given in Figure 2.1. We have argued in this thesis that the current pedagogy of science bypasses the visual imagery pathway, leading to routine processing of drawings.

Kosslyn and Koenig also postulate a top-down approach which verifies hypotheses about properties of an object (properties look-up) which they call top-down hypotheses testing.

Figure 2.1: Cognitive pathways underlying drawing based on the model of Guérin et al., 2002



An individual's mental images are given tangible form through exploratory sketches, scribbles and rough calculations. These initial impressions aid an artist (specially a designer) while revisiting and reworking ideas before a solution is reached. Architects' use of sketches to develop their internal mental representations have been studied by Suwa and Tversky (2002).

Hegarty (2004) has listed three different ways by which external and internal visualisations (or visuals and visualisations as we have used the terms) are linked. External visualisations may substitute for or serve as a 'prosthetic' for internal visualisations by helping a person have a better insight than what is possible by internal visualisation alone. Secondly, the use of an external visualisation depends on the possibility of being able to visualise internally. Thirdly a visual may augment or enhance the experience or understanding of an internal visual.

2.9 *Development of visuospatial understanding*

A developmental component also influences the production of pictures. Piaget saw drawing ability as an aspect of the child's developing concept of space (Gruber and Vonèche, 1977). Goodnow (1977) added to this view, the goals and expectations that children bring to a problem situation and the strategies they use to achieve their aims. Goodnow (1977) studied the development of children's drawings and found that drawings allowed for a flexibility, allowing the child to work within developmental constraints and still adequately express ideas. She looked at two aspects of children's drawings which are also of general interest to developmental psychologists: 'knowing that' the depiction represents reality is true, and 'knowing how' to go about doing something. 'Knowing how' is more important, since the child has to go through several stages of planning before translating something into action or into drawing something. In the 1930s, researchers in this area were interested in understanding the transition in drawing 'what one sees' to 'what one knows should be there'. Another line of interest which reflected a concern in education, was in the analysis of pictorial skills and ways of developing it. Drawing pictures, copying geometrical shapes, printing numbers or letters of the alphabet and copying or making maps are all forms of drawing. Goodnow's approach to understanding children's cognitive development though drawings is by analysing spatial patterns, looking at sequence, and understanding how one part may stand for the other or understanding of equivalents.

Project Zero's 'Artworks for schools' programme views the construction of images and communication through the Arts as a kind of literacy (http://www.pz.harvard.edu/Research/ArtWks.htm).The purpose of the program is to help teachers and students discover the power of the arts to enrich high-level cognition across school subjects.

In the Reggio Emilia schools in Italy, practicing artists work alongside children in ateliers or studios: shared workspaces where children "experiment or manipulate combined visual languages in isolation or in combination with verbal ones" (Edwards, 1993). Drawings are used as a mode of communication and children's work (primarily of a visual nature) is frequently exhibited thereby promoting a shared understanding while also allowing for differences. However, these are exceptional approaches to education. In most classrooms particularly in India a mostly verbal form of encoding and expression is still emphasised by the teacher and curricular materials.

A new-born baby's understanding of space develops through first tactile, and then visual experiences. In the pre-verbal stage a considerable amount of learning occurs through an interaction between the tactile, visual and motor modes (Newcombe and Learmonth, 2005). Sometimes, visual learning may lead the way to subsequent motor responses (Diamond, 1991).

Piaget proposed that early childhood imagery is "reproductive" in nature. Mental operations facilitate the development from reproductive mental imagery to transformational imagery. He however found large individual differences in the quality of such transformational images in the adult population. Piaget suggested extensive research on people with extraordinary visual achievements, for example earth scientists, and also those with psychopathological disruptions of visual imagery as in hallucinations.

Ausubel (1978) held that concept formation in early childhood occurs primarily through 'discovery learning' (through induction, and therefore through the use of concrete empirical props, visual models, etc.). In the later years 'reception learning' predominates, which may be largely verbal and may not require the use of concrete props. Kosslyn and Bower (1974) found that children rely on visual imagery to remember sentences unlike adults who encode sentences more in terms of their meaning.

Karmiloff-Smith (1995), in re-looking at cognitive development, argued for system-specific constraints in the notational domain, analogous to constraints acting in the domains of language and number. She found that older children (8-10 years) were able to 'redescribe' their drawings of, for instance, a house, to one that is not a house by inserting elements which violate 'househood' at its core. On the other hand, five year old children were unable to change the core of what they drew to be a house. They were unable to change its contours and were only able to add elements to the existing structure.

Ramadas and Nair (1996), in a comparison between verbal and drawing tasks related to the digestive system, found that younger students held an advantage in the drawing mode. In general, younger individuals are known to process information more in the visual modality than the semantic (Simpson, 1995).

Vygotsky (1930) traced the development of written language referring to gestures as the first visual sign for a child. Writing in the air progresses to written signs which may be considered to be fixed gestures. Gestures are an inherent part of pictorial writing, scribbling and playing games which in turn are linked to the development of written language. Gestures play a significant role in mental visualisation (Padalkar and Ramadas, in press) which needs to be addressed in science education studies.

2.10 *Socio-cultural context of visuals*

External representations are tightly bound to the domain, context (culture and situation) (Roth, 2005) and learner (learning styles, background). Liddell, 1997 refers to a few studies from developing countries on text interpretation with the help of pictures. Studies carried out in the Western context suggest that a depictive representation makes text interpretation easier and richer. However, Chen, 1992 reported that Peruvian Quechua children found pictures to be of little value while decoding text unlike their American and Asian counterparts. There is clearly an influence of training in learning to comprehend pictures. Liddell, 1997 found in her own study, that South African children interpret less from pictures than their Western counterparts, who spontaneously used pictures as a bridge to language development. In the case of the South African children however, the pictures were used in a passive form or for expository purposes, a practice that children appear to bring from home. Also, labelling and linking which are associated with picture interpretation seem to progressively decrease as children go through the school years. This is because there is no explicit teaching of Western pictorial conventions to children in the early school years. Also, encountering pictures is more a product of schooling in oral cultures such as the South African one. The situation appears to be similar in the Indian context too.

Workman and Lee conducted a cross-cultural study of the apparel spatial visualisation test and the paper folding test (2004). It was found that there were significant cultural differences in the pre-tests among Korean and U.S. students which decreased to non-significant levels after appropriate training was administered. The cultural context of the visual is therefore an important contributor to understanding visual practices.

2.11 *Visual thinking as a cognitive style*

There is documented evidence that some children are predominantly visual learners, or at least they respond more positively to visual stimuli (Lori, 2000). These children may perceive the world in great detail but they struggle at school due to their difficulty with language. Visual children tend to classify objects on the basis of patterns in their physical qualities rather than through culturally determined categories. This is a kind of inductive learning based on imagery. In this style of learning, images could serve as pegs to enable and enhance the recall of words (Paivio, 1991). According to Boekarts (1982) as cited in Reid (1990), there are four main clusters of cognitive style which can be distinguished:

1) Bicognitives (efficient in retrieval from both the picture and verbal matter)

2) Verbalisers (remember text better than pictures)

3) Visualisers (remember pictures better than text)

4) Indefinites (do not make efficient use of either text or pictures)

Gardner (1983) in his theory of "multiple intelligences", documented the existence of spatial intelligence referring to "capabilities to perceive the world accurately, to perform transformations and modifications upon one's visual experience even in the absence of physical stimulation". This type of intelligence is highly developed in artists, architects, designers, etc..

Alcock and Simpson (2004) have documented some interesting differences in styles of working, reasoning and attitudes of 'visual' and 'verbal' thinkers. The reported findings were the results of a study carried out on students of a first year course on real analysis at a British University. Alcock and Simpson found that students who visualise tend to introduce diagrams during interview tasks; gesture while explaining arguments; explicitly indicate a preference for thinking of pictures or diagrams rather than algebraic representations, and refer to a sense of meaning derived from a source other than formal expressions. They were also quickly convinced of the correctness of their conclusions, but were unable to produce a written argument. This led them to overlook or not attach significance to formal definitions. It was therefore thought that visualisers were not able to form links between formal structures and their visual picture of how things work. On the other hand, students who had comprehended correctly also visualised, but were able to move flexibly between visual and formal expressions, and sought to form relationships between them. This drive to search for systematic links and construct an integrated understanding seemed to interfere with their tendency to visualise. However this conflict helped them to resolve any initial alternative conceptions without having to be repeatedly prompted by the interviewers. The authors thought that these students who understood the subject content best, engaged in a kind of Piagetian accommodation to reconcile an informal understanding with formal material presented in the classroom (Piaget, 1966).

2.12 *Visuals and visualisation in the history of science*

In Section 1.1 we cited some examples from history which show that biology is a notably visual discipline. In other areas of science too, particularly in the process of discovery we find instances of this kind. Visuals and visualisation have characterised the thinking style of many well-known scientists. Galileo, Newton, Faraday, Maxwell and Einstein all attest to the use of some form of visual thinking in their work. The history of science is replete with examples of the important role played by visuals and visualisation in scientific enquiry. The progress of science has been aided considerably by visual communication of ideas and further by methods developed to reduce data and relationships to graphics of one form or the other (Hewes, 1978). The invention of the printing press also made possible the production and dissemination of visuals.

Nersessian (1995) notes that in the history of scientific change, we find recurrent use of: analogical reasoning, imagistic reasoning, thought experiments and limiting case analysis, all of which she terms “modeling activities”. Nersessian also points to the fact that since these activities are non-algorithmic, and do not fit into inductive or deductive reasoning methods, they have received scant attention from philosophers of science. Simon, M. (1996) also speaks about similar conceptual problems in characterising transformational reasoning in terms of the more established inductive and deductive methods, referred to in Section 3.2. Nersessian cites examples of scientists: Maxwell, Faraday, Galileo and Einstein to describe how such non-verbal heuristics have been used to guide the process of scientific discovery.

Barbara McClintock, Nobel prize winning cytogeneticist, used photographs to communicate her results. Photographs "were both her evidence and the key to her explanations" (Keirns, 1999). This form of communication was different from that used by scientists of that period who tended to use cartoons and more language-like representations. McClintock used photographs to communicate developmental "change over time", best seen and represented in maize. Maize is considered to be an organism unsuitable for genetic studies because of its complex genetic organisation. It however displayed intricate developmental patterns which McClintock studied and communicated using photographs. The choice of a photograph was beneficial since it represented four-dimensional change over time which a two dimensional diagram could not convey effectively. A photograph also fulfilled gestalt functions by representing a complex whole which a drawing or 'cartoon' could not depict. Such non-diagrammatic representation stood in contrast to the diagrammatic conventions of physicists and chemists who had moved into the emerging discipline of molecular biology.

In Section 2.14 we give some examples of the use of visuals in documenting human body systems and in Section 3.1 we give some further examples of analogical thinking in the history of science.

2.13 *Visuals and visualisation in science education*

The use of visual thinking and different kinds of visuals during the process of teaching and learning has been and continues to be extensively researched. The areas are diverse and range from the use of computer aided visualisations such as animations and models to the use of visualisation strategies while teaching and learning. In this section we review the literature on the pedagogical effectiveness of visuals followed by the use of visualisation strategies in science education. Some literature on functions of visuals and factors affecting their interpretation is reviewed in Sections 2.5 and 2.6. In the next few sections we summarise the results specifically in science education.

2.13.1 *Research on visuals in science education*

Drawings have been used to explicate the understanding of students in certain studies carried out at and in collaboration with researchers at the Homi Bhabha Centre for Science Education. Drawings have been used to explore students' understanding and ideas about the concept of light (Ramadas, 1982; Ramadas and Driver, 1989), motion (Ramadas, 1990), digestive system (Ramadas and Nair, 1996), plants (Natarajan et. al., 1996) and chemical combinations (Ladage, S., 1992). In the work of Carvalho (2004) and Ehrlen (2009) (reviewed in Sections 2.5 and 2.6.2), children's drawings were elicited to probe their ideas about the human body and the Earth respectively. In all these studies students' alternative conceptions were diagnosed using drawings as tools for communication.

Brooks (2009) used a Vygotskyan approach to explore the function of drawings in a collaborative environment and as a tool for thought comparable to language. Klemm and Iding (1997) explored the use of Visual Learning Logs (VLL) as an alternative to journals which have text content alone. Twenty pre-service teachers enrolled in an elementary science methods course were asked to submit a visual learning log along with a written journal entry each week throughout a semester. They were instructed to "draw a pictogram (a visual learning log) showing what they learned and what it means to them, including feedback on their feelings about their learning experiences." Feedback at the end of the course revealed that teachers found the VLL to be a powerful tool to express aesthetic and emotional attributes pertaining to an activity. It is also encouraging for learners who are visual thinkers. VLL also provides immediate visual feedback to the teacher on what the learner has expressed with respect to for example a hands–on activity. Also students found a pictorial representation a convenient method to demonstrate understanding of an activity. Concept maps have been used as a tool for students to integrate information presented in the textbook and for teachers to form links between their content knowledge and pedagogical practices.

2.13.2 *Research on visualisation in science education*

Gilbert and co-authors have contributed to our understanding of visualisation in science education through a series of books (Gilbert, 2005, Gilbert at al., 2008 and Gilbert and Treagust, 2009) which aims to bring together the diverse research in this new and emerging field. The first in the series of books 'Visualization in Science Education' (Gilbert, 2005) is organised into four broad areas dealing with the significance of visualisation in science education, developing the skills of visualisation, integrating visualisation into the science curricula, and assessment of visualisation skills. The areas span various science disciplines: physics, chemistry, biology and geology and give fascinating insights for beginning researchers on a range of research methodologies and theoretical positions in this field of research (book review by Ramadas and Mathai, 2008).

In this mentioned first volume, Briggs and Bodner describe the role of visualisation in understanding molecular structures. They argue that visualisation is an operation that brings about a one-to-one correspondence between a mental representation and its referent. Using qualitative data from college undergraduates preparing to take a course in organic chemistry, they propose a model of molecular visualisation. This process starts with visualising words and sentences and turning them into meaningful mental models. Clement et al (in the same volume) used think aloud protocols to understand the learning processes and teaching strategies which lead to the construction of mental models. The important role of prior knowledge in developing dynamic models in students and experts is highlighted. They also emphasise the need to come up with innovative research to uncover the use of visualisation strategies.

Computer based visualisation tools can enhance comprehension of three dimensional representations. Visualisation tools can be broadly divided into content specific and general learning tools. These tools should support spatial cognition by helping students comprehend spatial relationships between for example stereoisomers in Chemistry as well as manipulate them to solve a given problem (Stieff et al., 2005). Visualisation strategies have an advantage in being able to provide immediate feedback to the teacher and learner. It also permits a record of the individual student's work, thereby permitting collaborative efforts. Students will then learn to flexibly alternate between the use of visualisation strategies and non-imagistic heuristics with experience.

2.13.3 *Visuals and visualisation in biology education*

Visuals are used during the process of teaching and learning biology in a variety of ways. They may be used to depict an object or event as it exists: for example taxonomical diagrams in biology depicting detailed structural observations; to elucidate a problem at hand, such as the Punnett square used by geneticists which 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.

Cook (2008) found that high school biology students were able to understand meiosis in terms of labeling structures and describing phases but were unable to understand the overall purpose of meiosis. He also states that visual representations in science are useful for displaying multiple relationships and processes that are difficult to describe. All the students in this study had background knowledge about meiosis having studied it at college.

Genomics research is dependent upon visual comparative analysis of voluminous complex information. Therefore, this kind of processing is typically carried out by machines. There also exists a huge gap between the visualization skills of scientists and school students, and science education practices should aim to bridge this gap. Takayama (2009) suggests that awareness among students be inculcated by familiarity with genomic data, communication using a variety of visual representations, transfer from one mode of visual presentation to another, development of models and prediction of behaviour of new data based on previous visual models.

Brooks (2009) showed that drawings help children move from everyday, spontaneous concepts to more scientific concepts. Creating visual representations helps them to work at a metacognitive level, to collaborate with fellow students, and to explore increasingly more complex ideas.

2.13.4 *Visuals and visualisation in the Indian context*

In the Indian school context exposure to visuals is often low: even coloured illustrations are rare in textbooks, let alone availability of videos and animations. These studies of visual literacy and internal visualization are done in Western developed countries. Use of visuals in the classroom predominantly follows Western, Renaissance notions of exact representation. Traditional Indian folk art on the other hand has been rich in symbolism, use of geometric patterns, bright colours, and easily available graphic tools (Harle, 1986). Thus the implications of these studies for the Indian context remain to be seen.

2.14 *Documenting human body systems in the history of science*

In the context of our empirical work which is to follow in Chapters 4 and 5, we have chosen the domain of human body systems to probe students' understanding of structure-function relationships, and thereby mental visualisation. Human anatomy and physiology allow for a variety of ways of visual representation. To quote from the theme of the travelling exhibition 'Bodies' (http://www.bodiestheexhibition.com/) "The study of human anatomy has always operated on a basic principle: **to see is to know.** This same principle led Egyptian, Greek, Roman and Islamic cultures to a progressively more scientific understanding of the human form. Public dissections during the Renaissance furthered this understanding, laying the foundation for our modern medical institutions". In the Indian context, Charaka, Sushruta and Vagbata are commonly known as the great trio of Ayurvedic literature. *Charaka Samhita* and the *Sushruta Samhita* (composed around 200 A.D.) are treatises which are also representative precursors of the medical and surgical schools (Sharma, 1992). Arising from an oral tradition perhaps, these texts relied entirely on text-based communication. However, the Greek history of science is replete with examples which illustrate the role of diagrams and visual images to document the anatomy and physiology of the human body. Pioneering work by Galen (120-200 A.D.) made extensive use of diagrams. Several centuries later Vesalius made accurate drawings based on several dissections of the human body, which showed that the drawings of Galen were erroneous and reflected the anatomy and physiology of an ape rather than a human being. Vesalius' monumental work "On the fabric of the human body" published in 1543 was considered for several centuries hence to be the best illustrated atlas of the human body. He taught students through four very large anatomical diagrams.

Advances in medicine were aided by advances in technology. The discovery of the microscope in 1665 made possible a variety of observations of organisms which were invisible to the naked eye. As mentioned earlier in Section 1.1, Malpighi in the seventeenth century made extensive diagrams of tissues, capillary tubes and red blood corpuscles. His interests spanned fields as diverse as embryology, protozoa, life cycles of insects, etc. (Ronan, 1983). Recent advances in artificial intelligence have made possible the use of gadgets giving haptic feedback to surgeons in realistic simulations which parallel in vivo conditions.

2.15 *Children's ideas about human body systems*

In the empirical work reported in this thesis, we chose students from the middle school level. Children's ideas about human body systems in various contexts and situations have been a source of interest for several decades. In the early years of life, personal experiences of body functions largely determine our biological knowledge. Children form spontaneous conceptions of the human body through everyday experiences of breathing and eating, and also of illness. Gellert (1962) investigated ideas of the human body among children who were hospitalised for a variety of reasons. Children accorded most importance to the body system for which they were hospitalised. Many had an exaggerated idea about the stomach, imagining it to hold (besides food) organs such as heart and bones. A common alternative conception was that the stomach is involved in breathing. The possibility of one form of matter changing into another within the body was conceivable by about eight years of age. For the respiratory system too, the location and role of the lungs was exaggerated.

Carey (1985) reviewed literature on a child's understanding of himself or herself as a biological being. She found that their responses up to the age of seven years were predominantly ‘intentional’ or ‘psychological’ as opposed to ‘biological’. Older children were found to have acquired an intuitive understanding of biological processes or an intuitive biological theory. However they would not have had opportunities to see the internal organs and correlate structure with function. This is the contribution of school learning.

Reiss and Tunnicliffe (2001) studied children’s understanding of human organs and organ systems using predominantly diagrams to elicit responses. They found that students had a broad familiarity with internal structure but little understanding of how organs were related to form systems. They proposed that children’s understanding proceeds from names of organs to their location and finally towards meaningful structure-function relationships.

The general systems idea of structure and function has been used to characterize students’ ideas about body systems (Ramadas and Nair, 1996). In this study questions on the digestive system were framed using systems criteria: structure-function, static-dynamic, purposive or non-purposive, mechanistic-organismic and self-regulation. Written tests were administered as well as an open-ended drawing test. Guided drawings were used to ask children to connect the given drawings of individual organs. As in previous studies, older students were found to have a better understanding. However younger students were more capable of expressing themselves using drawings (rather than text). Students found the mechanical breakdown of food easier to understand than chemical transformation. Also, there was a spontaneous tendency at all ages to link structure with function.

Ainsworth and Loizou (2003) presented students with diagrams and text on the circulatory system and prompted them to self-explain verbally. It was found that diagrams elicited more self-explanations than text. However in a later study it was found that learners could overcome the disadvantages posed by text, if they drew self-explanations since drawing helped them to translate self-explanations across different representational formats (Ainsworth and Iacovoides, 2005).

3 | *Chapter 3: Theoretical rationale and framework for the study*

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In Chapter 2, we reviewed the literature on visuals and visualisation, on their role in and relevance to science education. We saw that there is a dialectic between expression through verbal and visual modes (Section 2.2). In Sections 2.5 to 2.10 we indicated that there must be a relationship between (external) visuals and (internal) mental visualisation. The research of Mayer and Gallini, Heiser and Tversky, and Johnson Laird reviewed in Sections 2.6 and 2.7, suggested that this relationship may come about through the formation of mental models. The idea of mental models is however too broad in scope and does not provide much direct guidance to tackle our problem of mental visualisation in the case of human body systems. Our aim is thus to make the problem tractable in some way. 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 literature in these two areas is reviewed here (Sections 3.1 and 3.2) leading to the rationale for this research.

Next, in Sections 3.3 and 3.4 we make an argument for assessing understanding of structure and function of human body systems through text and diagrams suggest how visualisation can be studied through transformations of structure and function (Section

3.5).

3.1 *Analogical thinking*

Justi and Gilbert (2006) bring out the close relationship between visualisation, mental models and analogical thinking in the history of Chemistry as well as in the teaching of Chemistry. Nersessian (1995) discusses mental models and analogical reasoning as used by Faraday and Maxwell and suggests that analogies help in visualisation (see Section 2.12). Nersessian refers to examples of analogical thinking in the history of science which include: Darwin's analogy between selective breeding and natural selection, the Rutherford-Bohr analogy between the structure of the solar system and subatomic particles, and many lesser known examples of reasoning with pictorial representations in the constructive practices of scientists. Kekule's dream about the snake swallowing its own tail as an analogue of the structure of Benzene is another oft-cited example. Venville and Treagust (1997) describe the important role played by analogies in the development of the science of biology: Harvey's discovery of the circulation of blood was based on analogy with two Aristotelian tenets (referred to in Section 1.1, and Konrad Lorenz's animal behaviour research used analogical thinking to compare animals in different taxonomical groups.

Analogical thinking requires explicit structural mapping between a (familiar) source domain and an (unfamiliar) target domain to indicate identity of parts of structures (Vosniadou and Ortony, 1989; Duit, 1991).

The analogical reasoning process (or mapping from the source to the target domain) creates an abstraction or 'schema' which lends itself to further problem-solving. Analogies are therefore not merely guides alone, but also do the inferential work and generate the problem solution.

The use of analogies as a pedagogical tool has been found to be effective particularly since learners come with varied conceptions and prior knowledge about a particular topic. In the context of science teaching and learning, the target (unfamiliar domain) relates to a scientific concept (Treagust, 1993). Analogical reasoning is inherently visual in nature since there is a process of pattern matching between the analog and target. Analogies help students bridge the gap between their real world knowledge and abstract concepts in the process perhaps increasing their motivation too.

Since there is a close connection between mental visualisation and analogical thinking, perhaps analogies could be used to elicit and to study mental visualisation. This was attempted in Phase I[1] of this study (Chapter 4, Sections 4.15 and 4.16). However, previous research points out limitations too in the use of analogies as reviewed by Venville and Treagust (1997). There are features of the analog which are unlike the target and care must be taken not to match those as the result could be impaired learning. Analogy helps students bridge the gap between their real world knowledge and abstract concepts in the process perhaps increasing their motivation too. Analogies can lead to alternative conceptions among students, especially if students transfer unique features of the analogical concept to the scientific concept. Students may also be unfamiliar with the analogous concept thus the outcome may not be similar to the teacher's understanding.

Gentner (1989) distinguished between different kinds of similarity, which is essential to understanding learning by analogy and similarity. In 'analogy' only relational predicates are mapped. In 'literal similarity', both relational predicates and object attributes are mapped. In 'mere-appearance' matches, only object attributes are mapped. It is possible that structural attributes of human body systems may elicit 'mere appearance' matches rather than relational matches while functional attributes may elicit relational matches. 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.

Vosniadou and Ortony (1989) distinguish between surface and deep similarity. Surface similarity is similarity in terms of readily accessible attributes, apparent only from the surface. Deep similarity is between deeper underlying properties. Given that structural attributes are usually seen from the surface while functional attributes are less visible, surface and deep similarity again seems to map on to structure and function attributes.

1 Phases and Parts of the study are explained in Section 3.7

Since there is a close connection between mental visualisation and analogical thinking perhaps analogies could be used to elicit and study mental visualisation. This was attempted in Phase I of this study (Chapter 4, Sections 4.15 and 4.16).

Our initial findings in Phase I regarding the use of analogies turned out to be consistent with the observations of Venville and Treagust (Section 4.19.1). We therefore did not use analogy questions in assessing visualisation specifically, but we did use analogy questions with some constraints to encourage students to form structure-function relationships (Sections 5.7.1, 5.7.4, 5.8.1, 5.8.3, 5.9.1 and5.9.3.

3.2 *Transformational reasoning*

Gilbert (2006) proposes the idea of 'metavisual capacity' to think about the development of mental visualization. This skill involves monitoring and control of an image being learnt, knowing how to rehearse and retain it in memory, retrieving the appropriate image when necessary and finally transforming the image according to the demands of the task at hand. Briggs and Bodner (2005) see mental visualisation as an operation, a dynamic component that brings about a one to one correspondence between a mental representation and its referent.

The classic studies that launched the scientific study of imagery (Shepard and Metzler, 1971; Kosslyn, 1990) employed tasks such as mental rotation, mental scanning and manipulation of an image. Performance on these tasks was taken as evidence for visualization. In mathematics and science too, dynamic play with images has been related to visualization and has been termed "transformational reasoning" (Simon, 1996). Simon suggested that transformational reasoning is neither inductive nor deductive, but draws on the characteristics of both forms. According to Simon (1996), the transformational 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 continuums 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”.

Ramadas (2009) reviewed research on ‘transformational reasoning’ as seen in science, in visual thinking 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.

Tests of spatial ability ask subjects to perform mental manipulations such as mental rotation, reflection, cutting, folding and perspective-change (Sorby, 2009). The literature on mental visualisation (Section 2.7) shows that mental transformations are linked to transformations related to perceptual processes (like rotations and scanning). Tversky (2005) suggests that the order of performing the transformations may be tied to motor processes, like the act of drawing or constructing a figure. Thus transformational reasoning has both perceptual and motor foundations. Spatial imagery (found to be distinct from visual imagery as mentioned in Section 2.7) could also perhaps be implicated in transformational reasoning. In Phase II of this research (Section 5.4.4), the notion of transformational reasoning is used to study mental visualisation.

3.3 *Understanding structure and function*

In the context of our study on human body systems, we had to identify and test for aspects which are essential to an understanding of the human body. In the systems biology approach that we adopted, two basic aspects of a system which are integral to this understanding are structure and function. The study of structure refers to construction of the system: its components and elements and combinations to form wholes. Function refers to the role of a particular part(s) or the combined action of two or more parts. An understanding of structure is linked to the function of those parts and vice versa. This characterisation of structure and function applies to all systems, mechanical or biological.

In biology, unlike in most simple mechanical systems, structure and function concepts are integrated in a highly complex manner. Inferences drawn from structure-function relationships often go across levels of organistion of the system. A correspondence between structure and function is sometimes not obvious. Further in terms of pedagogy, at the school level, while structure of the digestive system is understood at a gross macroscopic level, significant aspects of function involve chemical reactions which occur between molecules — a level of structure that is often not accessible to students. Nonetheless in characterising students' knowledge of body systems, we need to include the entire range of functions from macro to micro to chemical levels, as appropriate for students of middle school. In our study of visualisation (Part 1 of Phase II) when students had to connect structure with function, and in Part 2 of Phase II, when we designed passages to convey either structure or function, we largely considered macro-level structure and function.

3.3.1 *Conveying structure and function through diagrams*

Heiser and Tversky (2006) probed comprehension of diagrams of mechanical systems by college undergraduates. Students were asked to describe these diagrams under two conditions: either with or without arrows. The results showed that diagrams with arrows elicited predominantly descriptions about function, whereas those without arrows were described more in terms of structure. There was therefore a clear correlation between drawing arrows and a functional understanding.

In drawings of biological systems depiction of structure is quite common. Function is not easy to depict, so we were interested in seeing how students would do it. We have analysed both structural and functional aspects of drawings produced by students (Phase I and Phase II, Part 1). We have also looked at students' comprehension of diagrams depicting either predominantly structure or predominantly function (Phase II, Part 3) where we designed diagrams that might encourage students to connect structure with function, using techniques of magnification and schematisation in order to clue structure-function relationships across levels of organisation of the system.

We have focused on line drawings alone as a form of visual representation. Line drawings are the most commonly used representations at the school level. They have the power of abstracting out relevant content (Kearsay and Turner, 1999). They have been found to be useful in teaching factual content, and simpler for students to use for thinking and communication.

3.3.2 *Conveying structure and function through verbal descriptions*

Heiser and Tversky (2006) consider how language conveys structure and function concepts. They point out that functional descriptions are dynamic and tend to use verbs of motion and transitive verbs such as (in the case of bicycle pump and route maps) *enter, open, close* and *travel.* Functional descriptions also include verbs that express outcomes and causes, such as *accumulates, exerted, push, slow* and *causes*. On the other hand, structural descriptions are static, contain details of parts and use intransitive verbs such as: *to be* and *can*.

In an experiment with undergraduate students, Heiser and Tversky (2006) probed what kinds of diagrams students draw when presented with structural and functional descriptions of "complex" mechanical systems, namely, car brake, bicycle pump and a pulley system. Participants read a structural or a functional description of one of these three systems. They were then asked to sketch a diagram of the described system. The diagrams were coded by two independent coders for conventional diagrammatic elements: mainly arrows and lines. Their placement and function in the diagram were also coded. Students drew diagrams with arrows in response to verbal descriptions of function and diagrams without arrows in response to verbal descriptions of structure. Thus in a situation where students had to covert a verbal description into a diagram, arrows were found useful to augment structural diagrams and convey functional information.

Though language has terms to convey structural concepts in biology at some gross level of description, details of anatomy need to be conveyed through visuals such as photographs and diagrams. Function, on the other hand, is better expressed through text or propositions, and occasionally through highly schematised box or flow diagrams.

3.4 *Conceptual framework underlying text and diagrams*

Understanding of human body systems requires correlation of anatomy with physiology, i.e. of structure with function. 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. In human body systems we find a "segmentation" in terms of the organs composing that system, and "order" in the sense of the physical connections between them (it may indeed reflect a natural order in the process of drawing). With reference to function, we consider the "order" of action of the organs or their parts. "Hierarchy" is in the sense of gross-level and micro-level operations (i.e. the macro passage of food/air/blood and the corresponding cellular/enzymatic/molecular level of action).

In this view, the organisation represented through a drawing or text is a pointer to the conceptual framework that the student or learner may have represented to herself and one she is attempting to communicate to us. With this rationale we conducted an empirical study (Chapter 4 of this thesis; Mathai and Ramadas, 2006). Through this study we formulated a coding scheme for students' text and diagram responses (described in Section 4.7). The relationship between structure and function further helped us characterise mental visualisation (Chapter 5, Section 5.4.4).

3.5 *Visualisation and the structure - function relationship*

In Section 3.1 we considered the possibility of using analogy to study mental visualisation, but there were some problems along the way. Another possibility that we found more fruitful was to use transformational reasoning. The notion of transformational reasoning (Section 3.2) helps us to understand how diagrams with text facilitate the formation and manipulation of visual images, which in turn might enhance understanding of the human body. Ramadas and Nair (1996) tested for understanding of the digestive system through questions on the structure-function relationship, i.e. asking students to manipulate structure to see its effects on function. We conjectured that tasks of this type would elicit visualisation in relation to the human body systems. Correlation of form with function is inherent to understanding physiology. In the case of human body systems, both form and function are not directly visible. What students have are static representations of structure, as conveyed usually through diagrams. As for function, the macro aspects (for example expansion and contraction of parts, or movement of air, food or blood through the organs) can be correlated directly with mechanical manipulation of the parts of the body. But function at a micro or sub-micro level (for example, chemical transformation of food) cannot be correlated with the gross level structure that the students know.

In our study of visualisation therefore, we focused on gross level function and its correlation with structure. We have employed unfamiliar problem situations which might necessitate generating and manipulating visual images. The ability to relate structure with function in a new situation calls for transformational reasoning on a mental image or a diagram. In these tasks students are asked to explicitly relate drawings or mental images with propositional content through various means. More specifically, visualisation questions involving transformational reasoning 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.

3.6 *A framework for this study*

Following from the theoretical rationale, the following lines and concept map in Figure 3.1 explain the framework for the study

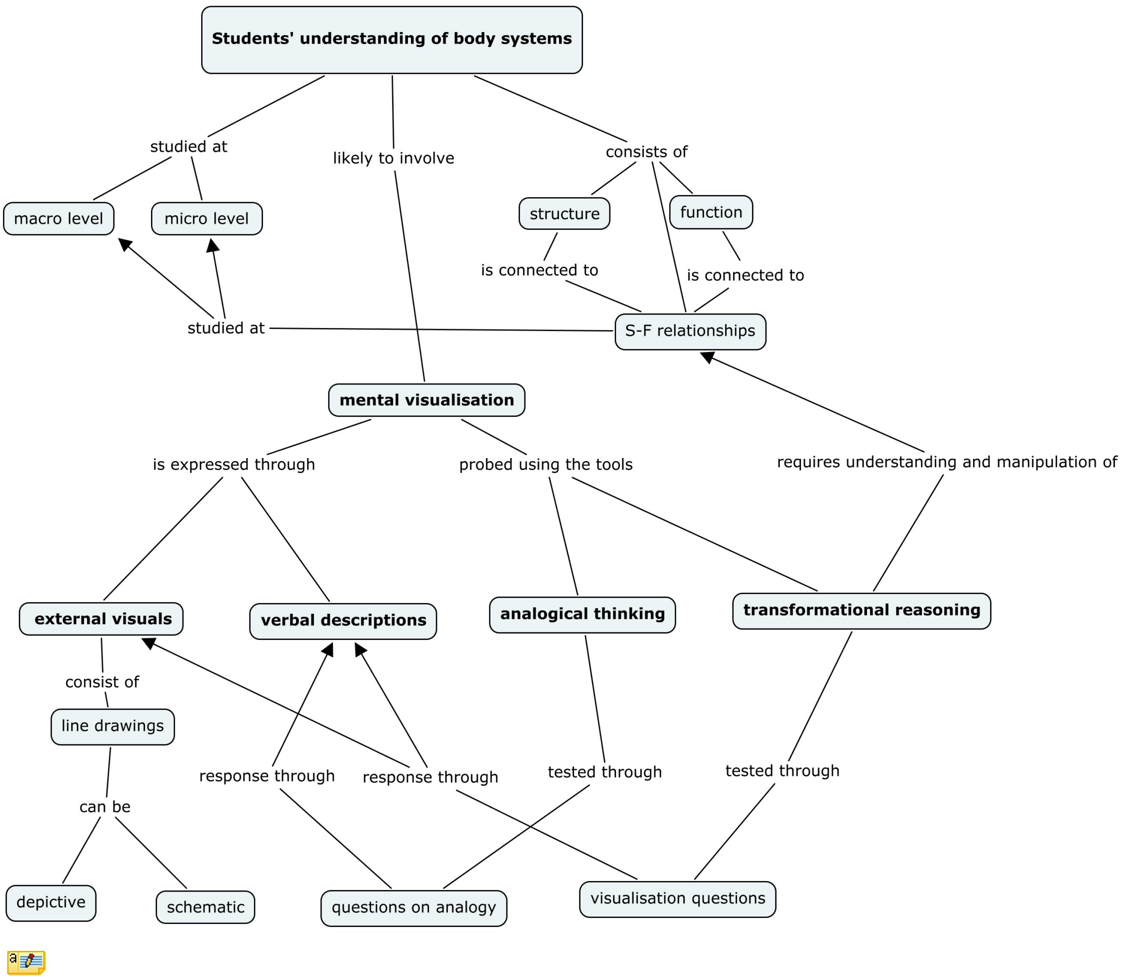
- We investigated students' understanding and expression through external 'visuals' and mental 'visualisation' in the context of human body systems.

- Our 'visuals' consisted of line drawings from more depictive to more schematic ones. Students were asked to produce line drawings in response to specific questions which required them to express understanding of structure, function and structure-function relationships. They were also asked to express their understanding using verbal descriptions.

- Students' mental 'visualisation' of the body systems was probed using the tools of analogical thinking and transformational reasoning. Visualisation questions mainly required transformations of structure and predicting its effects on function. A few questions required manipulation of function and also imagining structure from a different orientation.

- Students' understanding was studied at macro and micro levels of organisation

Figure 3.1. A framework for the study



Annotations for Figure 3.1.

1. Mental representations are usually assumed to have a propositional component, which for reasons of simplicity is not included in this diagram

2. Students were given a choice of responding through both verbal and diagram modes. They usually chose the former.

3. Structure diagrams that we obtained from students' responses were mostly depictive, whereas some function diagrams were amenable to a schematic representation.

3.7 *Research design*

The study was carried out in two phases. Phase I consisted of an exploratory study conducted with thirteen students from Classes 6, 7 and 8. Since the sample was small, detailed interviews were conducted with each of the students and these oral responses were pooled with the written responses to form a database from which using the criteria mentioned in Section 3.4 and elaborated in Chapter 4 (Section 4.7), Verbal scores (Vr) were arrived at. Using parallel criteria, diagram scores were also assigned. Phase I tested for basic knowledge of three body systems: digestive, respiratory and circulatory. In Phase I, visualisation was assessed using analogies.

Phase II of the study involved detailed testing of 87 students from Class 6 (completed), on two systems: the digestive and respiratory. There were three parts to this Phase. Testing during Part 1 (Phase II) concerned basic knowledge and visualisation of the two systems. Here the data was entirely in written form and it was coded to give Text (T) and Diagram (D) scores for each system. Visualisation was assessed in a different way from Phase I, using specific questions requiring manipulation of structure for which scores were assigned as described in Section 5.4.4.

Part 2 of Phase II concerned comprehension of text descriptions related to the digestive and respiratory systems. Following the idea of Heiser and Tversky (Section 3.3.2) of separating structure and function passages, we attempted to do the same for the body systems. Part 3 of Phase II concerned comprehension of diagrams related to predominantly structure or function of the digestive and respiratory systems.

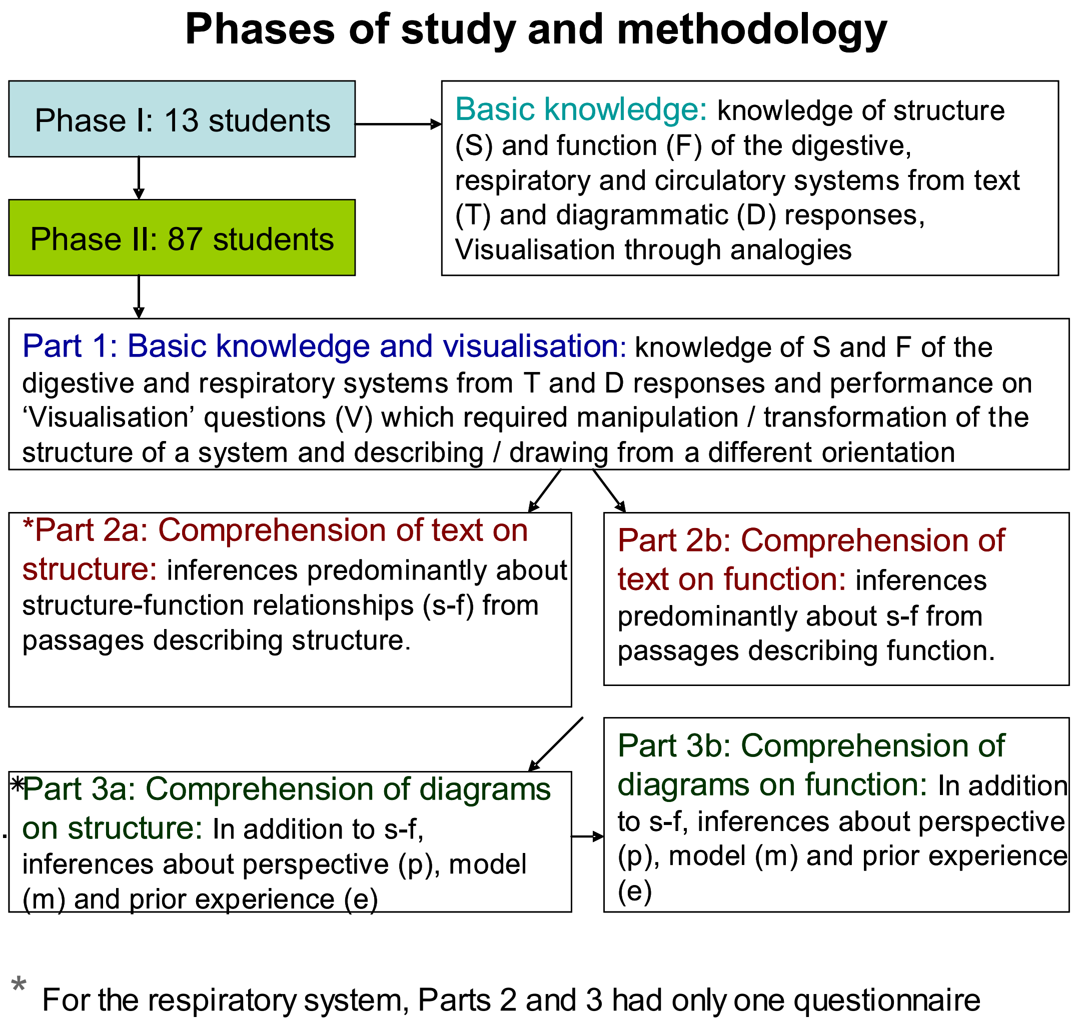
The design of the study was 'Mixed Methods'. A mixed methods research design is a procedure for collecting both quantitative and qualitative data in a single study (Creswell, 2003). The priority and sequence of data collection, analysis and reporting is determined by the objectives of the research study. The rationale behind such a method is that either qualitative or quantitative methodology alone is insufficient to capture the details and complexity of a research problem. Both methods should therefore complement each other to arrive at more robust analyses.

The data obtained from students was in the form of diagrams and verbal (written and oral) responses, all of which were qualitative in nature. Quantitative data was obtained in the form of Verbal (Vr), Text (T), Structure (S), Function (F), Visualisation (V), and Structure-Function relationships (S-F). The analysis of data was both qualitative and quantitative. Statistical analysis was carried out using the data. Qualitative analysis resulted in the case studies of two students (GP and TT) in Phase I, an understanding of problem areas and alternative conceptions pertaining to the content, and interpretation of results from the quantitative analysis.

The priority assigned to both forms of data collection varied in the two Phases. In Phase I, thirteen students had to respond to three questionnaires on the digestive, respiratory and circulatory systems with words and diagrams as they wished. These qualitative responses were quantified using a coding scheme. Following the written test, each student was interviewed. Both written and oral responses were used to obtain Verbal (Vr) scores. Diagrams were also coded. Quantitative analysis of these scores were supplemented with qualitative analysis. Student transcripts were also used as examples of instances of visual imagery (found in Section 4.15). In Phase II however, there were eighty seven students and eight questionnaires to be answered. There were several details in the questionnaires requiring detailed quantitative analysis. Time constraints therefore meant that clinical interviews could not be carried out. However, some analysis and interpretation of results was qualitative using student's diagrams especially while outlining their alternative conceptions.

The design of the entire study is given in the form of a diagram given below:

Figure 3.2: Phases of the study and methodology



4 | Chapter 4: Exploratory Phase (Phase I)

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4.1 *Objectives of Phase I*

In the first phase of the research, we explored middle school students' understanding of three body systems (digestive, respiratory and circulatory) through both verbal and diagrammatic modes. Since there are no prior studies in this area, the main objectives of this phase were to arrive at a baseline for students' understanding of the three systems, and for their facility with verbal and diagrammatic expression. Coding schemes were developed. In this phase, we also explored ways of studying visualisation of human body systems.

The following research questions served as motivation for the study:

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?

4.2 *Sample*

Thirteen students, six boys and seven girls who had completed Classes 6, 7 and 8 (ages 10 to 13) were selected from an English medium school in Mumbai, India. The sample was mixed in terms of ability level. Five students belonged to the top five rankers in their class. Another five were ranked between 6-15, and the remaining three were ranked below 15, in their class of 35. (Appendix A.1). 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.

4.3 *Curriculum followed at school*

The schools followed the curriculum and textbooks produced by the National Council of Educational Research and Training (NCERT, 2002 given in Appendix F). In Class Six, these students had been introduced to all the systems of the body: the digestive, respiratory, circulatory, excretory, nervous and reproductive systems. In Class 7, they had studied chemical aspects of digestion and cellular respiration while in Class 8 they had reference to organs that get affected in diseases. The maximum content on the body systems therefore was in the Class 6 textbook.

4.4 *Questionnaires*

Students were administered three questionnaires pertaining to the structure and functioning of the human body, specifically three systems: digestive, respiratory and circulatory. Students were asked to express themselves spontaneously using diagrams and words as they wished. The questions were designed keeping in mind the content of the textbooks for Class 6. In addition, the type and sequence of questions was similar for the three systems. Thus it was assumed that all students were familiar with the subject content of the questions. Each questionnaire, comprising six questions, was administered to students during the course of a three-week summer camp organised at the Homi Bhabha Centre for Science Education in April 2004. Each system was allocated one week for data collection. On the first day of the week, students were given two hours to complete one questionnaire. Following the written questionnaire, students were interviewed individually. The set of students' interviews were completed over the course of three days. On the last day of the week there was a feedback session, where students could clarify their doubts and ask questions. In addition there was a discussion based on the questionnaire in which the researcher addressed the issues raised by the students' responses. In the successive questionnaires therefore, students were expected to be better prepared and primed to answer the type of questions asked in them. The questionnaires for Phase I are in Appendix B.1.

Each questionnaire on each of the three systems had several segments. Some segments were common across all three systems, and some were specific to the system. In the first segment the students had to draw the digestive / respiratory / circulatory system within the outline of the human body given to them using plain lead pencils along with colour pencils or crayons. The second segment required them to imagine eating a favourite food (for the digestive system), or dust entering the nostrils (for the respiratory system), and to describe in words and drawings what happened. It was hoped that framing a question in this manner would encourage visual imagery in relation to the systems. An analogous question was not asked for the circulatory system, since this particular system has not been dealt with in great detail in textbooks. The third segment of the questionnaire required students to read a passage on the system, taken verbatim from their textbooks. They had to draw a diagram to explain certain parts of the passage as indicated, or to show through diagrams what the passage explained in words. The fourth segment contained two questions on analogous processes: one asked students to think of a process analogous to that system, verbally or with diagrams; the second consisted of open-ended questions which students had to complete, in which they had to say what organs of each system reminded them of. We expected that the analogy questions may further encourage visualisation. A question on visualising inspiration and expiration was part of the respiratory system alone (see Appendix B.1).

4.5 *Oral interviews*

In the clinical interviews, students were further probed on their drawn and written responses. Each interview lasted for roughly half an hour. Besides questions based on their previous responses, students were asked to imagine what may be held within the spaces of the organs, the similarities and differences between the analogous processes students had thought of and the actual process. In the circulatory system students were asked about a drop of blood as it went around the body. In addition they were asked about their preference for written or drawn expression and reasons for them.

4.6 *Analysis of data*

All the interviews were fully transcribed. The data from the written questionnaires and interview transcripts were pooled for each student. Two forms of responses were distinguished: "verbal" (both written and spoken) and "drawings". The responses classified as "verbal" were broken up into the smallest meaningful sentences. This was in the form of propositions which were derived from written responses to the relevant questionnaire as well as from the related transcripts of the clinical interview. Responses classified as "drawings" all came from the questionnaires. They included exact depictions or likenesses (mostly drawings conveying concepts of structure), as well as schematic diagrams. Both forms of responses were analysed for students' understanding of structure and function.

4.7 *Development of a coding scheme*

Research question No. I/1 in Phase I had to do with students' understanding of structure and function through text and diagrams. The coding scheme developed in this Phase helped us assign scores to students' verbal and diagrammatic responses. 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. In Chapter 3, Section 3.4 we described three aspects of a common conceptual framework for biological (or mechanical) systems, which encompasses structure and function, and which underlies expression through both text and diagrams. These systems aspects are: 1) segmentation, 2) order and 3) hierarchy. In order to facilitate identification of these aspects in students' verbal (written or oral) responses, each response was broken down into simple propositions, which described either structure or function. Examples of students' responses converted into propositions are shown in Section 4.7.1. The segmentation, order and hierarchy aspects were next determined within propositions, as described in Section 4.7.2. Determination of these aspects in students' drawings is described in Section 4.7.3. The entire coding scheme is summarised in Table 4.1.

4.7.1 *Distinguishing structure and function propositions*

Each simple proposition was classified as denoting either a structure or a function statement. This was determined based on the verb in each proposition. Functional descriptions are usually characterised by the presence of *transitive verbs*. They are dynamic expressions and are often "motion, action and cause verbs" (Heiser and Tversky, 2006). Some examples of function propositions derived from students' responses are:

- Digestion is the *breaking up* of complex molecules into simpler ones.
- The air *goes through* the trachea and bronchi and finally *goes* to the lungs.
- The heart is like a water pump which *takes* water to different houses.

Descriptions of structure often have *intransitive verbs*, which are usually static (Heiser and Tversky, 2006). Some examples of structure propositions are:

- The food pipe *is* connected to the stomach.
- The respiratory organs *are* nose, windpipe, bronchi, bronchioles, diaphragm, etc..

- The trachea has blood capillaries.

Analysed in this manner across all the systems, there were about 13 structure propositions and 52 function propositions per student per system. The range per student was between 8 and 111 propositions.

4.7.2 *Names of organs (segmentation), order and hierarchy within the propositions*

4.7.2.1 *Analysis of structure propositions*

The propositions thus derived were used as the data set for further analysis in which students' expression of the structure of a system was compared with a standard set of criteria derived from the systems' aspects (Section 3.4). These criteria were (for structure):

- *The names of the organs of a particular system (the analogue for "segmentation" within drawings)*:

For the digestive system there are twelve organs as per their textbook and which we expected students to include when they described the digestive system. The number of organs given by the students were counted and the proportion was calculated. For example, the total number of organs in the digestive system being twelve, if the student mentioned nine organs, then the score was calculated as: 9/12 = 0.75.

- *The order of location of organs relative to each other:*

The order of location for the digestive system comprises seven steps: 'mouth to oesophagus', 'oesophagus to stomach', 'stomach to duodenum', 'liver and pancreas connected to the duodenum', 'duodenum to the remaining part of the small intestine', 'small intestine to large intestine' and 'large intestine to anus'. The order of spatial location in students' responses was identified. The number of correct links was divided by the total number of links for that system to give a score for "Order of location". There was no hierarchy score assigned in relation to structure.The total structure score for verbal responses (VrS) was the average of the "Names of organs" (segmentation) and "Order of location" scores.

4.7.2.2 *Analysis of function propositions*

Comprehension of function was determined by analysing the propositions using the following criteria:

- *Order of action of the organs "order":*

  As discussed earlier, Order of action of the organs of the system in the form of linked pairs in students' propositions was identified and compared with total number of linked pairs for that particular system. Note that unlike spatial order (structure criterion), the order of action is the order of passage of either food , air or blood through each organ of the system.

- *Functional hierarchy in the system:*

In the case of the digestive system, there are two levels of functional hierarchy. The first is the digestion of food during its passage through the alimentary canal. The second level is the action of the accessory organs and the glands which secrete digestive juices. In particular, the liver and pancreas secrete their juices into the partly digested food in the duodenum. In the case of the respiratory system the hierarchy consisted again of two levels: breathing and cellular respiration. For the circulatory system, the two levels of hierarchy are: systemic circulation and pulmonary circulation.

There was no "segmentation" score for function. The verbal function score (VrF) for each student for a particular system was the average of the mean scores for Order of action and Hierarchy.

4.7.3 *Segmentation, order and hierarchy within the diagrams*

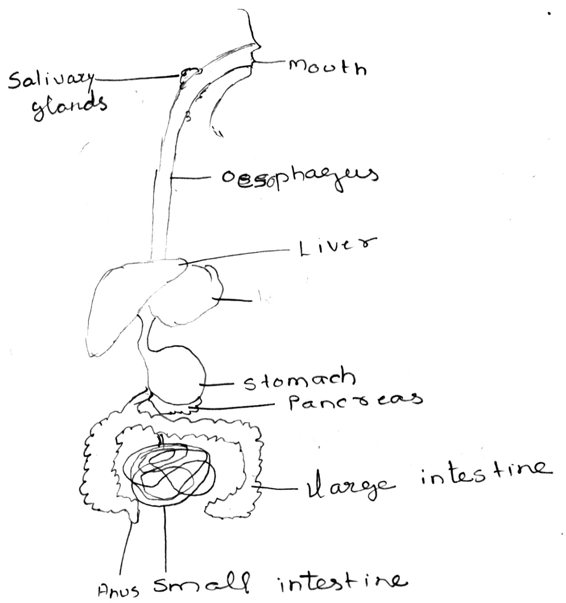
4.7.3.1 *Analysis of structure diagrams*

As discussed in Chapter 2, any depiction can be naturally "segmented" into its elements and the spatial relations between them. The elements may reflect spatial relations in the real world or they may denote abstract relations. In the case of the human body, the elements are the organs, and they denote spatial relations in the real world. These considerations lead to a way of analysing the comprehension of structure from drawings. The criteria for the systems were similar to those used for verbal responses, but they were applied to students' drawings of the three systems. The criteria were:

- Identifying the organs depicted by students in their diagrams and comparing them with a standard list of organs and
- Order of location of the organs relative to each other

An example showing the use of the scheme for calculation of the structure score for the digestive system is shown in Figure 4.1.

Figure 4.1: An example of the use of the coding scheme for calculation of structure scores for the digestive system



Segmentation: 9/12 = 0.75
Order of location: 3/7= 0.43
DS: (0.75 + 0.43) / 2 = 0.59

4.7.3.2 *Analysis of function diagrams*

Understanding of function was determined using two criteria:

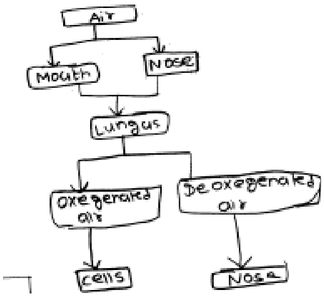
- Functional organisation of the organs of the system:

  the functional order denotes the order in which the organs work together to serve a particular function in the system. This could be quite independent of its structural order

- Functional hierarchy in the system

An example of the use of this coding scheme for calculation of function scores for the respiratory system is illustrated in Figure 4.2.

Figure 4.2: An example of the use of the coding scheme for calculation of function scores for the respiratory system



Order of action: 2/7
Hierarchy: ½
DF: (Order of action + Hierarchy) / 2 = 0.4

Every drawing was analysed as per the criteria mentioned above. On an average there were three diagrams per student for each system of the body. Scores were assigned as discussed for the verbal responses. The average structure score from drawings (DS) for each student per system, was the mean of the segmentation and order of location scores. The average function score from drawings (DF) was the mean of the order of action and functional hierarchy scores. As for the verbal scores there was no "segmentation" score for function for the diagram scores also.

This was the coding scheme used to arrive at a student's verbal and diagram score for each of the three systems. The scheme of analysis is shown in Table 4.1. Table 4.2. lists the abbreviations used in Table 4.1 and the results presented next. The criteria for analysis are given in detail in Appendix C.1.

4.7.4 *Comparison with textbook propositions*

Apart from calculation of VrS and VrF, students' structure propositions were compared with the textbook propositions to arrive at a PS score, and students' function propositions were similarly compared to arrive at a PF score. The matching was done by identifying the number of propositions in students' responses that were identical in meaning to the textbook propositions. The propositions that matched were counted and divided by the total number of propositions in the textbook to arrive at an average propositions structure score (PS) and propositions function score (PF) for each student.

Table 4.1: 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)

Table 4.2: List of abbreviations

Abbreviation	Score for
VrS	Structure expressed verbally
VrF	Function expressed verbally
DS	Structure expressed through diagrams
DF	Function expressed through diagrams
S = (VrS + DS)	Total Structure score
F = (VrF + DF)	Total Function score
Vr = (VrS+VrF)	Total Verbal score
D = (DS+DF)	Total Diagram score
Vr-dig, Vr-res, Vr-cir	Verbal score for the digestive system, respiratory system and circulatory system
D-dig, D-res, D-cir	Diagram score for the digestive system, respiratory system and circulatory system
PS	Students' structure propositions compared with textbook

Abbreviation	Score for
	propositions
PF	Students' function propositions compared with textbook propositions
P = PS +PF	All propositions compared with propositions in their textbook

4.8 *Statistical analysis*

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 (S) and a total Function score (F) (See Table 4.2). Similarly, a total Verbal (V) and Drawing score (D) was calculated for the three systems. 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.

4.9 *Overall performance across the three systems*

Table 4.3 shows the overall performance of the thirteen students across the digestive, respiratory and circulatory systems. On an average each student drew 1 – 3 diagrams per system. Often these were fairly well-reproduced but standard textbook diagrams. The exceptional diagrams are described in Section 4.13.

Table 4.3: Overall performance of the students across the three systems

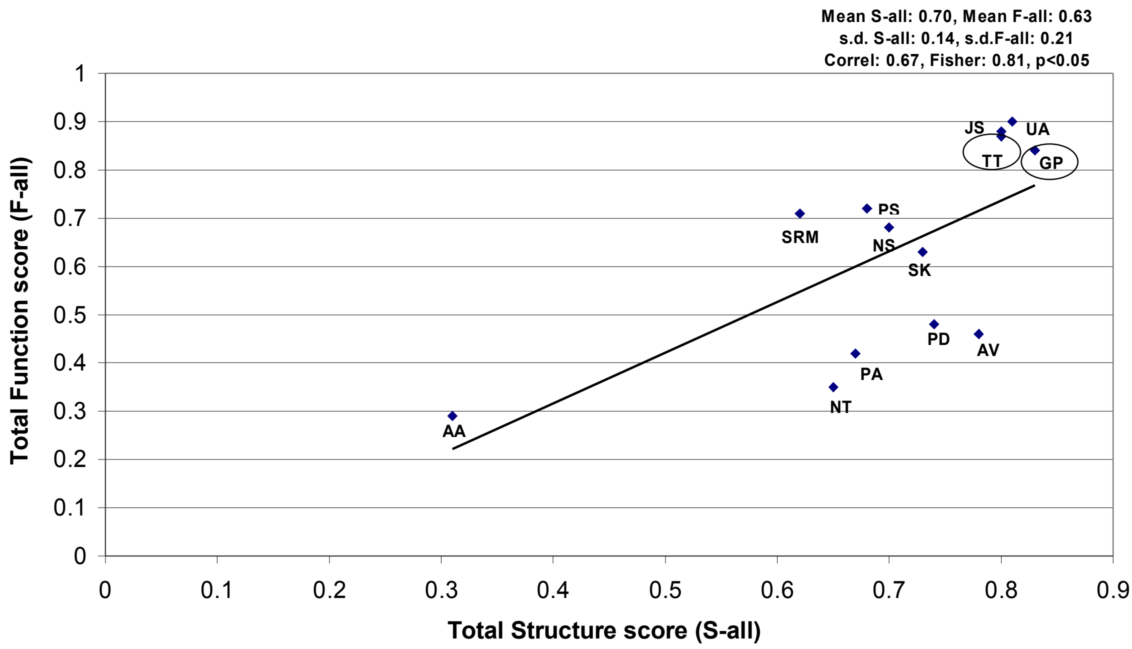
Student			**Digestive**			**Respiratory**			**Circulatory**			**Average score across the three systems**		
Code name	**Class**	**Sex (B/G)**	**P**	**Vr**	**D**	**P**	**Vr**	**D**	**P**	**Vr**	**D**	**P**	**Vr**	**D**
TT	6	G	69	0.64	0.86	81	0.81	0.71	80	0.92	1	76.7	0.79	0.86
GP	6	B	94	0.66	0.86	111	0.81	1	9	--	--	71.3	0.74	0.93
SRM	6	B	74	0.55	0.62	92	0.58	0.53	118	0.88	0.86	94.7	0.67	0.67
AV	7	B	78	0.61	0.71	98	0.81	0.65	--	--	0.43	88	0.71	0.6
SK	7	B	58	0.54	0.76	73	0.83	0.41	87	0.88	0.57	72.7	0.75	0.58
NS	7	G	39	0.54	0.71	53	0.61	0.76	73	0.88	0.64	55	0.68	0.70
PA	7	G	47	0.41	0.86	80	0.53	0.29	--	--	--	63.5	0.47	0.58
AA	7	B	--	--	--	46	0.48	0	146	0.7	0	96	0.59	0
PS	7	B	62	0.64	0.71	86	0.81	0.59	72	0.84	0.64	73.3	0.76	0.65
UA	8	B	46	0.77	0.81	58	0.95	1	52	0.92	0.79	52	0.88	0.87
NT	8	G	54	0.47	0.62	56	0.5	0.24	79	0.82	0.21	63	0.60	0.36
JS	8	G	76	0.65	0.62	92	0.89	1	--	0.92	1	84	0.82	0.87
PM	8	G	56	0.52	0.57	--	--	0.65	120	0.64	0.57	88	0.58	0.60

P: No. of propositions, Vr: Verbal score, D: Diagrams score

4.10 *Understanding structure and function*

Research questions No. I/2 and I/3 in Phase I had to do with students' understanding of Structure and Function, as expressed verbally and through diagrams. In this section we compare the results for Structure and Function, first across all systems, and then for each system separately. The scores plotted in all the figures in this section are obtained by combining the Verbal (Vr) and Diagram (D) scores. The scattergrams enable us to get an overview of the group's scores, as well as to track the performance of the individual students whose detailed scores are summarised in Table 4.3. Two high performing students, TT and GP, whose case studies are given in Section 4.18, are marked with circles in these figures. Figure 4.3 shows the scattergram of Structure and Function scores for all the systems combined (S-all and F-all). The trend line has a positive slope and the Pearson's correlation of 0.67 significant at 0.05 level.

Figure 4.3: Expression of understanding of structure and function across all systems

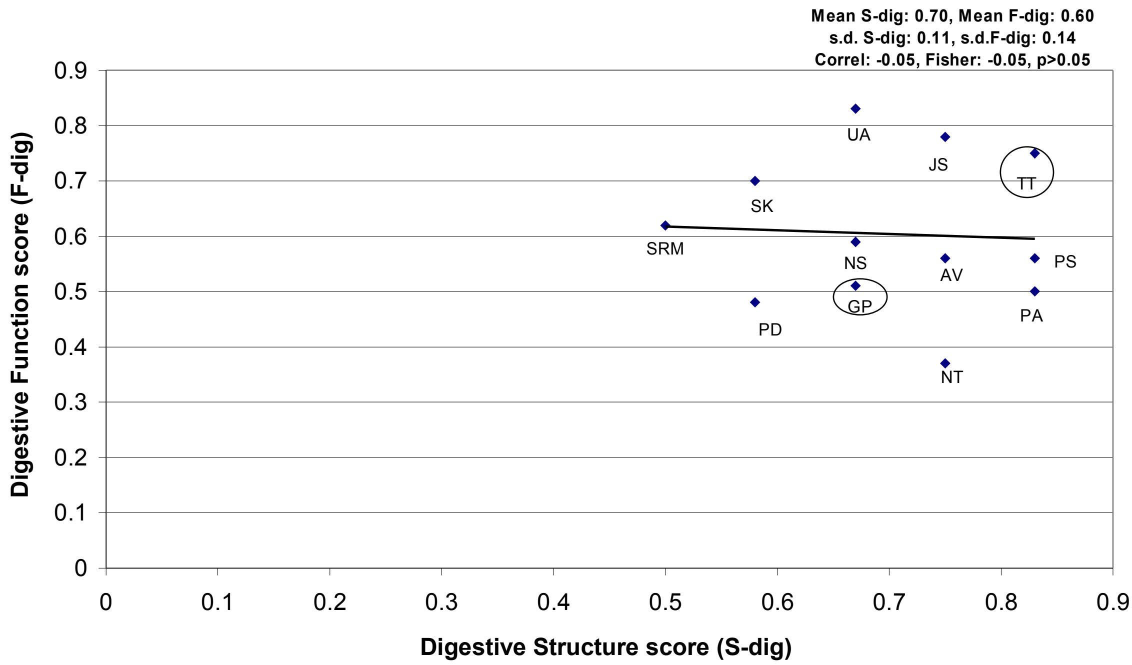


Figs. 4.4 to 4.6 show scatter plots of structure and function scores for the three systems after integrating verbal and diagrammatic scores. The scatter plots shows a cluster at the higher end of the scale, indicating that a majority of the subjects in this study were at roughly the same level of understanding. However, there was considerable variation in the structure-function correlation between the three systems. In the respiratory system the correlation was highest, while in the digestive system there was no correlation. The separate Structure-Function scatterplots for the three systems are shown in Figures 4.4. to 4.6. Table 4.3 summarises the mean and standard deviations for Structure and Function for all the systems. There were no significant differences between the structure and function scores. The last column of Table 4.4 gives the Pearson's correlation coefficients between the structure and function scores.

Table 4.4: Structure and function scores for the three systems of the body

System	Structure (S) mean (s.d.)	Function (F) mean (s.d.)	Pearson's correlation coefficient (r)
Digestive (dig)	0.70 (0.11)	0.60 (0.14)	-0.05
Respiratory (res)	0.66 (0.19)	0.66 (0.27)	0.82**
Circulatory (cir)	0.77 (0.18)	0.66 (0.29)	0.39
All systems	0.70 (0.14)	0.63 (0.21)	0.67*

Figure 4.4: Expression of understanding of structure and function of the digestive system (from both verbal and drawn responses)



The low correlation between structure and function scores of the digestive system (illustrated in Figure 4.2) is surprising. The digestive system is dealt with in most detail in textbooks and in classroom teaching. It is surprising that a competent understanding of the structure of the digestive system does not seem to be linked to an understanding of function. Qualitative analysis of the verbal and drawn responses point to two reasons for this lack of linkage between structure and function. The first was the role of accessory organs, the liver and pancreas and the gall bladder. Students knew that these organs had a place in the structure, but were not clear where they were to be placed with respect to the order of location and order of function. They were not aware of the role of these organs in secreting / storing the digestive enzymes. In fact they had no idea about chemical action of enzymes on food. This was a case of structure at the macroscopic level not being linked to function which happened at the chemical level.

In terms of our framework of analysis, the lack of correlation may arise from the functional hierarchy inherent in the system. The direct, easy to encode passage of food through the alimentary canal does not incorporate the action of the accessory glands: the liver and pancreas. Structure at the macroscopic level therefore does not fully specify the observed function namely, the chemical action of the digestive juices. This fact was related to a common alternative conception that came across, regarding the fate of the food after it passed through the stomach. Many students believed that food goes into the liver and pancreas just as it passes from one organ of the alimentary canal to the next (An example of this alternative conception is shown in GP's case study (Section 4.18.2, Figure 4.24). Even students who did not display this striking misconception had a difficulty in understanding the liver and pancreas to be accessory organs. Perhaps appropriately, this concept is also not elaborated upon in school textbooks at this level. Finally, this lack of correlation could have been to some extent an artifact of coding, in which “functional hierarchy” was given as much weightage as “order of action” in calculation of function scores. The scoring system was subsequently changed for Phase II, as discussed in Section 4.19.2.

The second difficulty (for three of the students) concerned the structural connection between the small and the large intestines. An understanding of function, that of food passing from the small to the large intestine, was surprisingly not accompanied by an understanding of this structural fact. This was perhaps a result of textbook drawings which are poor in clarity, portraying the small intestine to be an organ by itself, seemingly enclosed or framed by the large intestine. In students’ understanding of the intestines therefore, structure was not linked with function even though in this case (unlike in the case of the accessory organs as discussed above), a macroscopic link between structure and function was certainly possible. One explanation for the lack of correlation in this case could be that diagrams and content were learnt separately and by rote from textbooks. This observation is consistent with the non-visual pathway postulated in the model of Guérin et al. which is outlined in Section 2.8.

Figure 4.5: Expression of understanding of structure and function of the respiratory system (from both verbal and drawn responses)

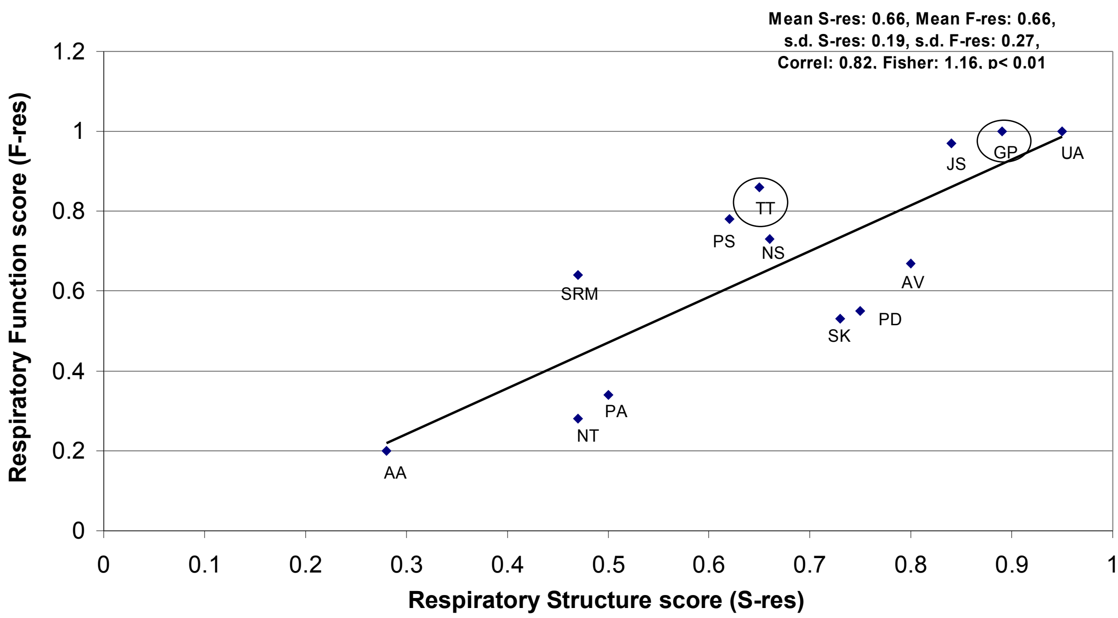
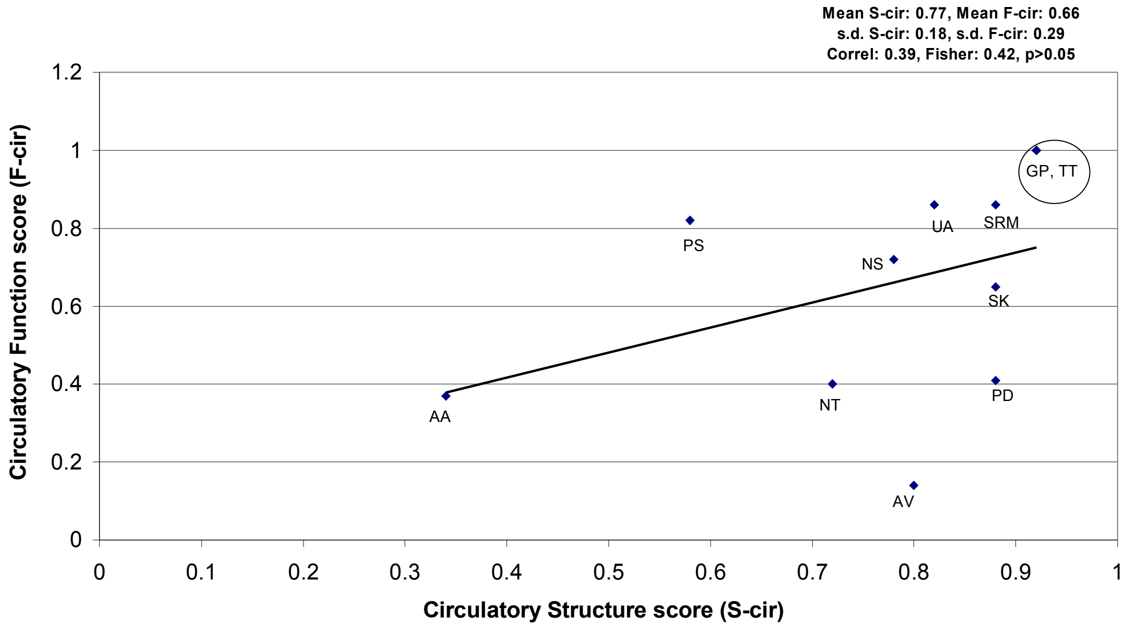


Figure 4.5 shows that for the respiratory system there was a strong correlation between structure-function scores. For this particular system there is an obvious direction in the structure of the system itself which helps in understanding its function. The structural order of the organs: nostrils-pharynx-trachea-bronchi-bronchioles-alveoli-bloodstream-organs of the body, is also the functional order of the system. Therefore understanding of structure and function may be easier for students to inter-link. This link was evident from both their written and drawn responses.

Figure 4.6: Expression of understanding of structure and function of the circulatory system (from both verbal and drawn responses)



The circulatory system presents an instance of a system whose structure does not give easy clues to the functional order of blood flow. This system has been treated quite cursorily in textbooks at the middle-school level. Understanding of structure could therefore be tested only at a very basic level: names of the organs, and the difference between an artery, vein and capillary. The structure of the heart was not mentioned and circulation of blood was described only briefly and schematically. Expression of understanding for this system is shown in Figure 4.6. In this system, it turned out that scores of structure and function were not significantly correlated. This lack of correlation is perhaps not surprising since the textbooks themselves do not elaborate on the structure-function relationship.

Most students considered the capillary to be another term for arteries and veins. This alternative conception was perhaps a result of inadequate knowledge of the functioning of the circulatory system. Students believed that the veins could be seen as being blue in colour because of the impure blood carried by them. They had also heard about the arteries as being carriers of pure blood. There were no significant differences between mean structure and function scores overall, and for the individual systems too (as seen by the Wilcoxon's signed ranks test). Students expressed both structure and function concepts spontaneously, though they could establish the connection only in some cases.

4.11 *Consistency between verbal and diagrammatic responses*

Research question No. I/4 in Phase I had to do with students' expression of their understanding through text and diagrams. Fig. 4.7 shows the scattergrams of Verbal and Diagram scores across all the systems. Table 4.5 shows the mean verbal and diagram scores for all the systems along with the Pearson's correlation coefficients between them. Overall there was a significant correlation between verbal and diagram scores. Comparing the three systems however, the correlation was maximum for the respiratory system and intermediate for the circulatory system. The separate scatterplots for the three systems are given in Figures 4.8 to 4.10.

Figure 4.7: Expression of understanding across all systems through verbal and drawn responses

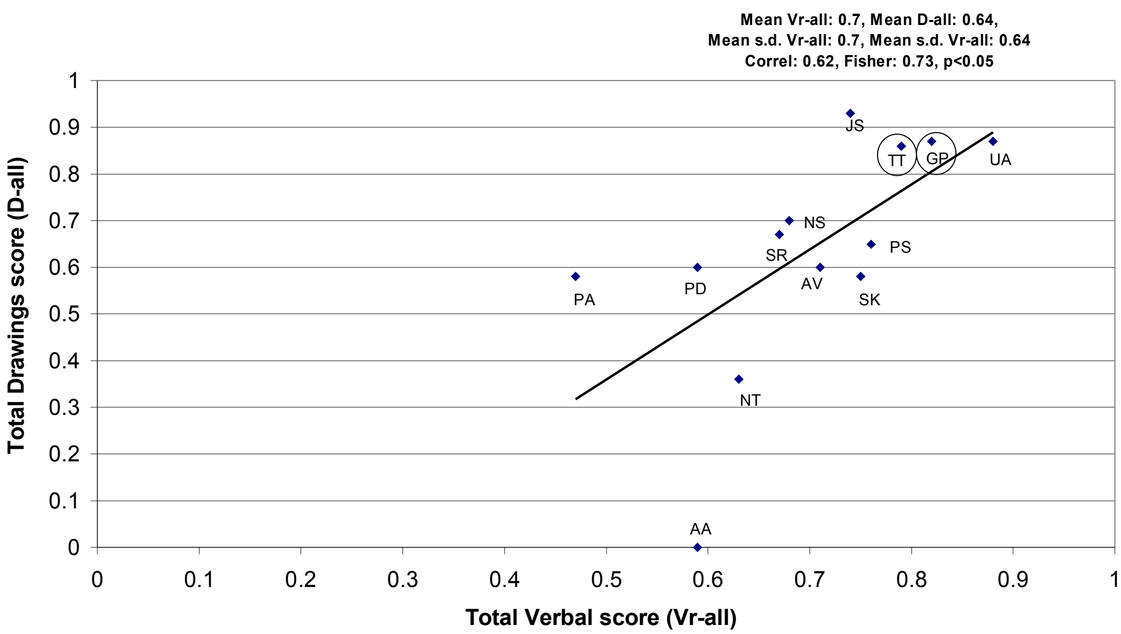


Table 4.5: Verbal and Diagrams scores for the three systems of the body

System	Verbal (Vr) mean (s.d.)	Drawing (D) mean (s.d.)	Pearson's correlation coefficient (r)
Digestive (dig)	0.58 (0.1)	0.73 (0.1)	0.24
Respiratory (res)	0.72 (0.17)	0.6 (0.31)	0.79**
Circulatory (cir)	0.84 (0.1)	0.61 (0.31)	0.67*
All systems	0.7 (0.08)	0.68 (0.16)	0.62*

Significant correlation at $p<0.05$ level, ** Significant correlation at $p<0.01$ level

Figure 4.8: Expression of understanding of the digestive system from verbal and drawn responses

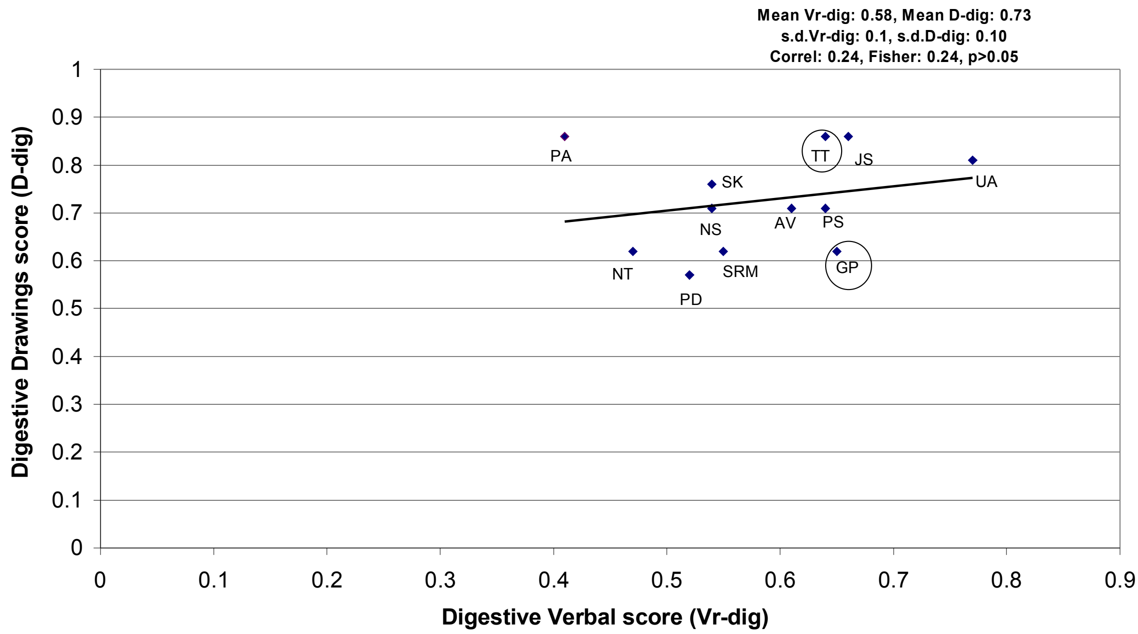


Fig. 4.8 shows the scattergrams of verbal and diagram scores for the digestive system. The plot, supported by the correlation coefficient in Table 4.5, shows that for the digestive system there was no correlation between verbal and diagram scores. For this system students in general had high diagram scores (Mean: 0.73) compared to verbal scores (Mean: 0.58), though the difference was not statistically significant. The diagram of the digestive system appeared to be well-learnt (barring a few problems, as described in the previous section on structure and function). However the connection between the diagram and text was missing in students' responses.

Figure 4.9: Expression of understanding of the respiratory system from verbal and drawn responses

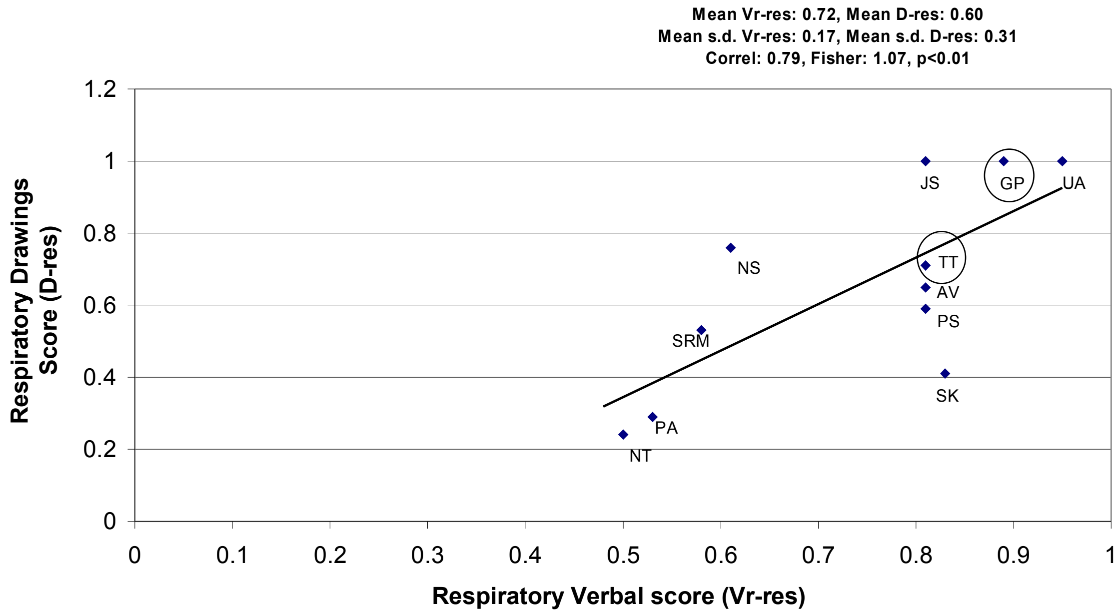
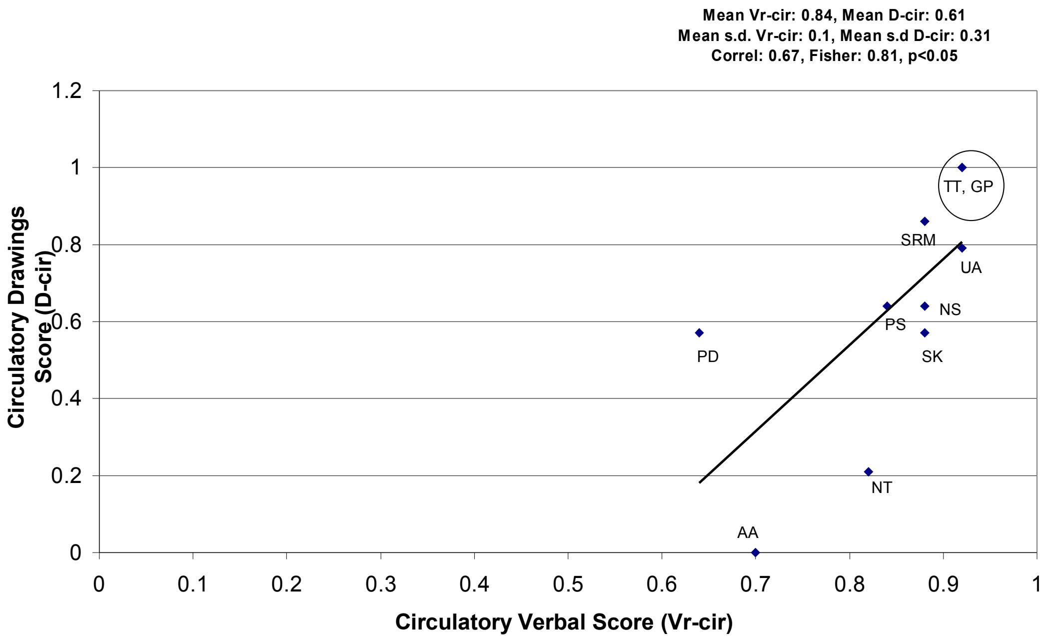


Figure 4.10: Expression of understanding of the circulatory system from verbal and drawn responses



For the respiratory and circulatory systems (scattergrams shown in Figures 4.9 and 4.10), students with high diagram scores were found to have high verbal scores too. This result is consistent with findings of previous researchers. Reid (1990) found that students of overall high academic ability comprehend diagrams better. Heiser and Tversky (2006) reported similar findings (discussed earlier in Chapter 3). High ability students could shift between text and pictures as required, with ease and therefore comprehend content in a textbook better than low-ability students. Our findings show that (excluding the exceptional case of the digestive system), it is not only comprehension of drawings but the expression of understanding through drawings that is correlated with its expression through the verbal medium. It seems likely that the use of both visual and verbal coding systems contributes to the effective understanding of content.

Across the three systems, there was a correlation between expression of structure and function through both verbal and drawn responses. There was also a significant correlation between the expression of structure and function through verbal mode alone and drawn responses alone as shown in Figures 4.11 and 4.12.

Figure 4.11: Expression of structure and function across all systems through verbal responses

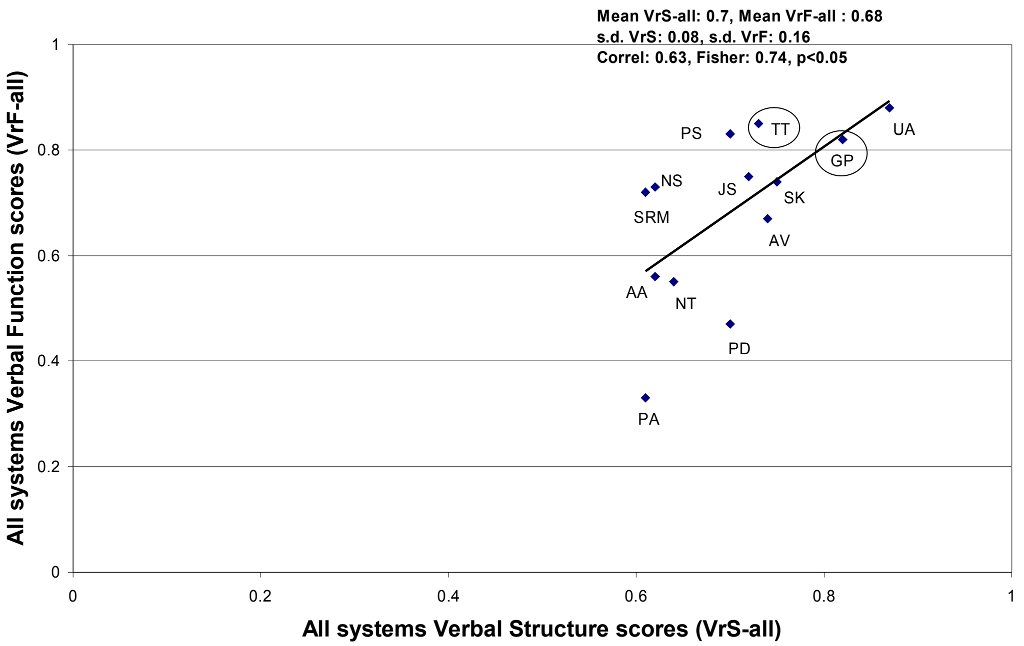
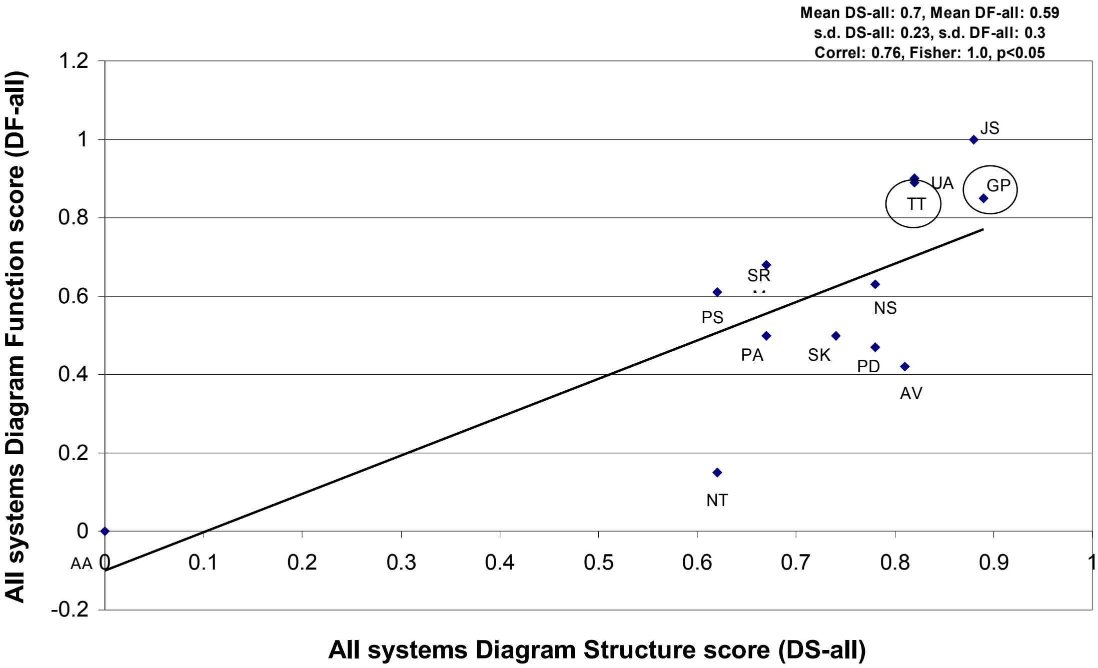


Figure 4.12: Expression of structure and function across all systems through diagrams



Wilcoxon's signed ranks test was used to check for differences between variables. It was found that there was a significant difference between the expression of structure and function through drawings. Students expressed more structure concepts through drawings than function concepts. Differences between all other variables were not significant.

Table 4.6 shows the means and standard deviations of structure and function scores for each of the three systems. The mean scores for all three systems were found to be high. Students had therefore expressed understanding of structure and function through both text and diagrams reasonably well, though correlations were not always significant.

Table 4.6: Mean scores and standard deviations across the three systems

System	Verbal Structure (VrS)	Verbal Function (VrF)	Diagram Structure (DS)	Diagram Function (DF)	Average score
	Mean (s.d.)				
Digestive system (dig)	0.72 (0.08)	0.44 (0.15)	0.7 (0.11)	0.76 (0.2)	0.66 (0.14)
Respiratory system (res)	0.63 (0.16)	0.8 (0.20)	0.68 (0.28)	0.53 (0.36)	0.66 (0.25)
Ciculatory system (cir)	0.77 (0.05)	0.89 (0.16)	0.76 (0.32)	0.48 (0.37)	0.73 (0.23)
All systems	0.71 (0.10)	0.71 (0.17)	0.71 (0.24)	0.59 (0.31)	

4.12 *Comparison with textbook propositions*

Table 4.7 shows the means and standard deviations of the students' scores based on correspondence of their structure and function propositions with those found in the textbook of Class 6.

Table 4.7 : Propositions scores for the three systems

	PS Mean (s.d.)	PF Mean (s.d.)	VrS Mean (s.d.)	VrF Mean (s.d.)	Pearson's correlation coefficient		
					PS-PF Mean (s.d.)	PS-VrS Mean (s.d.)	PF-VrF Mean (s.d.)
Digestive	0.47 (0.17)	0.43 (0.14)	0.72 (0.08)	0.44 (0.15)	-0.23 (0.15)	0.46 (0.18)	0.94** (0.14)
Respiratory	0.55 (0.12)	0.79 (0.29)	0.63 (0.16)	0.8 (0.20)	0.70 (0.25)	0.48 (0.35)	0.94** (0.25)
Circulatory	0.61 (0.05)	0.93 (0.00)	0.77 (0.05)	0.9 (0.16)	1 (0.06)	0.70 (0.14)	0.93** (0.47)
All systems	0.54 (0.13)	0.72 (0.2)	0.71 (0.08)	0.71 (0.17)	0.58 (0.17)	0.60 (0.19)	0.93** (0.22)

** significant at p<0.01 level

For comparison, the verbal structure and function scores as determined by our scheme of analysis are also shown in the Table 4.7. The trend of scores across the three systems are similar in the two schemes. Since there were few propositions related to the structure of the circulatory system (only 7 structure propositions) and some more pertaining to a very basic functional understanding (13 function propositions, Appendix C.1.3), many students knew them. On the other hand one students also had a zero score. Details are in the Appendix D.1.4. Due to the fewer number of textbook propositions, the PF score for the circulatory system is the highest of the three systems. The Pearson's correlation coefficient showed that there were strong correlations between PF and VrF scores for each of the three systems. This showed that students' understanding of function as measured from our questionnaires kept with the content in their textbooks.

4.13 *Qualitative characteristics of students' diagrams*

Diagrams are often seen as a tool used by those who are skilled at drawing, and not as tool that could be handled by everyone. In schools, diagrams are considered to be secondary to words. Diagrams used in textbooks are understood in a passive manner. It is not common or required in an examination to represent one's understanding through diagrams or use it as a tool for thought analogous to language.

Research Question No. 1/5 had to do with the qualitative characteristics of students' diagrams. Although the majority of diagrams were mere copies of textbook diagrams, there were some interesting and innovative diagrams (quite unlike those seen in the textbooks) which students used to convey their understanding. The diagrams which students came up could be classified into two kinds: within the constraints of the human-body outline (for e.g. Figure 4.15) 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 as shown in Figure 4.13.

Figure 4.13: AV's function diagram of the process of digestion using mainly descriptions and structure diagrams

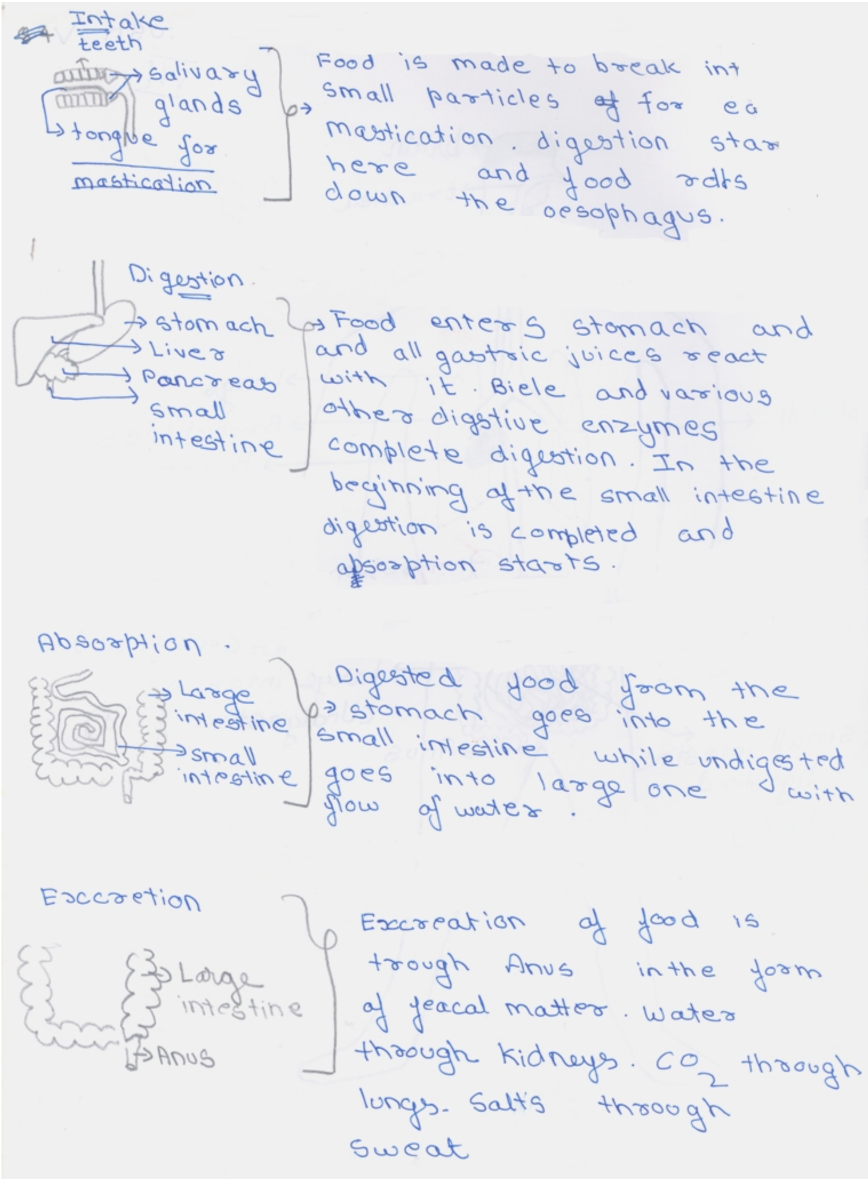
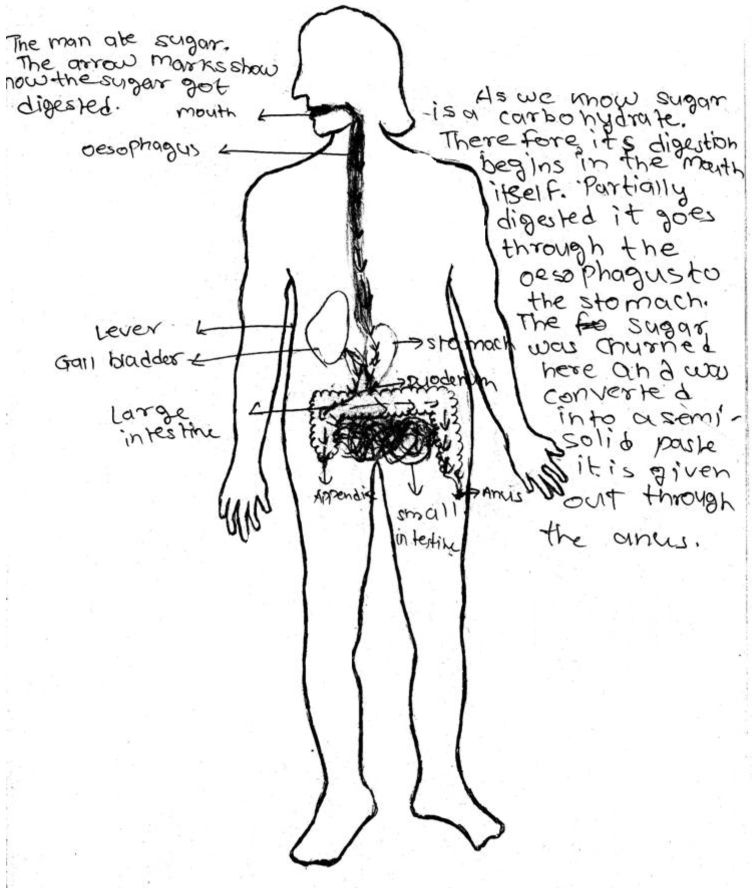


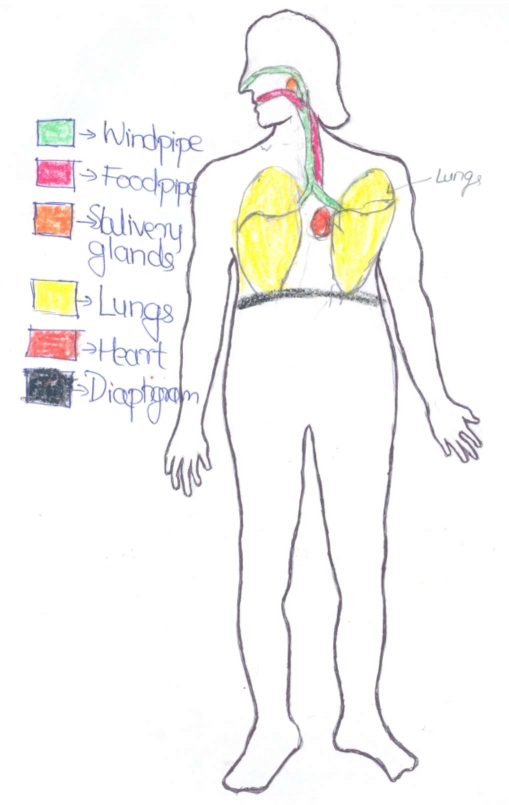
Figure 4.14: AV's representation of the path of a morsel of food with elaborate descriptions. The major alternative conception is two separate pathways for food: one through the large intestine and the other through the small intestine.



Some students drew schematic diagrams consisting of flow-charts of an informal kind, i.e. (without following conventions), and a list of concepts connected by arrows. Examples of this kind can be found in GP's case study in Section 4.18.2.

Students' drawings largely conformed to those in their textbooks, even for questions dealing with processes and functional attributes. In a few cases however, questions about processes spontaneously, elicited flow-charts, a list of organs or a list of concepts connected by arrows. Perhaps, even these drawings are a result of familiarity: from exposure to diagrams in different domains. For e.g. keys denoting colour codes as shown in Figure 4.15 are made use of in maps, equations with arrows are used in Chemistry, etc..

Figure 4.15: PS's diagram of the structure of the respiratory system, shows some of the respiratory organs as well as the region up to which they extend in the body. However, many of the parts are not marked and also not shown clearly. Some parts of the digestive system are unnecessarily represented.



Students were asked to colour their diagrams if they wished to do so. The colour schemes they had come up with could be broadly classified as: use of unique colours to distinguish each organ (an example of this is Fig. 4.17) and use of a background colour and a different colour (one colour) for the parts. This colour was usually brown or reddish brown as shown in UA's diagram in Fig. 4.16. UA has also drawn a function diagram without colour and using arrows showing the mechanics of inspiration and expiration (Figure 4.18). Some students did not make use of colour, or tried to use it as minimally as possible. Some of the students' diagrams elicited major alternative conceptions. These are indicated in Figures 4.13, 4.14 and 4.18 and further discussed in Section 4.17.

Figure 4.16: UA's diagram of the structure of the respiratory system shows the organs of the respiratory system depicted correctly in terms of order and location and also shows the diaphragm as a sheet of muscle rather than a line as often portrayed.

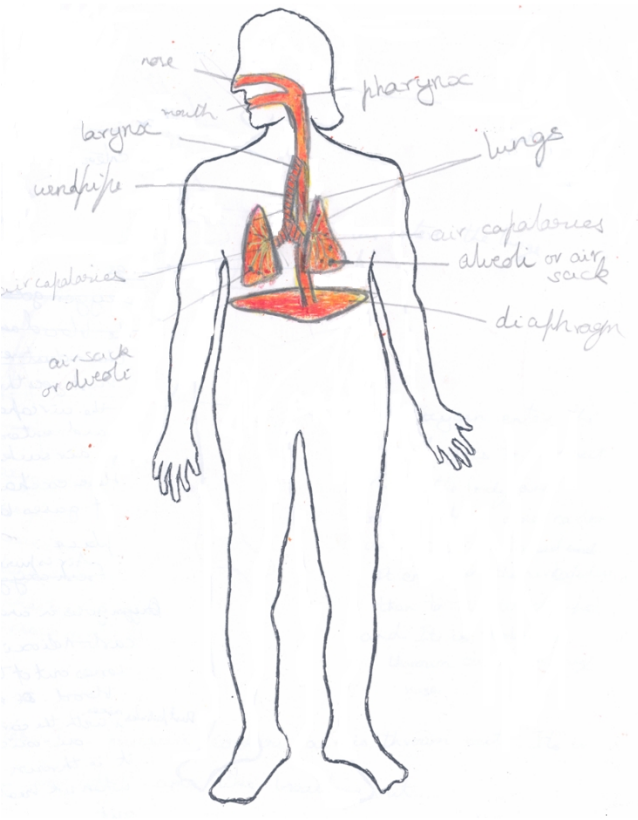


Figure 4.17: JS's figure shows the important organs with a colour scheme which separates out the main differences between the digestive and respiratory systems

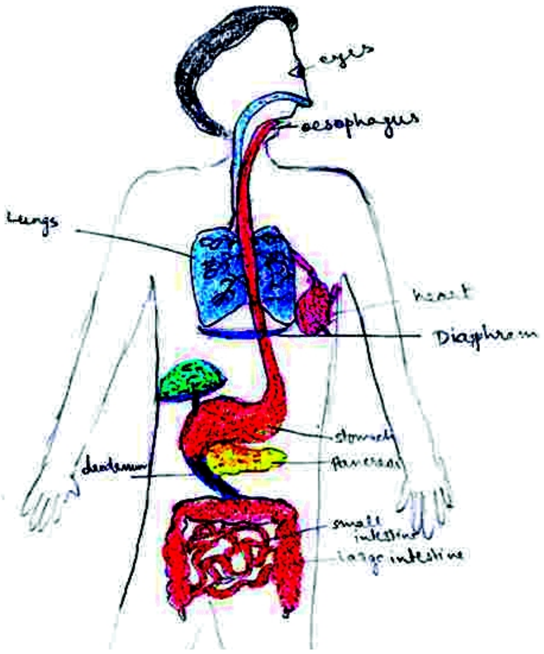
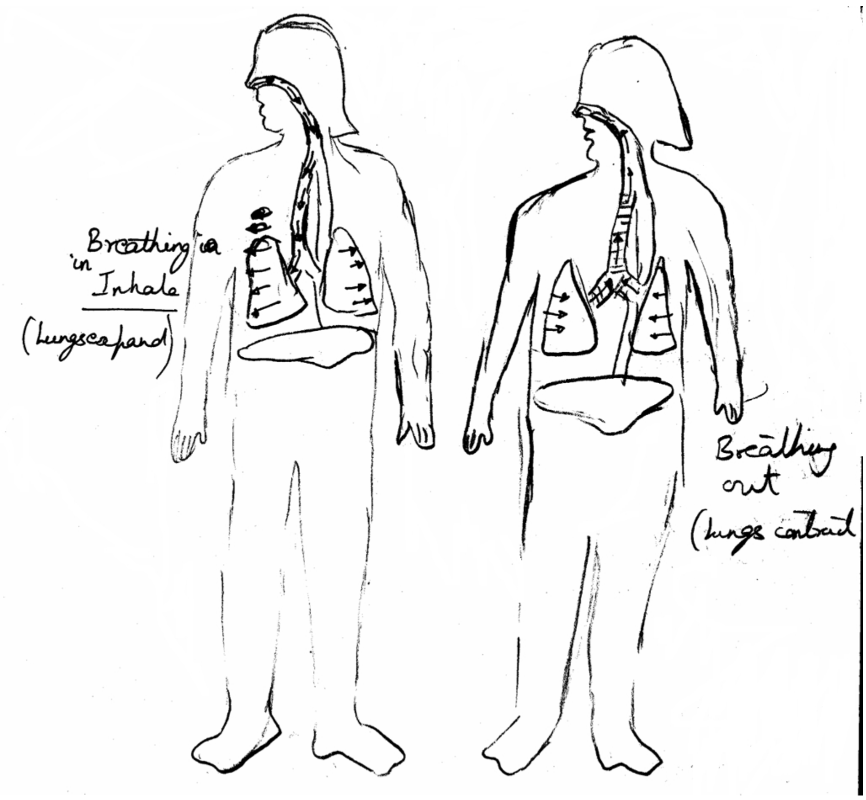


Figure 4.18: UA's representation of the processes of inspiration and expiration show the functional changes in organs using arrows. However the change in shape of the lungs is not shown clearly and the contraction of the diaphragm does not correspond to or is not a result of the change in shape of the lungs.



4.14 *Students' preferences: diagrams versus written expression for communication*

Research question I/6 dealt with students' preferred mode of expression: verbal or diagrammatic expression. A general observation from the tests and the interviews was that the students were more comfortable with expressing their understanding in words rather than through diagrammatic representations. Though this observation was not supported by the students' scores, or even their stated preferences, it came through in the clinical interviews in the students' reluctance to express themselves through drawings. With the exception of some of the diagrams shown in the previous section, students' diagrams were often stereotypical and close to diagrams found in their text-books. Even the new diagrams had liberal written descriptions. Though outlines of the human body were given to the students for ease of representing the position and relative size of the organs appropriately, they were encouraged to give alternative ways of representing their understanding through schematic diagrams.

Students' mean verbal and diagram scores were equal for Verbal (VrS and VrF) and Diagram Structure (DS) and was found to be 0.71 (Table 4.6). Diagram function scores alone were lower at 0.59. Also for six of the thirteen students, the mean diagram score across the three systems was higher than the verbal score. For one student, both mean scores were the same. Thus from what has come through from the study we see that there is an equal division between verbal and diagram scores (Table 4.3). Clear 'visualisers' and 'verbalisers' could not be distinguished in terms of scores. However through representation, we could distinguish two students who tended to be predominantly verbal or visual as reported in Section 4.18.

Students were asked as to their preferred mode of communication: whether diagrams or written expression. They were also asked if diagrams could replace written content in textbooks. Individually, the students did not indicate any strong preference or choice for text or diagrams. The group as a whole was equally divided among the preferences: four of the twelve students preferred writing over diagrams, four preferred diagrams over writing, and the remaining four thought that both diagrams and written expression was indispensable.

Reasons for preferring diagrams were the following: Diagrams give an over-all view; One has to read and understand written descriptions, but in diagrams that is not necessary; It is interesting to draw diagrams unlike writing; In Biology it is essential to use pictorial notations to understand concepts better for convenience to understand the process.

The reasons given for preferring text were: a) Diagrams are difficult to draw, especially in Biology. This is because it requires some skill to draw them. This skill is not possessed by everybody. b) Diagrams alone are inadequate to communicate one's understanding. c) Diagrams are useful only to score marks in exams. d) The weightage given to diagrams is low in the school and also in the board examinations. e) There is more exactness required when communicating through diagrams. “One single mistake and the whole thing goes wrong”.

4.15 *Assessing visualisation through analogy*

4.15.1 *Structural and functional analogies*

The role of analogy in visualisation in science was discussed in Section 3.1. Research question I/7 asked whether analogical thinking could be used as a tool to study the visual imagery of students. The Phase I questionnaires contained two types of questions based on analogy. One related to the entire system (e.g. Can you think of a process which is similar to or reminds you of the process of digestion, or of anything related to digestion) and the other related to individual organs of that system (e.g. the action of the lungs reminds me of____).

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. The kinds of images generated by students in response to these questions were analysed on two attributes: 1) images which are evoked because they are analogous with the structural attributes of the organ or system and 2) images dealing with the functional attributes of the organ/system.

The following categories therefore occur in the analysis that follows for each system:

1) Structural images: These images pertain to the similarity in the external appearance of a particular organ and the visual image generated.

2) Functional images: These images pertain to the similarity in the functional attributes of a particular organ or process and the analogous image generated. The images which come to mind on thinking about processes such as digestion, respiration, etc. will all fall in this category could also occur in the 'structural images' category because of the similarity in the structure of the organs and of the generated image.

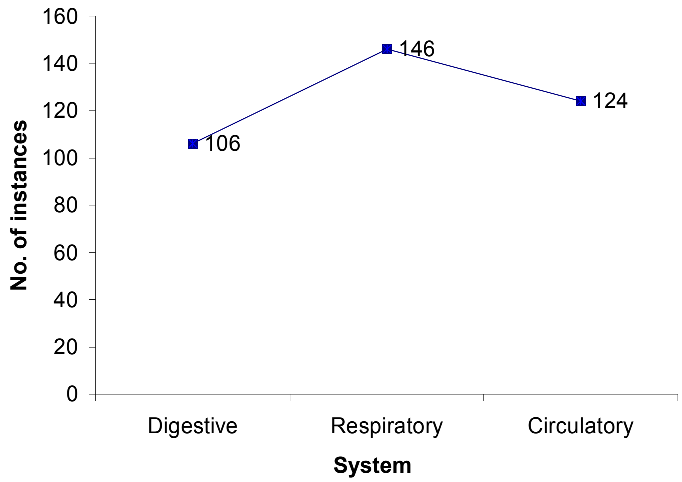
3) Described as they are: In this category, the subjects described the feature or characteristics related to that particular organ or process without generating an analogous visual image. Category 3 responses may mention features of the organ or process itself, which are not obviously suggestive of analogous visual images. It could be that the images which came to the subjects' mind on thinking about a particular organ or process were related to the organ or process itself. However it could also mean that the student was

unable to come up with a visual analogy and described it in terms of itself. This aspect was probed during the clinical interviews. Many of those who did not come up with analogous examples were often unable to, or were resistant to the idea of thinking of everyday examples. Some students who were unable to generate analogies nonetheless had a correct picture of the functioning of the human body. However, they were resistant to generating analogous examples.

4) Stated inability to generate images: Students clearly mentioned that they were unable to generate visual descriptions.

Fig. 4.13 shows the number of instances of generated analogies in the three systems. The student-wise number of analogies are shown in Appendix D.1.1. to D.1.3. The number of generated analogies was lowest for the digestive and highest for the respiratory system.

Figure 4.19: Number of instances of student generated analogies across the three systems



Tables 4.8 to 4.10 summarise the types of images that students generated with respect to the three systems in response to the relevant analogy question in written form as well as

the subsequent clinical interview. Both structural and functional images were elicited from students. However the responses in this form were not always easy to interpret. In the clinical interviews therefore the students were probed further on the analogies generated by them.

4.15.2 *Analogies for the digestive system*

Table 4.8 summarises the visual images students generated spontaneously in response to the two questions on analogy for the digestive system.

Table 4.8: Visual images pertaining to the organs and processes in the digestive system

S No	Organ/ process	Structural images	Functional images	Described without analogy
1	Food pipe	slightly tilted stick, food passage, water pipe	water pipe	feeding, food passage
2	Intestine	crawling movement of cobra, big pipe snake, long rope, crumpled snake, noodles		coiled tube, breaking down things
3	Stomach	mango, cashewnut, bag-like structure	grinder grinding food, bag which keeps getting filled	digestion
4	Liver	upside down triangle, unpolished chocolate piece, large bag, mushroom bowl	defecation	box producing things to complete a task,
5	Digestion		nervous system, cooking, respiration, cutting vegetables, process of purifying blood, respiration	

4.15.2.1 *Stomach*

The structure and function of the stomach makes it more amenable to be compared to a bag. Its unique shape also brought forth several analogies to visually similar objects in the environment.

(GP: Class 6)

I: What is the difference? How do we distinguish between a bag and a stomach?

S: A bag cannot be expanded too much. The stomach expands when it takes in food. The stomach is as big as my foot. It expands a little with large amounts of food.

4.15.2.2 *Liver*

Students' analogies regarding the liver were mostly pertaining to its structure. When probed further, they indicated an inadequate understanding of its structure and function.

(PA: Class 7)

I: The liver reminds you of a bowl?

S: Yes, the shape of an upside down bowl.

I: Is the bowl also concerned with its function?

S: In the liver, juices are kept. Similarly, we can keep it like that.

When asked for a difference between a bowl and a liver, the student replied: In bowls we can change the position. We can take food from it. It is not possible in the liver.

There were some vague responses which indicated a lack of knowledge of the structure and function of the liver such as “a box producing things to complete a task”.

4.15.2.3 *Intestines*

Analogies related to the intestines all had to do with structure. None of the students gave functional analogies for the small intestines perhaps because of lack of familiarity with its function or because the coiled structure was such a salient feature of the small intestine.

(GP: Class 6)

S: The intestine reminds me of a snake since the coils are there. A snake has coils passing through one another

I: Is there a difference between the snake and the intestines?

S: The coils of a snake are not tough to uncoil. The snake coils can be removed easily.

4.15.2.4 *The process of digestion*

The word "digestion" refers to a process, and therefore the images generated were also mostly functional. An everyday example generated was an analogy to the process of digestion.

(PS: Class 7)

S: When my mother cooks, I think of the whole process. I think it reminds me of digestion. What happens in cooking - the same thing happens in digestion. For example, in the mixer we grind food- which are grinded in our stomach. Some acids are mixed- lemon juice is mixed with the food (acid).

Another student considered the process to be analogous to oxidation.

(NT: Class 8)

S: The substance is burnt and the energy is released. It is similar to the process of digestion. Oxygen causing the burning is the similar thing.

I: Is there any difference that you see between the two processes?

S: Digestion is a particular term unlike oxidation. Oxidation can take place in several places.

4.15.3 *Analogies for the respiratory system*

Table 4.9 shows the analogous images generated for the respiratory system.

Table 4.9: Visual images pertaining to the organs and processes of the respiratory system

S No	Organ/ process	Structural images	Functional images	Described without analogy
1	Lungs	bag filled with air, triangles, balloon, two big boxes, cashewnuts, a broken heart, sponge-like structure	Aquaguard, purifier	sacs filled with air, they are protected by ribs.
2	Diaphragm	flat plate, strong rod with high tensile strength, it works like a balloon,a metal rod with little bend, a bent pipe, plate wings of an aeroplane	Heart, liver	a muscle separating the stomach from the abdomen, something which expands and contracts
3	Action of lungs	a sponge	action of kidneys, filling a balloon with air, air entering a balloon, a balloon inflated and deflated, the action of a kidney, a balloon contracting and expanding, action of the leaves	contracting and expanding
4	Respiration	a pipe which gets divided into two and is connected to two balloons	pressure cooker (releasing energy), excretory system, energy releasing process, fermentation, cooking, Photosynthesis, urinary system, a cooker, action of removing husk from the grains, the system of digestion, water cycle	inhaling and exhaling, a process due to which we are alive, a different system of the world

4.15.3.1 *Diaphragm*

Students usually could verbally state the role of the diaphragm in respiration, but they visualised it incorrectly perhaps because of its representation in textbooks. These diagrams show the diaphragm as a line below the lungs leading to an incorrect conception of the diaphragm being a rod-like or stick-like structure. The changes that take place in the diaphragm during inhalation and exhalation were described by one student as: "something which expands and contracts" (See Section 4.17.2).

(PS, Class 7)

I: You have said that diaphragm reminds you of a metal rod with a little bend. Are you saying that it looks like that?

S: Yes.

I: But if you're thinking of a difference?

S: Diaphragm is a muscle. The diaphragm is a part of our body. It helps our body for breathing. But metal cannot help.

4.15.3.2 *Lungs*

The structure of the lungs was visualised more or less correctly by the students. The popular analogy of likening the lungs to a pair of sponges is the most common analogy used by them. When asked if the lungs are hollow structures like balloons, AV responded:

(AV, Class 7)

S: No, it's not hollow. It's a solid full of muscles. It has muscles. When we take in air, it is a solid mass. It contains blood vessels. It increases in size. There are air-sacs.

I: What is the difference between the balloon and the lungs? Are the lungs also hollow?

S: No, it is filled with capillaries.

I: Except for capillaries, are they hollow? Can you compress and relax lungs?

S: The lungs are filled with muscles. The circulatory and the nervous systems are there.

The diaphragm and the lungs are considered to be opposed to each other regarding the changes that take place in them during inhalation and exhalation. During inhalation the lungs expand, and during exhalation they contract. The opposite is said to happen for the diaphragm. They do not think of the diaphragm as moving up and down.

4.15.3.3 *The action of the Lungs*

Since this indicated a process, most of the analogies generated were functional. PS drew an analogy between photosynthesis and respiration.

(PS, Class 7)

I: What about the action of the lungs? Why does it remind you of the action of the leaves?

S: The lungs are the main part of the respiratory system. They separate the Oxygen, and it is the same with the leaves. They do photosynthesis, and they take in CO_2.

I: So, what is the difference between photosynthesis and respiration?

S: In respiration, the humans take in O and give out CO_2. And the plants, during photosynthesis take in CO_2 and give out O.

When probed, students come up with the reasons for their analogies.

(NT, Class 8)

I: Why does the action of the balloons remind you of a sponge?

S: We first press it and then it comes back to its normal place. The shape can be changed.

The respiratory system generated a large number of visual analogies (Fig. 4.13). This is perhaps because students have a number of practical experiences related to this system, and therefore several spontaneous conceptions also, which led to a number of analogies. Also, perhaps the process of inhalation and exhalation being clearly visible lends itself to analogies.

4.15.4 *Analogies for the circulatory system*

Table 4.10 documents the visual images generated by students about the circulatory system.

Table 4.10: Visual images pertaining to the organs and processes of the circulatory system

S No	Organ/ process	Structural images	Functional images	Described without analogy
1	Heart	gum ball, red-coloured soft ball, beating drum	Pumping, water pump, pump	triangular bag with thick muscular tissue, ball, many veins and arteries
2	Arteries	current carrying wire, pipes carrying pure blood, pipes which supply water, tube carrying pure water, pipes	drinking-water pipes, flowing river, pipe carrying water to the park	something pure, tube carrying pure blood
3	Veins	Pipes, tubes	pipes carrying dirty water, sewage water pipeline, rivers taking water to the sea, pipes carrying waste water to the drain, tube carrying impure water, tube carrying impure blood	something not pure, pipes carrying impure blood
4	Capillaries	Capsules, nerves, drinking straws, funnels, many unsolved wires, model of arteries and veins, short / thin fibres		blood vessels carrying blood, network of connections of arteries and veins, connecting pipes
5	Blood	Water, something red, red-coloured water	multi-purpose fluid, carrier	liquid- very important and carried though the body by arteries and veins, solution of red-coloured water, liquid, thick fluid

S No	Organ/ process	Structural images	Functional images	Described without analogy
6	Movement/function of the heart	A flickering bulb	Working pump, cycle pump, hand pump, inflating and deflating a balloon	Lung, expand and contract
7	Pulse beat	Hammering, drum being beaten, some eruption, band heard when someone weds, drumbeat, drum, bouncing of ball		force pushing upward, heart-beat
8	Circulatory system	thousand pipes and a tank	drainage pipe, system forming a network in houses, water supply system, water cycle, nuclear reaction (in the interview), water pumped through arteries, water-cycle, food or Oxygen which is circulated around the body	heart-beat

4.15.4.1 *Heart*

A common analogy thought of about the heart is its comparison to a pump. The pump is a common analogy drawn in textbooks, and by teachers. NT had thought of both structural and functional analogies. A structural analogy drawn from a familiar object is the comparison drawn between a heart and a "gum ball" described by a subject as:

(NT, Class 8)

S: There is a ball available in the market. It will stick to the walls. It is a ball, and it has something coming out of it which sticks. It sticks to the wall. So I think that those things are arteries and veins.

(NT, Class 8)

S: The movement and functioning of the heart reminds me of a pump.

I: Why pump?

S: A pump reminds me of water, then there is pressure.

I: What really happens in a water pump? What do you do when you pump?

S: When we take in air, it goes inside, and then it is forceful, that it takes the water along with it.

4.15.4.2 *Pulse beat*

Most students were not aware of the reason for the occurrence of the pulse beat. They however knew that it could be felt at various points in the body. When probed further with cues such as: the similarity between the pulse rate and the heart-beat rate, they were able to guess that there was a connection between the two processes. There was variety in the analogies generated for the pulse beat.

4.15.4.3 *Entire circulatory system*

The most common visual image evoked when thinking about the circulatory system was the "water-cycle".

(TT, Class 6)

S: The path of the blood is the same as the water-cycle. Water evaporates from the sea, it goes to the atmosphere – forms a cloud, and then it rains – when it condenses, the left out water goes to the seas.

I: How is it that similar? What is the similarity with the heart?

S: The heart and the arteries have the same colour. The blood basically flows from the heart to the arteries. Pure blood is there in the heart as well as in the arteries.

One subject was reminded of a nuclear reaction when thinking about the heart. This analogy came out in the clinical interviews, following the written tests, and perhaps was a result of exposure to the term in an environment with nuclear scientists.

(PM, Class 8)

S: ... the uranium rod is the heart. Impure blood is the cool mercury. It goes to the various parts of the body- that is blood.

4.15.4.4 *Arteries and veins*

Analogies pertaining to arteries and veins, were mostly related to the difference between 'pure' and 'impure' blood. One student compared the arteries and veins to the plant cells- phloem and xylem. Arteries bring pure blood to the different parts of the body from the heart. Similarly, phloem brings the nutrients from the leaves after photosynthesis to the different parts of plants. Veins bring impure blood to the heart. The xylem brings nutrients and minerals from the roots to the leaves for photosynthesis.

4.16 *Discussion on structure and function analogies*

Students spontaneously thought of structural analogies for organs, and functional analogies for processes. There were a few instances which were exceptions to this rule, as can be seen from Tables 4.8 to 4.10. Examples of structural analogies are: stomach being compared to a mango, cashewnut, lungs being compared to a sponge-like structure, arteries and veins being compared to pipes, etc.. As suggested by Gentner (1989, referred in Section 3.1), the mere appearance analogies may be of limited utility in most cases but they are significant in the learning process since they are characteristic of novice learners.

The structural images 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.

Some examples of functional analogies are: the heart being referred to as a water pump, the action of the lungs to a balloon contracting and expanding, the stomach analogous to a grinder, etc.. These examples illustrate the fact that there is some overlap between structural and functional analogies. In general, structural analogies were perhaps the result of comparing the visual attributes of the source and target such as shape, colour and texture. These properties are referred to in the literature on visual imagery (Section 2.8) as 'physical properties' or 'object properties' (Kosslyn, 1994). Regarding functional analogies, students' responses suggest that these analogies may perhaps not be visual, as the attributes they rely on appear to be non-visual (Tables 4.8 to 4.10) and dealing with 'spatial properties' (explained in Section 2.8). Some responses were redundant, i.e. the object is described in terms of itself. The pattern matching that occurs to generate a functional analogy maybe propositional. For example: the analogy between the process of respiration and the water cycle and the pattern matching which generated such a match would perhaps be entirely propositional.

4.17 *Some common conceptual difficulties*

Through Research question No. I/8 we wished to find out the common conceptual difficulties prevalent among students pertaining to the three systems. Some common alternative conceptions that students held were brought out through diagrams, written expression and clinical interviews.

4.17.1 *Digestive system*

The stomach is considered to be an important organ perhaps because of its familiarity in terms of everyday knowledge. A common misconception however was that oxidation of food and release of energy takes place in the stomach.

The role of the liver and pancreas is misunderstood. Many students think food goes into the pancreas and liver for further digestion after digestion in the stomach. The place of accessory organs in relation to the linear pathway is not clearly understood. (Figure 4.24).

The connection between the small and large intestine is unclear. There is no clarity about which comes first: the small or the large intestine and whether they are connected both functionally and structurally. (Figures: 4.13, 4.14 and 4.24). This confusion maybe the result of a textbook diagram (as discussed in Section 6.4.1).

4.17.2 *Respiratory system*

The structure of the diaphragm was considered to be rod-like or pipe-like (referred to in Section 4.15.3.1, Figure 4.15). This too may have been misunderstanding caused by an unclear textbook diagram.

Changes in the lungs and diaphragm during inspiration and expiration tend to be the source of common alternative conceptions (Figure 4.18). During inhalation, the lungs expand and the diaphragm moves down to accommodate the increased size. During exhalation, the diaphragm moves up and the lungs relax and get back to their normal size. This can be easily understood and remembered if the structure of the diaphragm is correctly remembered to be a sheet of muscle rather than a pipe or rod.

(NT)

I: Does the diaphragm go through some change during inhalation?

S: Yes

I: What change does it go through? When we inhale, what are the changes that take place?

S: It may expand.

4.17.3 *Circulatory system*

Students had an incorrect understanding of the role of the capillaries ('Capillaries are smaller forms of arteries and veins'; 'Capillaries are the same as arteries and veins').

Another common alternative conception was that in the heart there is a process of "filtration" during which impure blood is purified. This process takes place in the lungs, but the connection between the respiratory and circulatory systems is improperly understood.

Students also considered "nerves" to be analogous to blood vessels.

4.18 *Case studies*

Students' preference and facility with diagrams or text, and their conceptions about the body systems, were interconnected in complex ways. We can see how these connections played out, by taking up two case studies, one of a girl (TT) and the other of a boy (GP). Both students were of high ability as judged by their rank in the class (Mathai and Ramadas, 2004). The scores and other details of the two students can be found in the first two rows of Table 4.3 and Appendix A.1. Their scores can also be located on the scattergrams of Sections 4.10 and 4.11. Both students can be located among the high scorers as seen in the scattergrams with TT performing better on the digestive system and GP on the respiratory system. For the circulatory system, their structure, function, verbal and diagram scores were similar. Their diagram scores were higher than verbal scores across the three systems. Thus the quantitative analysis of scores did not show any difference between the students in style of expression. However, their responses during clinical interviews along with qualitative analysis of their diagrams, showed a distinct difference in representational style.

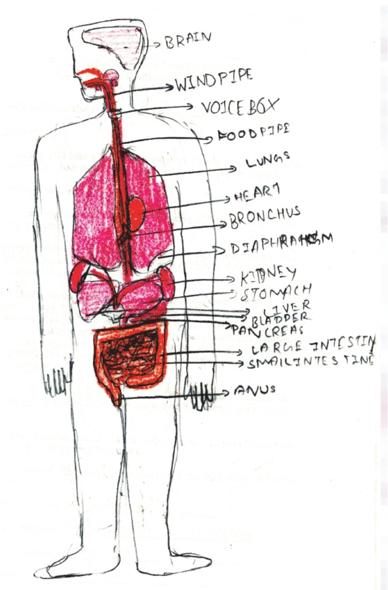
Both GP and TT appeared confident and mostly competent in their responses. As for style of their visual depictions, GP tended to respond using schematic representations, whereas TT preferred more depictive representations.

GP was very articulate and was able to reason verbally though, as we see later, he tended to get misled by his own depictions and thus formed some alternative conceptions. TT had learnt the textbook content adequately well, and did not indicate any major alternative conceptions. Both were however able to connect and refer to their written, spoken and drawn content, painting a consistent picture of their ideas.

4.18.1 *TT*

TT's diagrams were neat and attractive. She used almost realistic colours like pink and shades of red-brown, for aesthetic effect and clarity in distinguishing between the organs (Figure 4.20).

Figure 4.20: TT's diagram of the organs of the human body with shades of red distinguishing the important organs



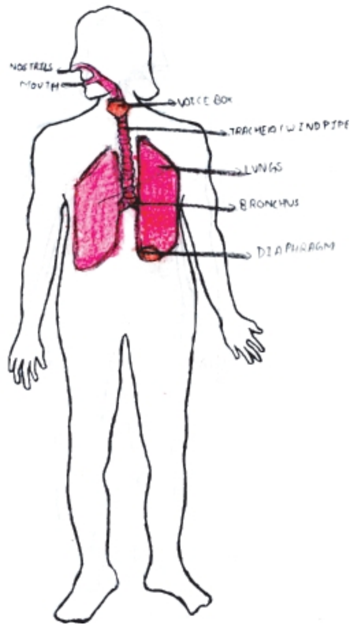
In her written responses, TT had no stated preference for either diagrams or words. In her interview however she suggested that diagrams are easier to draw unlike writing.

S: Why do you prefer diagrams?

T: In writing we have to think how to write. Diagrams – no need to think much. We have to think much in writing. We lose marks if we make spelling mistakes.

TT had a fairly clear idea about the process of digestion, except that she thought the liver had no role in digestion. TT did not have any major alternative conceptions, except one about the shape of the diaphragm, as seen in her diagrams of the respiratory system (Fig. 4.21, 4.22).

Figure 4.21: TT's diagram of the structure of the respiratory system with the diaphragm shown as part of the lungs



TT gave both structural and functional analogies which indicated visual imagery.

4.18.1.1 *Instances of visual imagery*

- *I: Can you think of another process which is similar to circulation?*

  T: Water cycle. The path of the blood is the same as the water cycle. Water- evaporates from the sea, it goes to the atmosphere- forms a cloud, and then it rains- when it condenses, the left out water goes to the seas.

  I: How is that similar?

  T: Then it goes on repeating- the cycle goes on and on.

  I: What is the similarity with the heart?

  T: The heart and the arteries have the same colour.. The blood basically flows from the heart to the arteries.. Pure blood is there in the heart as well as in the arteries..

- *I: Images which come to your mind:*

T: Artery- pipes.

I: Are veins also like pipes?

T: Yes.

I: Any other way of describing?

T: Stems in trees- carry water. Basically, both the functions are there in the trees- that of arteries and the veins. Capillaries- short, thin fibres- blood, water- both liquids- flow through the capillaries. We use water flowing through pipes- even blood is carried through the arteries and the veins. Movement and function- through a hand-pump.

I: Why bouncing ball?

T: We continue to bounce ball in basketball- like the pulse rate.

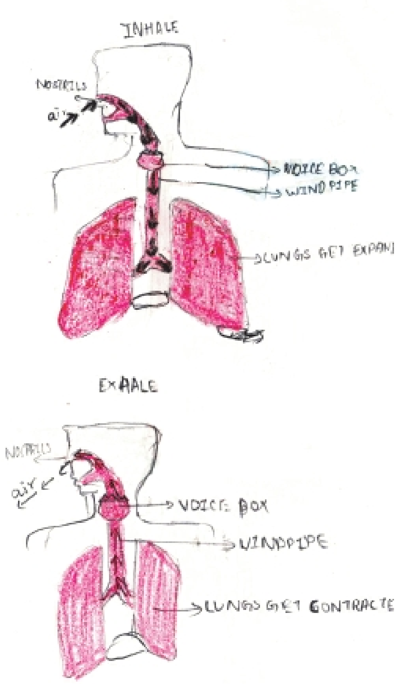
There was an instance of over-estimation of size in the case of the respiratory system:

- *I: How big is your lung? How big is it?*

  T: From the middle finger to the elbow...

From her drawings, it could be inferred that she was using it as a tool for thought. She did not have any major alternative conceptions (except some details pertaining to organs such as the structure of the diaphragm), perhaps as a result of greater attention paid to reading and understanding drawings in textbooks and other sources.

Figure 4.22: TT's representation of the movement of air through the respiratory system showing contraction and relaxation of the lungs. However, an erroneous understanding of the structure of the diaphragm is apparent through the diagrams.



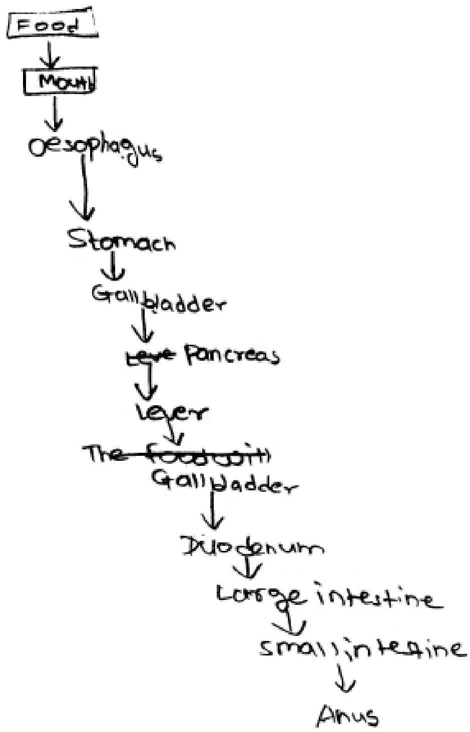
TT's diagram of the circulatory system is shown in Fig. 4.23. This diagram does not make any mention of the process itself, but is colourful, distinguishing between the arteries and veins.

Figure 4.23: TT's diagram of the structure of the circulatory system

4.18.2 *GP*

GP's diagrams were predominantly schematic. Examples of this kind are in Figures: 4.24, 4.26 and 4.27.

Figure 4.24: GP's representation of the order of action of digestive organs showing a linear pathway and alternative conceptions: the food moves into the liver and pancreas during the process of digestion, and the direction of passage is from the large intestine to the small intestine.



In Figure 4.24 we see GP's diagram of the digestive system consisting of names of organs placed in a linear sequence. GP connected the names with arrows to indicate his understanding of the passage of food. GP's diagrams of the respiratory systems were also in the nature of flow diagrams (Figure 4.26). He drew two diagrams to show two different aspects of function: the separation of dust particles from air in the nose and the different routes taken by oxygenated and deoxygenated air. GP's diagram of the circulatory system (Figure 4.27) was an attempt to reproduce a textbook diagram. The original textbook diagram is shown in Chapter 6, Figure 6.3.

4.18.2.1 *GP's alternative conceptions*

In the case of the digestive system, GP's diagrams showed up a clear alternative conception. He portrayed the passage of food in a linear form, in a sequence that incorporated between the stomach and duodenum, the gall bladder, pancreas, liver and then gall bladder again. (Fig. 4.24). In the interview he confirmed this misconception.

- S: What is the function of the liver?

  G: The liver functions as part of the digestive system. Food goes through the stomach, it enters the liver and then goes to the duodenum.

  S: What about the pancreas?

  G: It gives out juice- like acid- pancreatic juice. This helps in digestion. Food goes into the pancreas. It burns in pancreas using pancreatic juice. It goes to the duodenum, the small intestine and the large intestine. Digestion occurs in the stomach, liver and the pancreas. Then, absorption takes place. The food goes to the gall bladder too..

GP's other mistake in the sequence is to show the large intestine before the small intestine. He reiterated this in the interview. He also remarked that food is converted into starch in the stomach (*Starch is a liquefied form of food*). The absorbed food is taken from the large intestine to the small intestine.

> *G: Large intestine takes in the absorbed food and sends it to the small intestine. Then the unabsorbed food is sent to the anus... ..The absorbed food is saved in the small intestine".*

Both of these errors indicated that GP had perhaps not made a connection between the depictive diagram of the digestive system and the text connected with it. Thus he had to invent a schematic diagram in order to integrate his inadequate and separate understanding from the text and textbook diagram.

In the case of the respiratory system, GP had a clear idea about trapping of dust particles by "fluids present in the nose" (Fig 4.26). He had only a rough idea about oxygenation of blood.

S: Convert the paragraph into a diagram... Air goes into the trachea....

G: It then goes to the lungs. It is purified and mixed with the blood. Air contains many gases. Only Oxygen is taken in. The rest is given out through the nose. Oxygen is mixed with the blood in the lungs.

Through his flow diagrams, GP appeared to be trying to clarify his ideas (Fig. 4.24).

He had shown the two lungs using two different colours (Fig. 4.25). When asked for an explanation for this, he said:

G: One lung is cut in half - the alveoli has a flesh colour. Nowadays, pollution makes lungs black in colour (so the other lung has been given a black colour).

Figure 4.25: GP's diagram of the structure of the respiratory system showing the main organs with a unique colour for each part

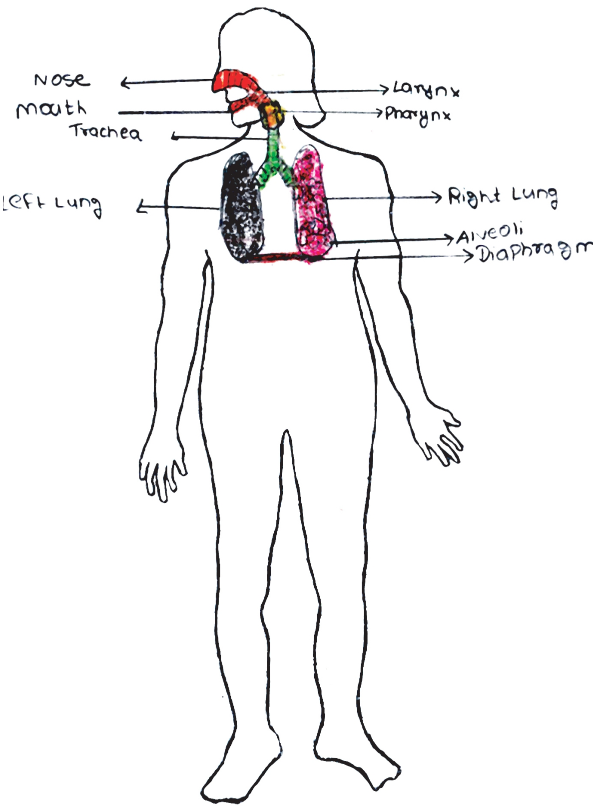
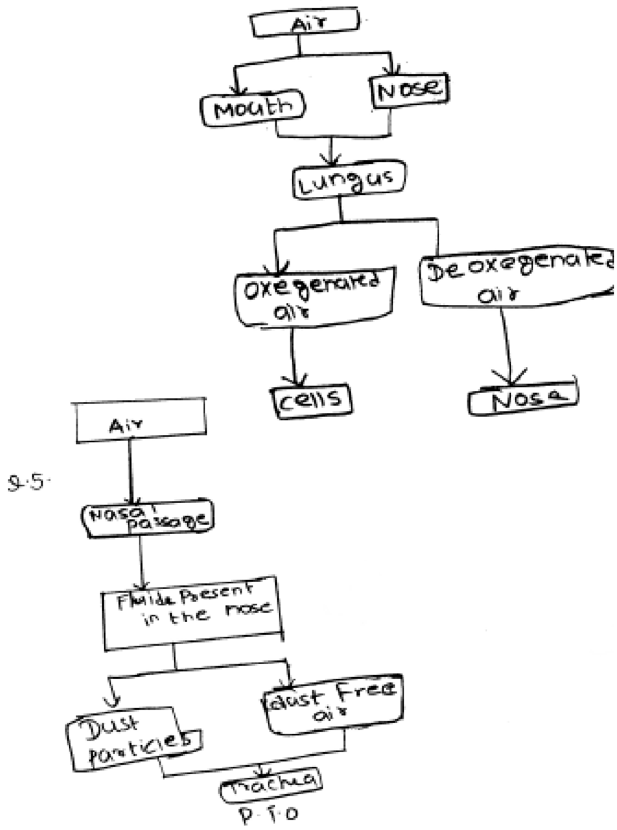
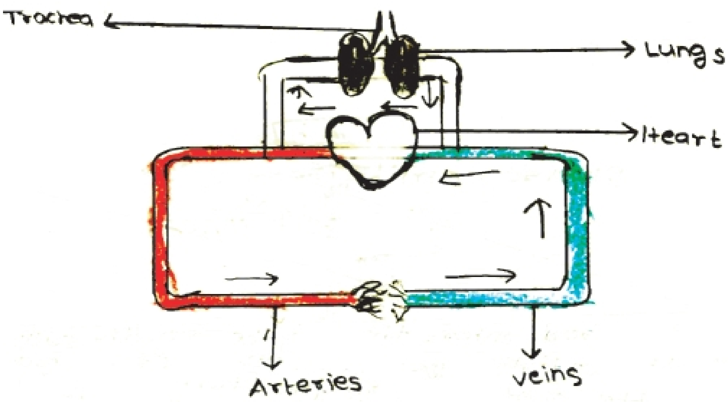


Figure 4.26: GP's schematic diagram of the function of the respiratory system and the connection between the digestive and respiratory systems



Regarding the circulatory system however, GP was not able to express much, not surprisingly since the Class 6 textbook only had one schematic diagram without explanation and some text which mentioned that arteries carry blood from the heart to all parts of the body, and veins carry blood from the organs back to the heart. He tried to make a diagram similar to the one in the textbook as shown in Figure 4.27. However an incorrect understanding led to a representation of pure and impure blood in the same direction. He seemed to have visualised the whole system as series of pipes with the same direction of blood flow.

Figure 4.27: GP's schematic diagram of the process of circulation, is analogous to the textbook diagram, but he has mixed the path of the pure and impure blood and also the inferences to be drawn from them



GP appeared propositional. This is not only evident from his use of schematic diagrams but also his stated preference for writing over drawing. His analogies however are visual: some being structurally correlated. For him, drawings *per se* were not interesting. However he could visualise a process (as evident from his verbal responses) and communicate that understanding through schematic drawings. His neglect of representational drawings (depicting structures as they are) interfered with his visualisation leading to alternative conceptions.

4.18.2.2 *Instances of visual imagery*

The following were instances of visual images generated by him through words:

- *G: Food enters the stomach and gastric juices act on it. It rolls down the stomach.*

  G: The intestine reminds me of a snake since the coils are there. A snake has coils passing through one another.

  I: Is there a difference?

G: The coils of a snake are not tough to uncoil.

- *I: Do you know anyone who has had asthma?*

  G: They cannot walk for a long time if they have that disease; difficulty to take in air,

  I: Why that difficulty?

  G: The dust blocks the pores. It prevents exchange of Oxygen through the lungs. Dust gathers here, and then they help to form this disease. Those people have asthma attacks. The person gets a bluish type colour and becomes unconscious, but is still breathing. Blocking of pores takes place- deoxygenated blood goes somewhere else. Therefore it mixes with the arteries and the whole body turns bluish in colour.

There was an instance of over-estimation of size between a bag and a stomach:

- *I: How do we distinguish between a bag and the stomach?*

  G: A bag cannot be expanded too much. The stomach expands when it takes in food. The stomach is as big as my foot. It expands a little with large amounts of food. The size of the stomach is approximately: 14-15 cm. When it expands it goes upto 17 cm.

As mentioned in Section 4.14, it was not possible to distinguish 'visualisers' and 'verbalisers' clearly. Even in the case of GP and TT, mean scores for text and diagrams indicated greater facility with diagrammatic expression. However, as explained in this section, their stated preferences and their depictions do tend to fall in two different categories indicating a distinct preference in style of representation.

4.19 *Methodological outcomes of Phase I*

4.19.1 *How to elicit mental visualisation*

In Phase I, we used analogy as a tool to elicit visualisation. However, there were several problems with students' responses to the analogy questions as outlined below.

The analogy was often based on vague surface similarity without referring to any analogous object or process. For instance a liver reminds me of an unpolished chocolate piece, lungs remind me of a broken heart, the diaphragm reminds me of the heart, respiration reminds me of a different system of the world, heart reminds me of a gum ball, the pulse beat being some eruption and also like a band heard when someone weds, etc..

Also, the analogy was often forced: for e.g. the liver is like a box producing things to complete a task seems like an attempt by the student to make do with what comes to mind first rather than think of appropriate analogical examples. Thirdly, the analogy was rarely apt.

Some analogies were contradictory to or inconsistent with the correct understanding, hence it may have led students astray. Examples are: digestion reminds me of the process of purifying blood, the food pipe is like a slightly tilted stick is not a correct analogy because it indicates a rigid, filled structure unlike the food pipe. Also the diaphragm being a metal rod with a little bend is a common alternative conception.

We found that with the type of prompt used in the questionnaire (for e.g. the stomach reminds me of ___), the analogies that were generated typically captured only a limited aspect of students' understanding; often, as explained in the first case above, only surface similarities were suggested by students. In fact the pitfalls of analogies as suggested by Venville and Treagust (1997, Section 3.1) are consistent with these observations. Responses to the analogy question were analysed qualitatively only, so we were not able to correlate performance on analogy questions with students' diagrammatic and verbal responses. In Phase II therefore we dropped analogy questions in Part 1, and used them sparingly and with some guidance and constraints in Parts 2 and 3. To assess visualisation we introduced 'visualisation' questions that required an element of manipulation or transformational reasoning (discussed in Section 3.2.) which we felt might be more closely mapped on to students' understanding.

4.19.2 *How to assess diagrammatic responses: a coding scheme based on systems criteria*

We developed a coding scheme for assessing diagrammatic responses modified from Tversky (1999) to human body systems. This scheme with a few modifications was used in Phase II of the study. The modification was with respect to the criteria for function.

There were two criteria for function: Order of Action and Hierarchy. For the digestive system, the criterion Order of Action had a maximum of seven steps whereas that of 'Functional Hierarchy' had a maximum of two levels. In Phase I, scores for both criteria were calculated separately and combined at the end to arrive at a score for function.

This procedure was therefore resulting in excessive weightage to hierarchy in the overall function score. For example, for the digestive system, the two levels for functional hierarchy are: 1) alimentary canal and 2) liver and pancreas carrying a maximum of two points for the two levels. Students who have understood the functioning of the digestive system invariably answer correctly about the linear pathway being from the mouth to the anus (level 1) and the liver and pancreas being accessory organs which add their secretions into the duodenum (level 2). However those who have not understood this difference tend to incorporate the liver and pancreas too in the path of the linear structure assuming that food moves into it during digestion. Thus they would not receive a score for both levels. Students' scores therefore tended to be either 0 or 1 on hierarchy which had 50% weightage in the function score. In a few cases where they had understood one level but not the other, the score would be 0.5. This particular criterion was therefore loading scores or not yielding a score at all. The coding scheme for function criteria was therefore modified in Phase II.

In Phase II, the number of steps for Order of Action was combined with the number of levels for Hierarchy to give a maximum point of 9. Students' responses pertaining to the two criteria were combined in the final calculation of scores for Phase II. The difference in coding is illustrated through Figures: 4.2 and 5.1 (in Chapter 5: Phase II).

4.20 *Summary of results on students' understanding*

Phase I being an exploratory phase, we intended to arrive at some guidelines for carrying forward this study on a larger scale. Methodological outcomes to carry forward the study are discussed in Section 4.19. The main results regarding students' understanding and expression are summarised here.

1. Given that the sample for Phase I was drawn from a fairly privileged background, it was perhaps not surprising that students' mean scores on structure and function

across the three systems in Phase 1 were high. Another factor that may have possibly affected performance was the provision, as part of the questionnaire, of a short but key passage on each system taken verbatim from the students' Class 6 textbook. The purpose of this passage was in fact to ensure that all the students (who were drawn from Classes 6, 7 and 8) had ready access to some basic background information. Although the passage was of a general nature, it may have facilitated recall of the details of structure and function. However correlational analysis painted a different picture with both aspects being highly correlated for the respiratory system with lower correlations for the circulatory system and no correlations for the digestive system. Lack of correlation in the digestive system is mainly because of difficulty in integrating a linear structure and path taken by food with the accessory organs: the liver and pancreas and therefore the action of these organs is understood.

2. Higher correlations between structure and function for the respiratory system may be in part because of the simpler structure in terms of number of organs of the system and order of action. It is also possible that hierarchy in the system is not completely understood because of the textbook content. This is discussed in Chapter 6. However their understanding seemed to have kept with the content in their textbooks as seen from scores obtained from comparison with standard propositions (Table 4.7).

3. Students were more comfortable expressing structure concepts through drawings than function concepts (results from previous research : Heiser and Tversky, 2006 were also consistent with these findings). Verbal scores were high for all the systems, except in the case of functioning of the digestive system. Diagram scores were high for expression of structure of all the systems and for the function of the digestive system. Digestive function scores were exceptional among the systems in being expressed well through diagrams but not through text. This could have been because of the inclusion of responses obtained in clinical interviews where difficulties in understanding were diagnosed better through probing questions. Students indicated better functional understanding in response to the questionnaire,

but showed insufficient understanding in the interviews which may have depressed their verbal scores and led to higher diagram scores. It must however be borne in mind that scores for the digestive system were anomalous compared to that of the other systems.

4. Though not supported by quantitative analysis, during clinical interviews, the interviewer got a sense that students tend to use verbal descriptions with greater facility and ease compared to diagrams. They also found it difficult to spontaneously form a visual image. However, when forced by the constraints of a specific task and the use of probing questions they were able to do so.

5. Students drawings of structure largely conformed to the textbook diagrams. However questions about processes elicited a variety of function diagrams, which were usually depictive (i.e. modifications of the textbook diagrams) but also made use of arrows and text annotations, colour coding using keys. Only GP used schematic diagrams such as flow-charts using boxes and other symbols, etc..

6. Students' mean verbal (Vr) and diagram (D) scores did not indicate a clear facility with one form over the other, but in their interview responses the students did express mild preferences for either verbal or diagram mode. There were however two students whose written and drawn responses indicated a distinct preference. GP tended to be more propositional in his expression compared to TT who was more depictive. Both students however were able to generate structural and functional analogies in response to the analogy question. Also, their mean diagram scores were higher than their text scores. Apart from these individual cases, clear 'visualisers' and 'verbalisers' were not distinguishable in the group as a whole.

7. Some common problem areas pertaining to the three systems were identified.

   - For the digestive system these were: food moving into the liver and pancreas during digestion, no connection or unsure connection between the small and large intestine, function of the small intestine (absorption of nutrients) during digestion and, digestion in the duodenum.

   - For the respiratory system some problem areas were: structure of the alveolus and diaphragm and therefore its bearing on function such as gas exchange in the alveolus and the changes in the diaphragm during inspiration and expiration.

- For the circulatory system difficulties pertain to: the function of the capillaries and its distinction from arteries and veins, the function of the heart, and connection between the respiratory and circulatory systems

8. Students came up with structural and functional analogies in response to questions pertaining to analogies. They indicated a variety. Structural analogies were often 'mere appearance' matches. Some structural analogies also took into account functional aspects too. In Phase I therefore we arrived at a baseline for students' understanding of body systems and the qualitative characteristics of their diagrams. We developed and refined our coding scheme to assess basic understanding of human body systems expressed verbally and through diagrams. Students' use of analogies was explored.

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

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5.1 *Objectives of Phase II*

In Phase II, students' understanding of the digestive and respiratory systems was tested in a larger sample (than in Phase I). Students' responses were sought only in written (text) and diagram modes, unlike in Phase I where spoken descriptions were also included in the data. The objectives of Phase II were, first to test the results obtained in Phase I on students' understanding of structure and function in a larger sample (under slightly different conditions as described later). Secondly in Phase II, we aimed to test out a new approach to assessing mental visualisation, since the method of analogies used in Phase I seemed not to always capture aspects of understanding and visualisation. These two objectives applied to **Part 1 of Phase II**.

In **Parts 2 and 3 of Phase II**, our objective was to study students' comprehension of new (i.e. unfamiliar) text and diagrams related to human body systems, and their ability to derive structure-function relationships from these texts and diagrams. Further, in **Part 3 of Phase II**, we hoped, through exposing students to some novel diagrams, to derive some insights into the pedagogical possibilities of diagrams for the teaching of human body systems.

Part 1 of Phase II tested for basic knowledge as well as visualisation of the digestive and respiratory systems. The research questions which motivated Part 1 were:

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?

In Part 2 students were given new text passages (i.e. not from their their textbooks) on structure or function, and were asked to answer specific questions after reading the passages. Part 3 looked at comprehension of diagrams conveying structure or function. The questions posed in Parts 2 and 3 required students to make connections between structure and function.

The research questions motivating Parts 2 and 3 were:

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

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?

Additionally in Phase II, there were research questions that arose as an outcome of the results of 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 conceptual difficulties 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?

The objectives, methodology, observations and results for the three parts of Phase II are summarised in brief in Mathai and Ramadas (2009).

5.2 *Comparison between Phases I and II*

Table 5.1 summarises the differences in the sample, questionnaires, data and coding schemes of Phases I and II. Some of these differences are explained in the Sections that follow.

Table 5.1: Comparison between the two Phases of the study

Criterion	Phase I	Phase II
Sample	• 13 students • 6 girls, 7 boys • Classes 6, 7 and 8 • drawn from one school • from scientists' families	• 87 students • 46 girls, 41 boys • Completed Class 6 • 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	• 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.

Criterion	Phase I	Phase II
	taken verbatim from the textbook • Questions on the system as a whole • Open-ended questions on analogies	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 obtain the F score.	• Structure criteria: Same as Phase I • Function criteria: Order and Hierarchy combined during calculation to obtain the F score

5.3 *Sample*

The sample consisted of 87 students, 46 girls and 41 boys, and mixed in terms of ability, who had recently completed Class 6. This sample was drawn from four schools located on the same campus as were the students in Phase I. These schools also followed the NCERT curriculum, 2002. (The relevant content pertaining to the human body systems is given in Appendix F). However the schools from which these students were drawn were four other schools, different from the one from which the Phase I sample was drawn. In comparison to the Phase I sample, in which most of the students came from scientists' families, the sample in Phase II was broader in terms of socio-economic background of the families. In terms of level of schooling however we restricted the sample to students who had completed Class 6 (in Phase I we had students from Classes 6, 7 and 8). We found students who had completed Class 6 to be suitable because the textbook of Class 6 has the maximum content pertaining to human body systems. Also we noticed, during the Phase I interviews, that at the end of the school year, just after the final exams, this content is fresh in the students' minds. Another reason for restricting the sample to a single Class level was to ensure uniformity of standards while assessing responses across the sample.

5.4 *Part 1: The digestive and respiratory systems through text and diagrams*

The questionnaires for Part 1 of Phase II incorporated questions on:

a. basic knowledge (structure and function) and

b. mental visualisation (using the notion of transformational reasoning)

5.4.1 *Structure of the questionnaires for Part 1*

The questionnaires for Part 1 began with an instruction to students "to use words and drawings in any way that you wish". The first question was a general one asking students to describe the system which was followed up with specific questions on each organ of the system. The question on each individual organ first asked for a description of the organ, and then asked about the function of the organ. Questions related to each organ were asked sequentially. A question on structure and function of each organ was followed by a 'visualisation' question related to that organ (see Section 5.4.4).

This ordered sequence of questions was different from that in the Phase I questionnaires, which did not question students explicitly on each individual organ but rather asked open-ended questions testing for an overall understanding of structure and function of that system. Another difference in the Phase II Part 1 questionnaires was that outlines of the human body were not given to students unlike for Phase I. The reason was that in Phase I we felt that students might have been constrained to produce depictive representations as a result of the provision of an outline of the human body. We hoped that, without the constraint of an outline, they might represent their ideas with greater variety and also schematically if they wished. The third difference was that the text passages taken verbatim from the textbook that had been used in the Phase I questionnaires to cue the content, was dropped in Phase II Part 1, and instead, separate comprehension passages on structure and function were prepared as part of the Part 2 questionnaires. Finally, questions probing analogical thinking were dropped in Part 1 of Phase II, though in Parts 2 and 3 analogical thinking tasks of a more focused kind were employed, as one means of testing for structure-function relationships (see Section 5.8.1, 5.8.3, 5.9.1 and 5.9.3).

5.4.2 *Basic knowledge questions for the digestive system*

The first, open-ended question on the digestive system was, “Describe your digestive system”. It was followed by questions on each organ beginning with the food pipe, the stomach, the small intestine and the large intestine. Questions for each organ thus followed the order of location in the system. However, given the confusion found among students in Phase I regarding the auxiliary organs, questions on the liver and pancreas were not inserted in this ordered series of questions. Instead, in the first and last questions the students had the opportunity to mention these organs.

The last question asked students to imagine that they were eating a piece of bread toast and what changes the toast would go through during each stage of the digestive process, which had to be recorded in a given table. In this table, students could have explained the role of the liver and pancreas while mentioning the function of the duodenum. Incidentally, this question is also an example of a visualisation question, details of which are explained in Section 5.4.4. The questions can be seen in Appendix B.2.d.1.

5.4.3 *Basic knowledge questions for the respiratory system*

The first two questions on the respiratory system were open-ended ones, asking students what they understood by the term “respiration” and then asking for a description of the respiratory system. Further there were questions testing for basic knowledge of each organ: the nose, trachea, lungs, alveoli and diaphragm. In addition there were questions which incorporated aspects unique to the respiratory system such as the mechanics of breathing. At the end there were two application questions related to sneezing, coughing and experience of the common cold.

5.4.4 *Questions on visualisation*

Questions on "visualisation" used the notion of transformational reasoning as explained in Section 5.4.4. "Visualisation" questions for both the digestive and respiratory systems were of five different types as mentioned in Section 3.5. Examples illustrating these type 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.

These two questions require the student to imagine the inside of the mouth from an orientation different from what she has seen in the textbook diagram, and to make a drawing of it. 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*

   - 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?

The visualisation questions have been indicated and starred in the criteria for analyses (Part 1) of the two systems, in Appendix C.2.d.1 and C.2.r.1.

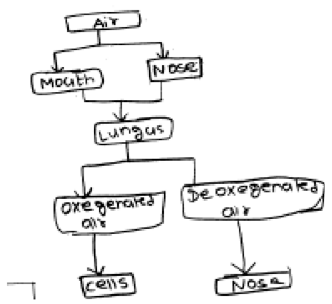
5.5 *Coding scheme for Phase II, Part 1*

5.5.1 *Coding of basic knowledge*

Students' responses were scored using the conceptual framework described in Section 3.4 and a slightly modified form of the coding scheme from Phase I (see Sections 4.7and 4.19.2). To recall, basic knowledge was analysed for structure and function separately. The criteria of 'segmentation' (or 'names of organs' for text responses) and 'order of location' were used for structure responses and 'order of action' and ‘hierarchy’ for function responses. All scores were assigned as proportions of a maximum total score, and thus ranged between 0 and 1.

Figures 4.1 and 4.2 in Chapter 4 may be recalled as examples illustrating the coding scheme for diagrams in Phase I. Figure 4.1 (coding of structure in diagrams) applies as well to the coding system in Phase II Part 1 being described here. The coding of function was however modified (for both text and diagrams), with Order and Hierarchy being combined before calculating the proportion. Figure 5.1 illustrates the coding of function in diagrams as carried out in Phase II Part 1. For clarity, the same student diagram is used in Figures 4.2 and 5.1.

Figure 5.1: An example of the use of the coding scheme for the calculation of function scores for a student's diagram of the digestive system in Phase II Part 1



DF = Order of action with Hierarchy combined

DF = (2+1)/(7+2) = 0.33

Table 5.2 summarises the coding scheme followed for the Phase II Part 1 analysis.

Table 5.2: Coding scheme for Phase II Part 1

Basic knowledge				Visualisation (V)
Text responses (T)		Drawn responses (D)		Generation and transformation of images (Text and Diagrams)
Structure (TS)	**Function (TF)**	**Structure (DS)**	**Function (DF)**	
Names of Organs	-	Segmentation (depiction of organs)	-	
Order (described location of organs)	Order of action and Hierarchy (description)	Order (depicted location of organs)	Order of action and Hierarchy (depictions)	

The five variables in Table 5.2 are: Structure expressed through Text (TS), Function expressed through Text (TF), Structure expressed through Diagrams (DS), Function expressed through Diagrams (DF) and Visualisation (V). It maybe recalled that, similar to the procedure for Phase I, TS, TF, DS and DF were derived from responses to the same set of questions and that scoring for text and diagrams, though independent, followed a common scheme. The complete coding system used for both digestive and respiratory systems is elaborated in Appendices C.2.d.1 and C.2.r.1.

5.5.2 *Coding of visualisation*

There were 11 questions on visualisation of the digestive system, each carrying four points. The four points for scoring were: i. Generation of an image, ii. correctness of the generated image, iii. manipulation of the generated image and iv. correctness of the manipulation.

Here are examples of some common responses to a visualisation question on the food pipe, with scores assigned on a four-point scale.

If the food pipe were longer:

–*it would take more time for food to travel from the mouth to the stomach.* (4: for generation of a correct image of a longer foodpipe and the correct manipulation of the passage of food through a longer pipe)

–*the location of organs would change because of the increased length thereby disrupting the process of digestion.* (3: in this case the role of the food pipe is not understood and therefore the manipulation of the image (the fourth point) is incorrect)

–*if the food pipe was involved in digestion the food would take longer to get digested in the food pipe.* (2: here there is no correct image generation or correct manipulation (points 3 and 4)

If the food pipe were shorter:

–*the food pipe serves as a passage to the stomach, so food will reach the stomach faster.* (4: correct generation and correct manipulation of the image)

–*There will be no change in the digestive process.* (1: a correct conclusion but not a result of generation and manipulation of the image)

–*there would be improper digestion.* (0: no image generated and manipulated and incorrect conclusion)

On the respiratory system there were 9 visualisation questions, also carrying 4 points each, as before. The points were for: i. Generation of an image, ii. correctness of the generated image, iii. manipulation of the generated image and iv. correctness of the manipulation. An example of coding of students' responses on a question relating to the trachea: "What would happen if the trachea was a smooth flexible structure?" is given below:

The trachea is a pipe which serves an important function as a passage for air. It should therefore have strong supportive tissue so that it remains open when needed and passes the air to the bronchi. If it was a smooth structure, it would easily collapse under pressure and will not be able to facilitate air passage (4: correct generation and correct manipulation of the image of a structurally changed trachea)

If it was a smooth structure it would be like the oesophagus and more suitable for food (3: incorrect conclusion of manipulation, generation is correct, plus there is evidence of some manipulation)

It does not make a difference (0: no generation and manipulation of image)

5.5.3 *Inter-rater reliability of coding*

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 to check if there were significant differences between scores. Tables 5.2 and 5.3 show the inter-rater correlations for the Part 1 variables for the digestive and respiratory systems respectively. The correlations ranged from 0.65 to 0.84 ($p<0.01$) for the digestive system. For the respiratory system the correlations between scores assigned by the two coders were high: 0.68 to 0.88 ($p<0.01$) for all the variables except TS and PS, for which the correlations were significant only at $p<0.05$.

Table 5.3: Inter-rater correlations for Part 1 variables of the digestive system

Variable	Digestive system
TS	0.84**
TF	0.80**
DS	0.83**
DF	0.71**
V	0.65**
PS	0.90**
PF	0.85**

** Significant at 0.05 level*
*** Significant at 0.01 level*

Table 5.4: Inter-rater correlations for Part 1 variables of the respiratory system

Variable	Respiratory system
TS	0.41*
TF	0.88**
DS	0.88**
DF	0.79**
V	0.75**
PS	0.60*
PF	0.68**

** Significant at 0.05 level*
*** Significant at 0.01 level*

5.6 *Statistical analysis for Part 1*

Statistical analysis was carried out on the variables listed in Table 5.2. Frequency distributions were plotted along with descriptive statistics for all variables. t tests were done to check for differences in mean scores between the variables. Spearman's correlation coefficient (ρ) was used to check for significant correlations between scores on the variables.

5.7 *Observations and results for Part 1*

Research questions II/1, II/2 and II/3 in Section 5.1 deal with students' expression of understanding of structure and function through text and diagrams. Our observations and results pertaining to these aspects are discussed below in Sections: 5.7.1 for the digestive system and 5.7.2 for the respiratory system. Table 5.5 summarises the mean scores and standard deviations on all Part 1 variables for both systems. Absolute scores for the respiratory system were lower than the digestive system.

Table 5.5. Mean scores and standard deviations on all Part 1 variables for both the digestive and the respiratory systems

Variable	Digestive system		Respiratory system	
	Mean score	s.d.	Mean score	s.d.
Text Structure (TS)	0.67	0.15	0.38	0.10
Text Function (TF)	0.63	0.21	0.29	0.14
Diagram Structure (DS)	0.32	0.34	0.23	0.21
Diagram Function (DF)	0.39	0.37	0.17	0.17
Visualisation (V)	0.57	0.20	0.22	0.20

5.7.1 *Digestive system*

Table 5.6 summarises the comparisons between mean scores on the five variables for the digestive and respiratory systems. These Tables were constructed on the basis of 5X5 paired t-tests on the variables TS, TF, DS, DF and V. Results from all the 5X5 comparisons ($p<0.05$) were completely consistent. Thus we can summarise all the comparisons in a compact way, as is done in Table 5.6.

Table 5.6: Comparison of mean scores on all variables for the digestive system

Category of students	No. of students	Comparisons of mean scores (t-tests, p<0.05)
All students	70	TS > TF > V > DF > DS .67 > .63 > .57 > .39 > .32
Only students who drew diagrams	41 (64%)	TS > TF > DF > V > DS .72 > .70 > .65 > .61 > .54
Students who did not draw diagrams	29 (36%)	TS > TF > V .61 > .53 > .50

Table 5.6 shows that students more effectively expressed themselves through text rather than through diagrams. They also showed a preference towards expression through text: more than a third responded exclusively through text. About 36% students drew no diagrams of the digestive system. Among students who drew diagrams, text scores were

significantly higher than diagram scores.

Following results from the exploratory study in Phase I (Section 4.11 of this thesis; Mathai and Ramadas, 2006) and also Heiser and Tversky's (2006) results on mechanical systems, we anticipated that structure may be better expressed through diagrams than through text, and function may be better expressed through text. The latter hypothesis was confirmed, but to our surprise we found that, on an average, structure concepts too were better expressed through text than through diagrams. Thus text expression was better than diagrams for both structure and function concepts. Results from the respiratory system also supported this observation (Section 5.7.2). Most student diagrams were stereotypical but imperfect copies of a canonical textbook diagram of the digestive system.

Correlation matrices between the Part 1 variables is shown in Tables 5.7 a, b and c. Since there were a large proportion of students who did not draw diagrams, these correlation matrices were calculated for the whole sample (Table 5.7 a) and also separately for the sub-samples of students who drew diagrams (Table 5.7 b) and those who did not (Table 5.7 c). In the total sample, as well as in the sub-sample of students who drew diagrams, there were high correlations (Spearman's rho) between TS and TF ($rho=0.9$, $p<0.01$) and between DS and DF ($rho=0.7$, $p<0.01$). Among the sample of students who did not draw diagrams too there was a high correlation between TS and TF ($rho=0.8$). These consistently high correlations indicated a consistency **within** the text and diagram responses. **Between** text and diagrams the correlations were lower, though still significant (between TS and DS, 0.4 and between TF and DF, 0.6). Correlations with 'Visualisation' are discussed in Section 5.7.4.

Tables 5.7 (a-c): Correlation matrices for the digestive system: a) for the total sample of students, b) for the sample of students who drew diagrams, c) for the sample of students who did not draw diagrams. (*Correlations above 0.6 are circled)*

a) Spearman's Rho for the total sample of students (70)

		TS	TF	DS	DF	V
TS	Correlation Coefficient	1.0	0.9**	0.4**	0.6**	0.5**
TF	Correlation Coefficient	0.9**	1.0	0.4**	0.6**	0.6**
DS	Correlation Coefficient	0.4**	0.4**	1.0	0.8**	0.3*
DF	Correlation Coefficient	0.6**	0.6**	0.8**	1.0	0.4**
V	Correlation Coefficient	0.5**	0.6**	0.3*	0.4**	1.0

b) Spearman's Rho for the sample of students who drew diagrams (41)

		TS	TF	DS	DF	V
TS	Correlation Coefficient	1.0	0.9**	0.4**	0.7**	0.5**
TF	Correlation Coefficient	0.9**	1.0	0.3	0.6**	0.6**
DS	Correlation Coefficient	0.4**	0.3	1.0	0.7**	0.3**
DF	Correlation Coefficient	0.7**	0.6**	0.7**	1.0	0.4**
V	Correlation Coefficient	0.5**	0.6**	0.3*	0.4**	1.0

c) Spearman's Rho for the sample of students who did not draw diagrams (29)

		TS	TF	V
TS	Correlation Coefficient	1.0	0.8**	0.3
TF	Correlation Coefficient	0.8**	1.0	0.4**
V	Correlation Coefficient	0.3	0.4**	1.0

* Correlation is significant at 0.05 level

**Correlation is significant at 0.01 level

In order to look more closely into the scores of individual students we recoded the scores into low (0-0.33), medium (0.34-0.65) and high (0.66–1.0) categories. Cross-tabulations of TS and TF scores are shown in Table 5.8 a and those of the DS and DF scores are shown in Table 5.8 b. The cross-tabulations of Text scores (TS and TF) showed that there were 31 students who had medium scores and 25 who had high scores in both Text Structure and Text Function. There were no students with low text scores. A similar cross-tabulation for Diagram scores (DS and DF) showed that there were 31 students with low scores on both DS and DF (of whom 29 did not draw diagrams at all) and 13 and 14 students respectively with medium and high scores on both DS and DF. The consistency in structure and function scores enabled us to separate the samples of students with low, medium or high text or diagram scores for further analysis. The answer-scripts of the sub samples of students with low, medium and high scores on TS, TF, DS and DF were examined to identify conceptual problems, as explained in the next section.

Table 5.8 a: Cross tabulations of TS and TF scores for the digestive system

	TS-l	**TS-m**	**TS-h**
TF-l	0	4	0
TF-m	0	31	6
TF-h	0	2	25

Table 5.8 b: Cross-tabulations of DS and DF scores for the digestive system

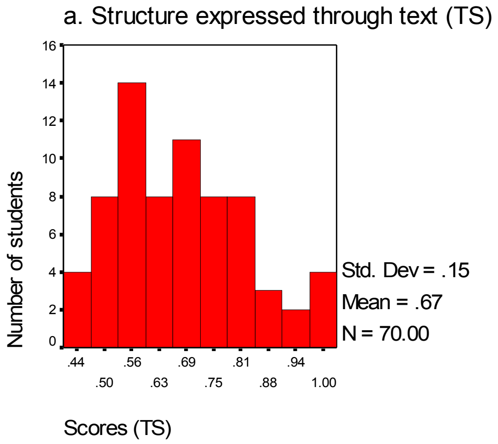
	DS-l	**DS-m**	**DS-h**
DF-l	31	2	0
DF-m	3	13	1
DF-h	2	4	14

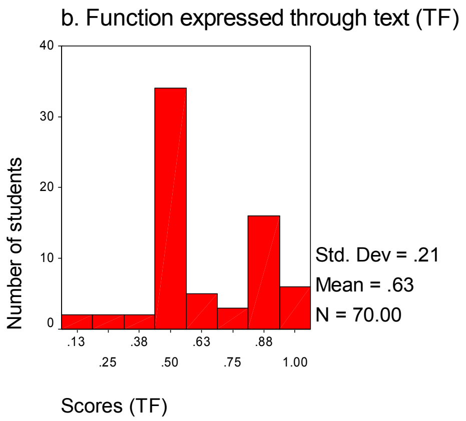
5.7.1.1 *Conceptual problems for the digestive system*

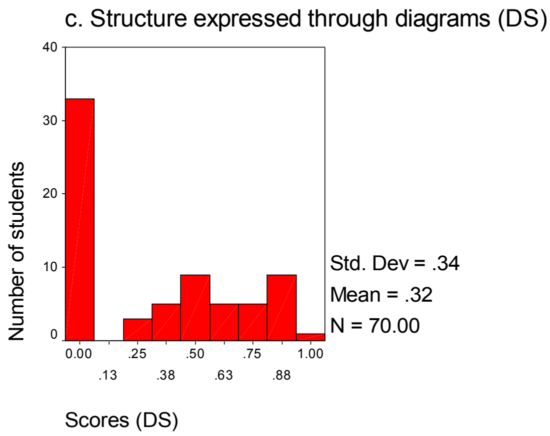
Research question no. II/4 had to do with students' difficulties in understanding the body systems. Research question No. II/11 asked specifically whether the alternative conceptions found in Phase I were found in Phase II as well. The comparison between structure and function scores for the digestive system (previous section) showed that the mode of expression (text or diagram) mattered when it came to expressing structure or function. Thus we could not say for sure that structure was easier for students than function in case of the digestive system. What we can say with justification is that even though students might have expressed their understanding adequately through text, when it came to drawings or depictions their confusions and misunderstandings came to the fore.

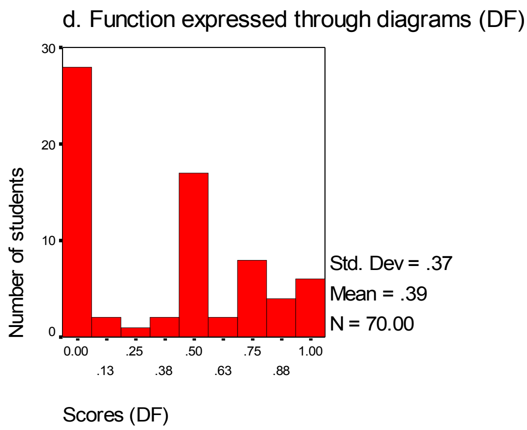
Frequency distributions of scores on TS, TF, DS and DF for the digestive system showed some interesting effects (Figures 5.2 a-d).

Figures 5.2 (a-d): Anomalous distributions of scores on the digestive system indicating (i) a low incidence of diagrams drawn and (ii) relatively large sub-populations of students with 'medium' scores, who turned out to hold common alternative conceptions









One observation from Figures 5.2 a-d is the high incidence of students not drawing diagrams at all. The other striking aspect of all the distributions is their bimodal nature, with a disproportionately large number of students in the middle.

Using the Low, Medium and High categories (as described above) to sort the original responses, we identified discriminating factors between the medium and high-scoring students to be their understanding of accessory organs, namely, the liver and pancreas (the gall bladder was rarely mentioned) and the small intestine. In Phase II therefore we were able to quantify the percentage of students who had each alternative conception and also locate these students within the score distributions of the sample. A detailed breakup of alternative conceptions for the digestive system within the low and medium scorers is shown in Figure: 5.3. The numbers in the figure refer to the percentage of students within that category who had that conceptual difficulty. The breakup of alternative conceptions in each category do not always add up to hundred since most students had more than one alternative conception.

Figure 5.3: Alternative conceptions found among students for the digestive system (all numbers are in percentages)

TS (L 0, M 53, H 44):

-- L: 0

-- M: 53

- 75: incorrect understanding of the role of accessory organs in the digestive process
  - 20: food passes through the liver and pancreas
  - 55: miscellaneous alternative conceptions pertaining to the liver and pancreas: not mentioning the organs, incorrect understanding of its function
- 63: role of the small intestine as the site of absorption

-- H: 44

most organs and locations have been understood correctly

TF (L 5, M 53, H 39):

-- L: 5

- 100: all have difficulty understanding the function of organs involved: mainly the role of accessory organs, the small intestine-large intestine connection and the role of the small intestine in absorption

-- M: 53

- 82: did not understand the role of the accessory organs
- 60: had not understood the role of the small intestine
  - 46: did not understand the small-intestine as a site of absorption
  - 14: did not know about the small-intestine – large-intestine connection

-- H: 39

most function attributes have been understood correctly

DS (L 51, M 27, H 21):

-- L: 51

- 92: have not drawn diagrams
- 8: have drawn irrelevant / vague diagrams without marking parts, etc..

-- M: 27

- all have difficulty in representing order of location spatially

-- H: 21

- Most organs' names are known and marked correctly, spatial organisation mostly accurate

DF (L 47, M 25, H 29):

-- L: 47 have not drawn diagrams

-- M: 25

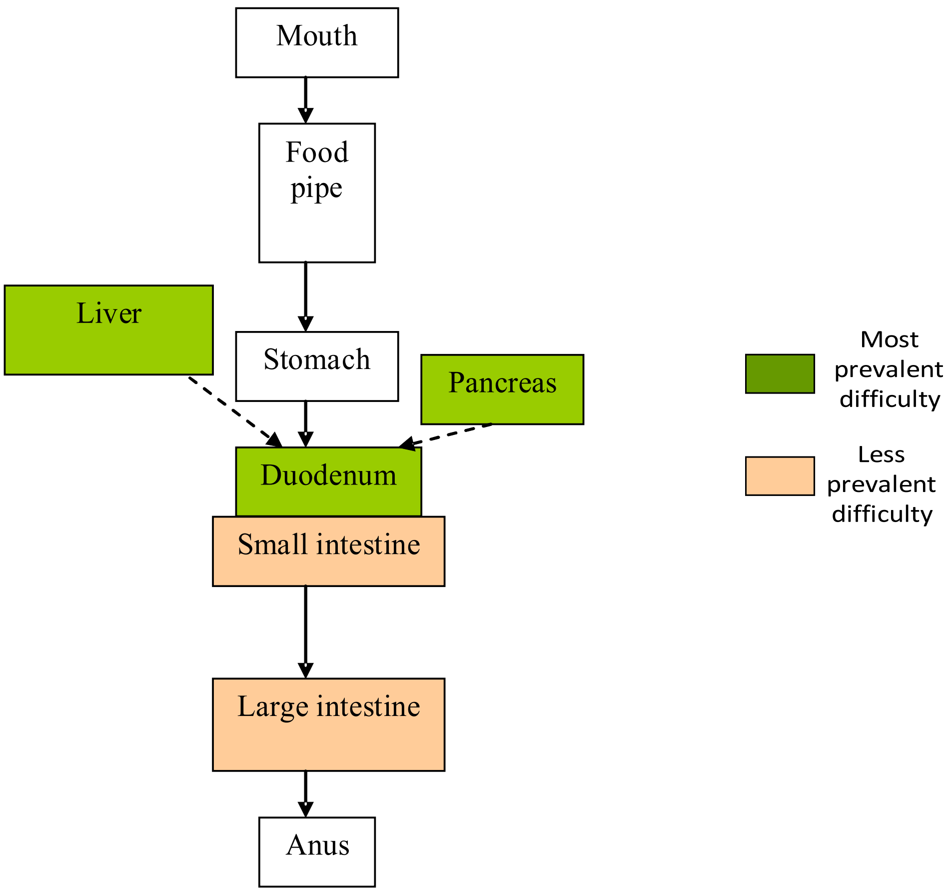
- 75: have difficulty representing hierarchy
- 93: difficulty in representing order of function spatially

-- H: 29

Most functional attributes have been understood correctly

Figure 5.3 shows that 75% students in the 'Medium' category of TS and 82% in the 'Medium' category of TF had an incorrect understanding of the location and function respectively of the accessory organs. The most common error was to consider the food to go into the liver and pancreas during digestion thereby maintaining a linear pathway (an example was shown in GP's diagram in Phase I, Chapter 4, Fig. 4.24). The other common error had to with the connections between the stomach / duodenum and small and large intestines. 63% and 60% students in the 'Medium' categories of TS and TF located the small intestines incorrectly or misunderstood its role as the site of 'absorption'. The latter problem may have to do with an inadequate understanding of the link between the digestive and circulatory systems. From text responses therefore it was clear that the common difficulties encountered were similar to what we found in Phase I: the role of the accessory organs and the small intestine, and the connection between the small and large intestine. Most medium diagram scorers had difficulty representing order of location and function. Functional hierarchy was also difficult to represent. Figure 5.4 summarises these results within a schematic representation of the common problems in understanding the digestive system.

Figure 5.4: Common problems in understanding the digestive system



5.7.2 *Respiratory system*

We now consider Research questions II/1, II/2 and II/3 for the respiratory system. Table 5.9 shows the mean scores for the respiratory system of the Part I variables: TS, TF, DS, DF and V, and the inequalities between them. This Table is constructed on the basis of 5X5 paired t-tests on the variables TS, TF, DS, DF and V.

Table 5.9: Comparison of mean scores for the respiratory system and the inequalities between variables

	No. of students	Respiratory system
All students	66	TS > TF > DS, V > DF .38 > .29 > .23, .22 > .17
Only students who drew diagrams	45 (68%)	TS > TF, DS > V , DF .41 > .33, .33 > .26, .25
Students who drew no diagrams	21 (32%)	TS > TF > V .32 > .19, .14

As in the case of the digestive system, results from all the 5X5 comparisons were completely consistent ($p<0.05$). The observation in the case of the digestive system, that text expression was better than diagrams for both structure and function concepts, was confirmed in the case of the respiratory system also. Structure scores were higher than function scores for both text and diagrams. This result was different from the digestive system, where diagram structure scores were the lowest. This is perhaps because the digestive system has 12 organs and a more complex organisation because of the additional level of hierarchy imposed by the liver and pancreas. In comparison, the depicted structure of the respiratory system has fewer (8) organs and a simple linear flow.

Table 5.10 (a-c): Correlation matrices for Part 1 variables of the respiratory system: a) for the total sample of students, b) for the sample of students who drew diagrams, c) for the sample of students who did not draw diagrams (*Correlations above 0.6 are circled*)

a) Spearman's Rho for the total sample of students (66)

		TS	TF	DS	DF	V
TS	Correlation Coefficient	1.0	0.9**	0.6**	0.5**	0.4**
TF	Correlation Coefficient	0.9**	1.0	0.6**	0.6**	0.4**
DS	Correlation Coefficient	0.6**	0.6**	1.0	0.9**	0.5**
DF	Correlation Coefficient	0.5**	0.6**	0.9**	1.0	0.5**
V	Correlation Coefficient	0.4**	0.4**	0.5**	0.5**	1.0

** Correlation is significant at 0.01 level

b) Spearman's Rho for the sample of students who drew diagrams (45)

		TS	TF	DS	DF	V
TS	Correlation Coefficient	1.0	0.8**	0.5**	0.4**	0.5**
TF	Correlation Coefficient	0.8**	1.0	0.4**	0.4**	0.5**
DS	Correlation Coefficient	0.5**	0.4**	1.0	0.7**	0.5**
DF	Correlation Coefficient	0.4**	0.4**	0.7**	1.0	0.5**
V	Correlation Coefficient	0.5**	0.5**	0.5**	0.5**	1.0

** Correlation is significant at 0.01 level

c) Spearman's Rho for students who did not draw diagrams (21)

		TS	TF	V
TS	Correlation Coefficient	1.0	0.8**	-0.1
TF	Correlation Coefficient	0.8**	1.0	0.1
V	Correlation Coefficient	-0.1	0.1	1.0

** Correlation is significant at 0.01 level

Correlation matrices were plotted between Part 1 variables as for the digestive system (See Tables 5.10 a, b and c). These matrices indicated a consistency between TS and TF (0.9, $p<0.01$) and between DS and DF (0.7, $p<0.01$) for the sub-sample of students who drew diagrams. Between text and diagram variables the correlations were lower, but significant (0.5 between TS and DS and 0.4 between TF and DF). For the sub-sample of students who did not draw diagrams too, correlation between TS and TF scores were high. The matrices are shown in Tables 5.9 a, b and c. These results paralelled those for the digestive system.

Research question No. 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. In the case of Phase I the questions had been phrased in terms of a system as a whole. Perhaps the ordering of questions on structure and function as per the order of each individual organ of the system served a pedagogic role so that students may have found it easier to correlate structure with function.

As done for the digestive system, for the respiratory system too, the scores were recoded into three categories: Low (0-0.33), Medium (0.34-0.66) and High (0.67-1.00). Cross tabulations between Text scores (TS and TF) showed that there were 24 students with low scores, and 9 students with medium scores in both. In comparison for the

Diagram scores (DS and DF) there were 44 students with low scores and 3 students with medium scores on both. Unlike for the digestive system, in the respiratory system there were a fair number of students with medium structure scores but low function scores. (28 and 17 students respectively in terms of text and diagram scores), as seen in Tables 5.11 a and b. Thus for the respiratory system, function was a particular source of difficulty. Overall, the number of low scorers were far greater for the respiratory system than for the digestive system. The cross-tabulations are shown in Tables: 5.11 a and b.

Table 5.11 a: Cross-tabulations of TS and TF scores for the digestive system

	TS-l	TS-m	TS-h
TF-l	0	4	0
TF-m	0	31	6
TF-h	0	2	25

Table 5.11b: Cross-tabulations of DS and DF scores for the digestive system

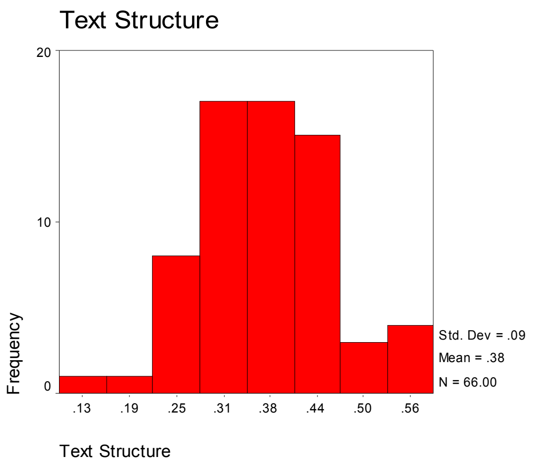
	DS-l	DS-m	DS-h
DF-l	44	17	0
DF-m	1	3	0
DF-h	0	1	0

5.7.2.1 *Conceptual problems for the respiratory system*

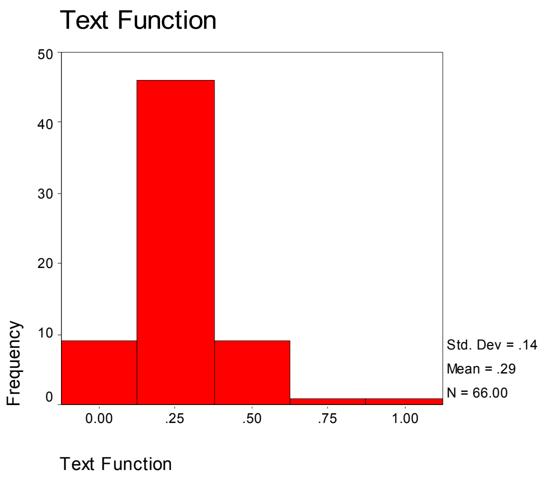
The frequency distribution of scores on TS, TF, DS and DF for the respiratory system are shown in Figures 5.5 a-d.

Figure 5.5 a-d: Distribution of scores for the respiratory system showing i) a low incidence of diagrams, ii) normal distributions for text scores and among the medium scorers for the diagram scores

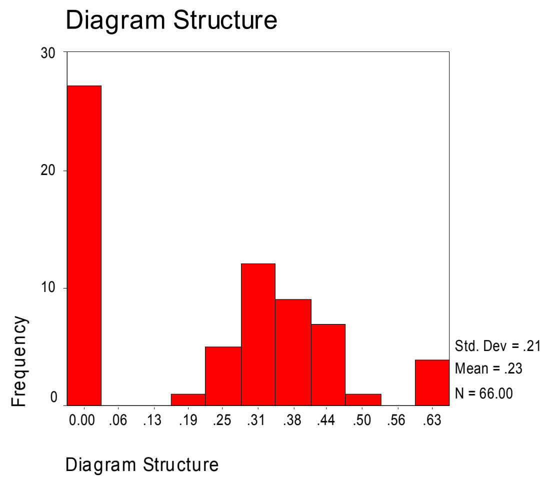
5.5 a. Structure expressed through text (TS)



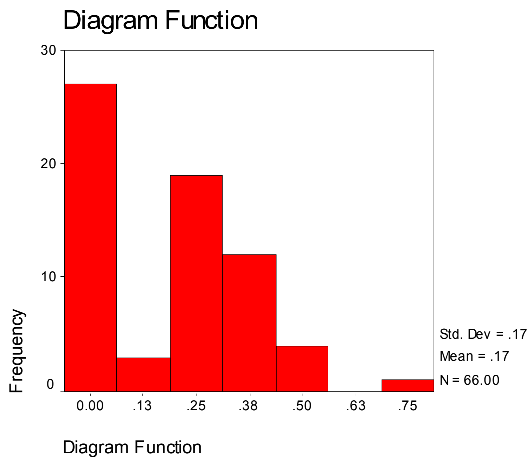
5.5 b. Function expressed through text



5.5 c. Structure expressed through diagrams



5.5 d. Function expressed through diagrams



The distributions are 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. These distributions thus did not show the anomalies reported for the digestive system. In response to Research question II/4, it turned out that conceptual misunderstandings about respiration, involving the pharynx, bronchioles, alveoli and diaphragm, were uniformly present across low and medium scoring students. A detailed breakup of alternative conceptions among the medium and low scorers is shown in Figure

5.6.

Figure 5.6: Alternative conceptions for the respiratory system (all figures are in percentages)

TS (L 36, M 59, H 0) :

-- L: 36

- All have difficulties naming the organs of the system and describing it structurally, specially the bronchioles, alveoli, pharynx and diaphragm

-- M: 59

- 95: Mostly homogenous understanding, difficulty pertaining to the structure of the alveoli and diaphragm
- 5: have difficulties with most organs

-- H: 0

- Most organs and locations have been marked correctly

TF (L 79, M 13, H 3):

-- L: 79

- 78: difficulties pertaining to the functioning of the alveoli
- 80: have difficulty understanding the connection between the respiratory and circulatory systems
- 62: have both difficulties mentioned above

-- M: 13

- 62: have difficulty understanding the connection between the respiratory and circulatory systems
- 38: have difficulty understanding the function of the alveoli
- 20: have both difficulties mentioned above
- 45: have difficulties with mechanics of inspiration and expiration

-- H: 3

- Functional aspects of most organs have been understood and marked correctly

DS (L 68, M 32, H 0)

-- L: 100

- 90 have not drawn diagrams
- 10 have drawn mostly irrelevant diagrams

-- M: 32

- 86: not drawn pharynx, bronchioles and alveoli
- 78: structure of alveoli not represented
- 50: shape and location of diaphragm
- 92: structural connection between respiratory and circulatory systems

-- H: 0

DF (L 92, M 6, H 1):

-- L: 92

- 96 have not drawn diagrams
- 4 have drawn mostly irrelevant diagrams

-- M: 6

- 83 have difficulty spatially representing order of action
- 75 have difficulty understanding functional hierarchy in the respiratory system
- 70 have both difficulties

-- H: 1

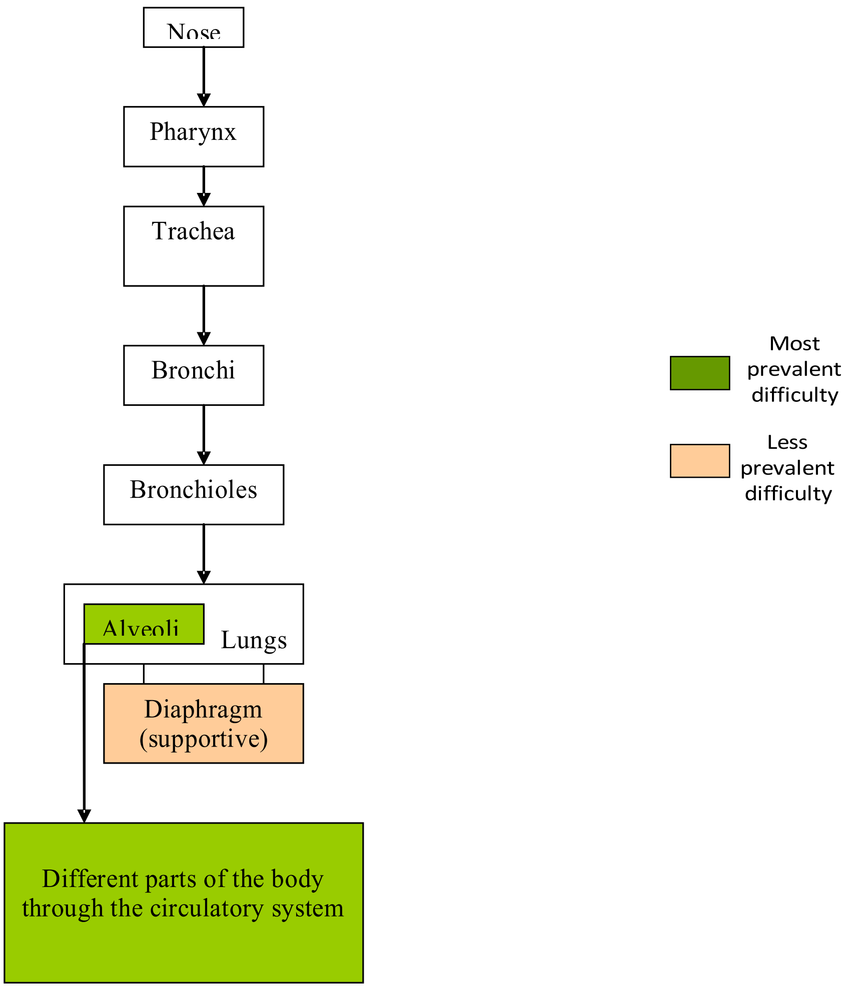
- Functional diagrams have been drawn, order of action and hierarchy sufficiently well understood

The following common difficulties were identified in text responses as seen in Figure

5.6 (with percentages of the respective groups in brackets): structure of alveoli and diaphragm (95% of medium TS scorers), connection between the respiratory and circulatory systems (80% of medium TF scorers) and mechanics of respiration (45% of medium TF scorers). The following common difficulties were identified in diagram responses (shown in Fig. 5.6): existence of the pharynx, bronchi, bronchioles and alveoli (86% of medium DS scorers), shape, location and function of the diaphragm (50% of medium DS scorers) and connection between the respiratory and circulatory systems (92% of medium DS scorers), A common error was to consider the diaphragm also to expand and relax like the lungs, in place of its motion as a supportive muscle.

Research question No. II/11 had to do with a comparison of alternative conceptions from Phase I and II for both the digestive and respiratory systems. It was found that for the respiratory system also, similar alternative conceptions were found in Phase II as in Phase I. 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. The major difficulties encountered for the respiratory system is shown schematically in Figure: 5.7.

Figure 5.7: Common problems in understanding the respiratory system



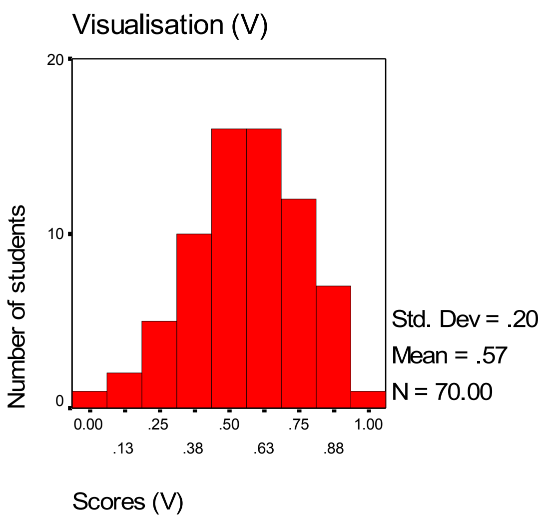
5.7.3 Comparison with textbook propositions

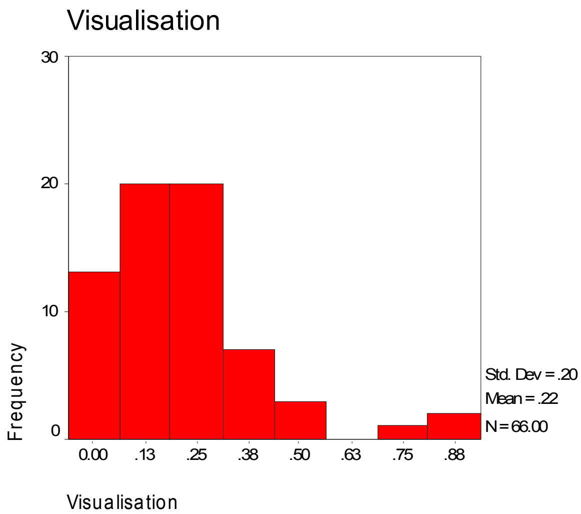
As in Phase I, students' text responses were compared with a list of standard propositions taken from the school textbooks. Inter-rater reliability for PS and PF scores were found to be 0.90** and 0.85** respectively for the digestive system, and 0.60* and 0.68** respectively for the respiratory system. The mean scores were PS-dig: 0.74, PF-dig: 0.52, PS-res: 0.37 and PF-res: 0.63. Thus students' understanding of structure for the digestive system, and that of function for the respiratory system largely corresponded with the content given in their textbooks. In relation to textbook content on structure of the respiratory system, the students' score was quite low. It may have been because of the nature of the textbook content which presented several facts pertaining to mostly breathing alone: such as respiratory rate, components of inhaled and exhaled air, etc. without integrating it with an overall understanding of respiration and its connection with the circulatory system.

5.7.4 *Visualisation of the digestive and respiratory systems*

Research question nos. II/5 and II/6 had to do with characterising mental visualisation in the context of our study. The distribution of visualisation scores is shown in Figure 5.7 a and b.

Figure 5.8 a and b: Visualisation scores for a) digestive and b) respiratory systems





For the digestive system, the distribution was nearly normal (Mean: 0.57) whereas for the respiratory system it was skewed to the left (Mean: 0.22). In parallel with scores on basic knowledge, visualisation scores too were significantly higher for the digestive system compared to the respiratory system ($t=3.76$, $p<0.00$).

Looking for a simple way to characterise 'visualisation' in terms of the other variables, we found, for the digestive system, higher correlations of visualisation with the text scores (Spearman's rho=0.6 and 0.5 for TF and TS respectively, $p<0.01$) than with the diagram scores (rho=0.4 and 0.3 for DF and DS respectively, $p<0.05$). (See Table 5.7 b). For the respiratory system, correlations of visualisation with the text and diagram scores were all 0.5 (see Table 5.10 b). These preliminary results being inconclusive we did not proceed further with regression analysis. Rather we looked more closely at the cross-tabulations as described next.

Research question No. II/12 (which was a question leading from results of Phase I) asked if visualisers and verbalisers were distinguishable. We tried to check this from cross-tabulations of students' recoded mean scores and visualisation scores shown in Tables: 5.12 and 5.13 (a-c). The Text (T) and Diagram (D) scores in these Tables combine Structure and Function scores.

Table 5.12 (a-c): Cross tabulation between Text (T), Diagram (D) and Visualisation (V) scores for the digestive system

	T-l	T-m	T-h
D-l	4	24	7
D-m	0	14	6
D-h	0	2	13

	T-l	T-m	T-h
V-l	1	6	1
V-m	1	27	8
V-h	0	7	18

	D-l	D-m	D-h
V-l	6	2	0
V-m	19	10	7
V-h	8	8	9

Table 5.13 (a-c): Cross tabulation between Text (T), Diagram (D) and Visualisation (V) scores for the Respiratory system

	T-l	T-m	T-h
D-l	29	16	0
D-m	2	11	0
D-h	0	0	1

	T-l	T-m	T-h
V-l	30	20	0
V-m	2	7	0
V-h	0	2	1

	D-l	D-m	D-h
V-l	43	8	0
V-m	6	3	0
V-h	0	2	1

After recoding the scores as Low, Medium and High we found that of 26 students who had 'High' Text scores on the digestive system, 13 also had 'High' Diagrams scores while 7 had 'Low' diagram scores. Thus a group of high-scoring students were good in both 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 (Table 5.12 a).

For the digestive system, of the 25 students with high visualisation scores, 18 had high text scores while 9 had high diagram scores (Table 5.12 b and c). Thus mental visualisation was likely to be associated with good text scores (for the digestive system only) as was indicated also by the correlations. 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 there were only 1-3 students in the High categories, as seen in Tables 5.13 (a-c). Unlike for the digestive system, we could not identify a group of pure 'verbalisers'. Nor could clear 'visualisers' be identified.

In general, visualisation scores for the respiratory system were lower than for the digestive system. Textbook content on the respiratory system is not as detailed as for the digestive system. Also, our tasks were prepared keeping content knowledge as an important precursor. Therefore we can conclude that 'Visualisation' as defined here, is closely predicated on prior knowledge of the domain (we believe this should be so in any science context).

5.8 *Part 2: Comprehension of structure – function relationships from text*

Research question no. II/5 had to do with students' comprehension of structure-function relationships from text. Taking a cue from the study of Heiser and Tversky (2006), described in Section 3.3.2, we attempted to compose comprehension passages on the digestive and respiratory systems, that would convey structure alone, and function alone. The difficulties that we faced in composing such passages were educative in themselves, and showed us how closely structure and function at different levels of the system are integrated in biology. For the digestive system we were able to compose two pairs of passages, both dealing with macro aspects of the system, in which structure and function were largely separated. For the respiratory system however, parallel (equivalent) structure and function passages as in the case of the digestive system were not possible to prepare due to the higher degree of structural complexity and the close dependence of function on the detailed structural features in the system. The three passages describing structure and function of the respiratory system therefore dealt with different aspects of the system. The questions in both the systems however dealt with relating of structure with function. The questionnaires, observations and results are detailed in the subsequent sections.

5.8.1 *Questionnaires for the digestive system (Phase II Part 2)*

For the digestive system, two text passages were prepared in two different versions: a 'structure' version (Part 2A) and a 'function' version (Part 2B) which were administered to two sub-samples of 44 and 34 students respectively. The students were assigned randomly to the two groups. The passages went a little beyond the content level of the textbooks at the middle school level. For the purpose of enabling structure-function correlation the selected content had mechanical action predominant in comparison with microscopic or chemical action. The questionnaires are in the Appendix B.2.d.2.

The first passage described the chewing of food. A sample line from the '*structure'* version: "*Incisors are the front teeth which are flat in shape. On both sides of the incisors are the long and pointed canine teeth...*" The '*function'* version stated: "*The teeth chew the food in the following way. First the incisors break off a piece of food. Tough foods are torn up by the canines...*" A common question for both passages asked students to correlate the shape and location of each kind of tooth with its function.

The second passage focused on the mechanism of swallowing (the term 'oesophagus' was used here onwards as it was very familiar to students). A sample in the '*structure'* version: "*The oesophagus is a flexible tube. This tube begins at the back of the mouth. The walls of the tube can repeatedly relax and contract to push the food along the oesophagus.*" The '*function'* version was: "*When food is swallowed, it goes from the mouth into the oesophagus. The food is pushed along with the help of repeated contractions and relaxations of the oesophagus*." A common question here was: "*How do you think the food is pushed from the mouth to the stomach through the oesophagus? Make a drawing of it*."

The difficulty of separating structure and function into two separate passages has been commented on at the beginning of this section. In complex biological contexts the distinction between 'structure' and 'function' passages was somewhat artificial: either kind of passage could not be completely free of the complementary (function or structure) information, and yet make sense. Consequently the difference lay in emphasis more than in content. For example, in the description of the mouth, the presence of enzymes in the saliva had to be mentioned for the 'structure' passage to be readable, and also comparable in content to the 'function' passage. Similarly, in the description of swallowing, its mechanical action on the food was unavoidably mentioned.

All the questions based on these passages called for drawing of inferences from the passages. Some of them required diagrams. The main thrust of the inferencing required in the questions was towards finding connections between structure and function (henceforth abbreviated as s-f). Some of the s-f questions involved transformational reasoning. An example a question calling for transformational reasoning is: 'What would happen if there was no layer of mucus on the inside of the stomach?'

Some of the s-f questions were of a kind that required analogical reasoning. Unlike in Phase I, these analogical tasks were not open-ended, but constrained by some conditions that were specified within the questions. Examples of questions calling for analogical reasoning are: 'Which of these words might describe the walls of the oesophagus: soft, hard, strong, flexible, bony?', 'Where else can you see a similar process (as peristalsis in the food pipe) in the human body itself?'

Recall that the content of the passages presumed the students' prior exposure to the digestive system in the previous school year. Therefore responses to the questions too could be facilitated by the students' prior knowledge (henceforth abbreviated as pk).

Table 5.14a: Nature of Part 2A questions for the digestive system

Passage	Question no.	Nature of questions	What was tested	Maximum points tested
Mouth - description of structure	1c*	shape, location, function of teeth	s→f, pk, d	12
	1e*	what if hard and bony tongue	s→f, t	1
	1g*	taste buds in tongue	s→f, pk	1
	1a	diagrams of teeth	f→s, pk, d	4
	1b	position of teeth	d	1
	1f	chewed roti	inf	1
	1h*	examples of food, combination of tastes	s→f	1
	1d*	role of water and mucus in saliva	s→f	1
	1i	function of saliva when finger is cut	inf	1
Oesophagus and stomach – description of structure	2j*	structure of stomach, function	s→f, pk, d	2
	2a*	describe walls of oesophagus	f→s, a	2
	2f*	effect of food landing on epiglottis	s→f, pk	1
	2c*	peristalsis in other organs	f→s, a	1
	2d	looks of epiglottis	pk, d	1
	2h*	idea of 'mucus'	f→s	1
	2e*	what if epiglottis not there	s→f, t	1
	2b*	drawing of food pushed through food pipe	s→f, t, pk, d	1
	2i*	what if no mucus	s→f, t	1
	2g*	role of gland	f→s, t	2

Key: s→f: structure to function, f→s: function to structure, inf: inference, t: transformational reasoning, a: analogy, pk: prior knowledge, d: diagram

Table 5.14b. Nature of Part 2B questions for the digestive system

Passage	Question number	Nature of question	What was tested	Maximum points tested
Mouth - description of function	1d	role of water and mucus in saliva	answer in passage	1
	1e*	what if hard and bony tongue	s→f, t	1
	1c*	shape, location, function of teeth	f→s, pk, d	12
	1g*	taste buds in tongue	s→f, pk	1
	1a*	diagrams of teeth	f→s, d, pk	4
	1f	Why does a chewed roti taste sweet?	inf	1
	1h	examples of food, combination of tastes	s→f	1
	1i	function of saliva when finger cut	inf	1
	1b*	action of teeth	d	1
Oesophagus and stomach: description of function	2h*	idea of 'mucus'	f→s	1
	2b*	drawing of food pushed through food pipe	f→s, t, pk, d	1
	2c*	peristalsis in other organs	f→s, a	1
	2f	effect of food landing on epiglottis	s→f, pk	1
	2i*	what if no mucus	s→f, t	1
	2j*	structure of stomach, function	s→f, pk	2
	2a*	describe walls of oesophagus	f→s, a	2
	2e*	what if epiglottis not there	s→f, t	1
	2d*	looks of epiglottis	pk, d	1
	2g*	role of gland	f→s, t	2

Key: s→f: structure to function, f→s: function to structure, inf: inference, t: transformational reasoning, a: analogy, pk: prior knowledge, d: diagram

Tables 5.14 a. and b. lists the nature of each question, what the question tested for, and the maximum possible score for each question of Parts 2A and 2B. The questions are arranged within each passage, according to the order of students' scores from the highest to the lowest scoring ones. Although the results (i.e. scores) are presented only in the next section, the ordering of Table 5.14 is done in anticipation in order of the scores, so as to facilitate matching between Tables 5.14 and 5.15. The questions themselves can be found in Appendix B.2.d.2.

The first column of Table 5.14 gives the question number, the second column recalls the question in brief and the third column indicates what was tested in that question. It is understood that all the questions called for inference (abbreviated inf). However since our focus was on questions that connected structure and function (s-f), the code 'inf' is used only for questions that required inference but did not involve s-f relationships. Directionality of the expected connection (structure to function: s→f or function to structure: f→s) as shown in the Table is notional. The reason is that although the information in the passages may have concerned predominantly structure or function, students did have prior knowledge of the content which could have complemented the content (with function or structure information respectively). The exercise of checking for the directionality of the link (s→f or f→s) was instructive because it showed up the parallels and differences in the tasks involving inferences drawn from the 'structure' and 'function' passages. For several of the questions the tasks were in fact identical for the two passages.

Questions probing transformational reasoning are marked as 't' and analogical thinking as 'a'. As stated before, all the questions may have tapped prior knowledge. However if the response was strongly suggested by the content of the Class 6 textbook, it is marked 'prior knowledge' (pk) in Table 5.14. Questions calling for diagrams are marked 'd'.

The last column of Table 5.14 shows how many aspects (points) were tested in that question. The score on that question was the proportion of the maximum number of points. The scores thus ranged from 0-1. The number of points are given against each question in Appendix C.2.d.2A and C.2.d.2B.

The procedure for determining inter-rater reliability was the same as that described in Part 1 (Section 5.5.3). Inter-rater reliability estimated through Spearman's rho was 0.75 ($p<0.01$) for the digestive system.

5.8.2 *Observations and results for Phase II Part 2: digestive system*

Tables 5.15 a and b list the mean scores for each question of the digestive system for

Parts 2A and 2B respectively. The questions are arranged within each passage from the highest to the lowest average scores. The following observations can be made from these scores.

Table 5.15 a: Mean scores for the digestive system: Part 2A

Passage	Q no.	What was tested	Mean score
Mouth - description of structure	1c*	s→f, pk, d	0.89
	1e*	s→f, t	0.82
	1g*	s→f, pk	0.80
	1a	f→s, pk, d	0.75
	1b	d	0.71
	1f	inf	0.60
	1h*	s→f	0.50
	1d*	s→f	0.45
	1i	inf	0.18
Oesophagus and stomach: decription of structure	2j*	s→f, pk, d	0.47
	2a*	f→s, a	0.47
	2f*	s→f, pk	0.45
	2c*	f→s, a	0.45
	2d	pk, d	0.36
	2h*	f→s	0.34
	2e*	s→f, t	0.32
	2b*	s→f, t, pk, d	0.32
	2i*	s→f, t	0.25
	2g*	f→s, t	0.16

Key: s→f: structure to function, f→s: function to structure, inf: inference, t: transformational reasoning, a: analogy, pk: prior knowledge, d: diagram

Table 5.15 b: Mean scores for the digestive system: Part 2B

Passage	Question number	What was tested	Mean score
Mouth - description of function	1d	answer in passage	0.97
	1e*	s→f, t	0.85
	1c*	f→s, pk, d	0.83
	1g*	s→f, pk	0.76
	1a*	f→s, d, pk	0.73
	1f	inf	0.44
	1h	s→f	0.41
	1i	inf	0.24
	1b*	d	0.18
Oesophagus and stomach: description of function	2h*	f→s	0.62
	2b*	f→s, t, pk, d	0.56
	2c*	f→s, a	0.56
	2f	s→f, pk	0.50
	2i*	s→f, t	0.50
	2j*	s→f, pk	0.49
	2a*	f→s, a	0.43
	2e*	s→f, t	0.41
	2d*	pk, d	0.38
	2g*	f→s, t	0.25

Key: s→f: structure to function, f→s: function to structure, inf: inference, t: transformational reasoning, a: analogy, pk: prior knowledge, d: diagram

Not surprisingly, questions calling for prior knowledge from the textbook were easier than those which were outside of the textbook. On the whole questions pertaining to Passage 1 were easier than those pertaining to Passage 2, a result that is discussed further along with Table 5.16. 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, the questions requiring transformational reasoning were most difficult, an exception being a question that asked students to imagine what would happen if the tongue, instead of being muscular, was hard and bony. Perhaps this question was possible to address based on one's everyday use of the muscular tongue. On the other hand the other questions requiring transformational reasoning 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.

Question Nos. 1b and 1c were the only questions which were differently phrased in the two versions of the passages. In Part 2A, the question 1c was: *"From the shape and location of each kind of tooth, what can you say about its function? Answer in the table given below. Draw diagrams if necessary."* The question was followed by a table in which the student had to fill details about the shape, location and function. In Part 2B, the question was modified as: *"From the function of each kind of tooth, can you guess its shape and location? Answer in the table given in the next page. Draw diagrams if necessary."* The mean scores for both questions were similar (0.89 and 0.83). The drawings of the four kinds of teeth are given in the Class 6 textbooks so it is not surprising that the students' scores were about the same in both versions of the passages. However, this was not the case for question 1b. The questions in both versions were: *"Draw a diagram to illustrate the position* (Part 2A) / *action* (Part 2B) of the different kinds of teeth". The mean score for Part 2A was 0.71 and for Part 2B was 0.18. Drawing a diagram from the structure passage was perhaps easier also because of familiarity as in the case of question 1c. Drawing a function diagram would require some imagination from the student especially since such diagrams are not common or familiar from their textbooks.

Question numbers calling for drawing inferences regarding structure-function relationships (which were in the majority) are marked with a * in Tables 5.15 a and b. Further quantitative analysis was done with the scores on these questions only. From the scores on these questions, mean s-f scores were calculated for Passage 1 and Passage 2. Wilcoxon's signed ranks test (a non parametric test used to check for differences in mean scores between paired samples) 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. The Mann Whitney U test is a non-parametric test to check for differences between mean scores for two independent samples. The results of this analysis are shown in Table 5.16.

Table 5.16: Effect of content on comprehension of 'structure' and 'function' passages

Mean scores and (s.d.)			
	2A (Structure version)	**2B (Function version)**	**Significance Mann Whitney U**
Passage 1 (mouth)	0.69 (0.20)	0.67 (0.19)	N.S.
Passage 2 (oesophagus and stomach)	0.36 (0.23)	0.47 (0.24)	$z = -2.0$, $p < 0.05$
Significance Wilcoxon Signed ranks test	$z = -5.7$, $p = 0.00$	$z = -3.7$, $p = 0.00$	

Table 5.16 shows that 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.

5.8.3 *Questionnaires for the respiratory system (Phase II Part 2)*

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 class level of the sample. Chemical aspects of respiration could not be probed in detail, so only mechanical action was considered. All students answered a single version of the test.

The first passage contained information on each organ of the respiratory system and its structural connection with other organs of the system. It was a somewhat more detailed version of the content in their textbook. Students had to understand the differences and relationships between the organs in terms of aspects of appearance such as shape and size as well as order of location. The information was not entirely new as they had previous exposure to a diagram of the respiratory system in their textbook. This was a predominantly 'structure' passage.

The second was a predominantly 'function' passage, which contained new information on the action taken by certain organs of the respiratory system in order to prevent the entry of dust and other foreign particles. Three mechanisms which help to achieve this: ciliary action, peristaltic motion of bronchioles and the cough reflex, were explained. The third passage was a short 'function' description of the changes that take place to the lungs and diaphragm during inhalation and exhalation.

Table 5.17: Nature of questions for Part 2 variables of the respiratory system

Passage	Q No	Nature of question	What was tested	Max points tested
Structure of the respiratory system	1a	draw respiratory organs mentioned in passage along with location with respect to each other	d, pk	9
	1c*	why is larynx located in the beginning?	s→f, t	1
	1b*	what if no pharynx or common passage before it divides into trachea and oesophagus?	s→f, t	1
	1d*	why trachea has soft as well as tough tissue	s→f, a	1
	1e*	why does trachea divide further and further until it reaches the alveoli	s→f	1
	1f*	what is a capillary	s→f, pk	2
Removal of foreign bodies in the upper respiratory passages	2e	difference between cough and sneeze	d, answer in passage	2
	2c	what is peristaltic motion of bronchioles?	s→f, a	1
	2a*	how do small and large particles get trapped or stuck in the mucus lining the respiratory passage?	s→f, d	2
	2d	how do you think peristaltic motion	s→f, a	1

Passage	Q No	Nature of question	What was tested	Max points tested
		could help in removing foreign particles?		
	2b*	what is meant by ciliary action?	s→f, d	1
Mechanics of Breathing	3b*	another object / process similar to appearance, functioning of lungs	s→f, a	1
	3c*	what would happen if no diaphragm in the respiratory system?	s→f, t	1
	3a*	how does a C S of lung look like?	f→s, d	1
	3d*	diagrams to show the differences between inspiration and expiration	f→s, d	4

Key: s→f: structure to function, f→s: function to structure, inf: inference, t: transformational reasoning, a: analogy, pk: prior knowledge, d: diagram

Tables 5.17 lists the nature of each question related to the passages on the respiratory system, what the question tested for, and the maximum possible score for each question. As before, the questions are arranged within each passage according to the order of students' scores from the highest to the lowest scoring ones in anticipation of the results presented in the next section to facilitate comparisons. The questions themselves can be found in Appendix B.2.r.2.

The first column of Table 5.17 gives the question number, the second column recalls the question in brief and the third column indicates what was tested in that question. As described for the digestive system, all questions called for drawing of inferences. Some of them required diagrams (marked as d). Again, the main thrust of the inferencing was towards finding structure-function relationships (s-f). As before the direction of the relationship was conjectured and is indicated in the Table but it was not taken into account in further analysis.

Some of the s-f questions involved transformational reasoning. An example of a question calling for transformational reasoning is: "What would happen if there was no pharynx or common passage before it divides into the trachea and oesophagus?" Some of the s-f questions required analogical thinking (marked as a). An example of such a question is: "Taking a clue from what we have seen in the case of the digestive system, what do you understand by the peristaltic motion of the bronchioles?" Questions probing analogical thinking are designated as 'a'.

Prior knowledge of the school textbook content on the respiratory system may have facilitated all the responses. Only where the response was strongly suggested by the content of the Class 6 textbook it is marked 'prior knowledge' (indicated as pk).

The last column of Table 5.17 shows how many aspects (points) were tested in that question. The score on that question was the proportion of the maximum number of points. The scores thus ranged from 0-1. The number of points are given against each question in Appendix C.2.r.2.

The procedure for determining inter-rater reliability was the same as that described in Part 1 (Section 5.5.3). Inter-rater reliability estimated through Spearman's rho was 0.76 ($p<0.01$) for the respiratory system Part 2.

5.8.4 *Observations and results for Part 2 of the Respiratory system*

Table 5.18 shows the mean scores for each question of Part 2.

Table 5.18: Mean scores and maximum scores for Part 2 of the respiratory system

Passage	Q No	What was tested	Mean Score
Structure of the respiratory system	1a	d, pk	0.58
	1c*	s→f, t	0.57
	1b*	s→f, t	0.35
	1d*	s→f, a	0.30
	1e*	s→f	0.22
	1f*	s→f, pk	0.20
Removal of foreign bodies in the upper respiratory passages	2e	d, answer in passage	0.61
	2c	s→f, a	0.30
	2a*	s→f, d	0.25
	2d	s→f, a	0.22
	2b*	s→f, d	0.11
Mechanics of Breathing	3b*	s→f, a	0.37
	3c*	s→f, t	0.35
	3a*	f→s, d	0.22
	3d*	f→s, d	0.13

Key: s→f: structure to function, f→s: function to structure, inf: inference, t: transformational reasoning, a: analogy, pk: prior knowledge, d: diagram

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 for students. Except for question 1a which required drawing of the respiratory organs, the other 'diagram' questions were difficult for students. The respiratory organs are mentioned in the school textbooks and are therefore familiar to students. The 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 were easier for students compared to passage 2 and 3 about functional aspects. Question 2b on ciliary action was the most difficult for students (mean score 0.11) followed by mechanics of breathing (passage 3). In general, students did not have a clear conception about the bronchioles, alveoli and capillaries.

Further quantitative analysis was done with the scores on questions marked with a * in Tables 5.18. These included the questions calling for inferences regarding structure-function relationships from the passages. Two of the s-f questions in Table 5.18 which called for analogical reasoning, but based on information not in the passages (peristaltic motion of the bronchioles) are not included in the s-f score. The mean s-f score for each passage was thus calculated and the Wilcoxon's signed ranks test was used to check for difference in the mean scores between the passages. Tables 5.19 and 5.20 show the results of this analysis.

Table 5.19: Mean scores and standard deviations for passages in Part 2 of the respiratory system

Passage no.	Mean score	Standard deviation
Passage 1	0.33	0.26
Passage 2	0.18	0.27
Passage 3	0.26	0.26

Table 5.20: Wilcoxon's tests between mean scores across passages in Part 2 of the respiratory system

Tests done between Part 2 S-F scores	Z scores	Significance level
Passage 1 and 2	-3.228	0.00
Passage 1 and 3	-1.938	0.05
Passage 2 and 3	-1.791	0.07

Table 5.19 indicates that the mean score was lowest on Passage 2, which had to do with respiratory functions related to the removal of foreign bodies from air. The difference between mean scores on Passages 2 and 3 (the two `function' passages) was not significant at the 0.05 level as seen by the Wilcoxon's signed ranks test (Table 5.20). Passage 1 which dealt with the structure of the respiratory system was the easiest; we have noted already that it was the closest in content to the textbook for Class 6.

5.9 *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 micro level. This final part of the study has a direct bearing on pedagogic practice.

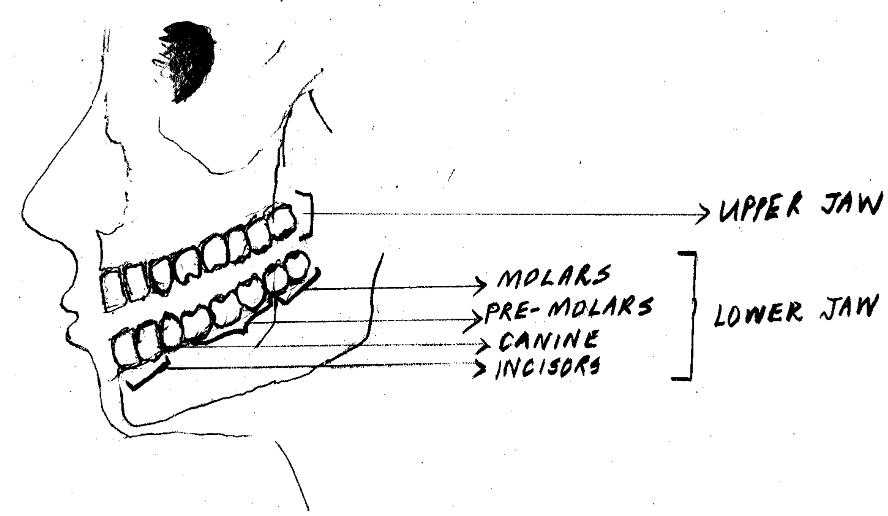
This part of the study addressed Research questions no II/6 and II/7 on students' understanding of structure-function relationships through diagrams, and the implications that can be drawn for pedagogy. Pedagogical implications are discussed in further detail in Chapter 6.

5.9.1 *Questionnaires for the digestive system*

There were two questionnaires for the digestive system: Parts 3A and 3B. Part 3A consisted of four tasks (Tasks 1-4) which used 3d structure diagrams. Part 3B had three tasks (Tasks 5-7) which made use of function diagrams.

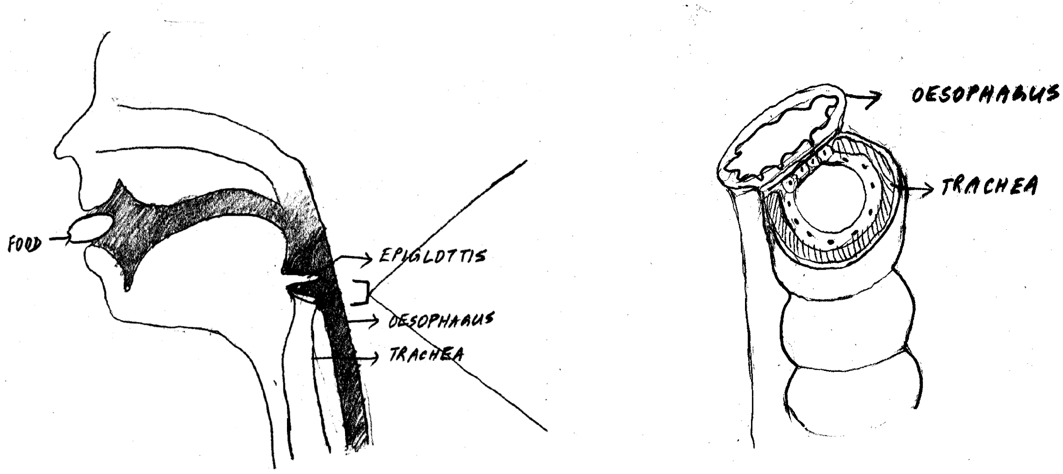
Tasks 1 and 3 involved comprehension of structure diagrams concerning placement of teeth in the jaw, and positioning and cross-sections of the oesophagus and trachea. Task 2 required examining the cross-section of an electric cable. Task 4 required students to draw a diagram of the small intestine based on a description. Task 5 was a precursor question to Task 6 which 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). Tasks 1-4 were administered to 75 students and Tasks 5-7 to 73 students of the Phase II sample. The questionnaires can be found in Appendix B.2.d.3. A brief description of each task is given below along with the diagrams given to students in these tasks (Figures 5.8 to 5.11).

Figure 5.8: Orientation and arrangement of teeth in lateral view of jaw (Task 1)



Task 1 showed a diagram of a skull of a girl in profile (Figure 5.8) with a short conversation cited between the dentist and her asking her to open her mouth wide. Students were asked to draw what the dentist sees from his viewpoint using a given diagrammatic hint (two curves indicating the jaw).

Figure 5.9: Depiction of structure and function at the micro level: Detail of trachea and oesophagus (Task 3)



In Task 2, students were provided with an electric cable holding three covered wires, and asked questions relating to cross-sections. The purpose of this task was to orient the students towards the notion of cross-section in a situation that was visible to them. In Task 3 they had to use their knowledge of cross-sections (possibly gained from the previous task) to understand the cross-sections of the trachea and oesophagus (shown in Figure 5.9). They also had to re-draw one of the diagrams but after indicating the changes that take place to the position of the epiglottis while breathing in, out, and while choking.

Task 4 required students to convert a short passage describing the small intestine and 'villi', which are the absorptive units in it, into a diagram of a cross-section of the small intestine. Task 5, the first task in Part 3B, asked students about where the food goes after it is digested in the stomach and reaches the small intestine. It served as a precursor to the next task on the fate of the digested food in the large intestine.

Figure 5.10: Depiction of structure and function at the macro level: Cartoon of the large intestine (Task 6)

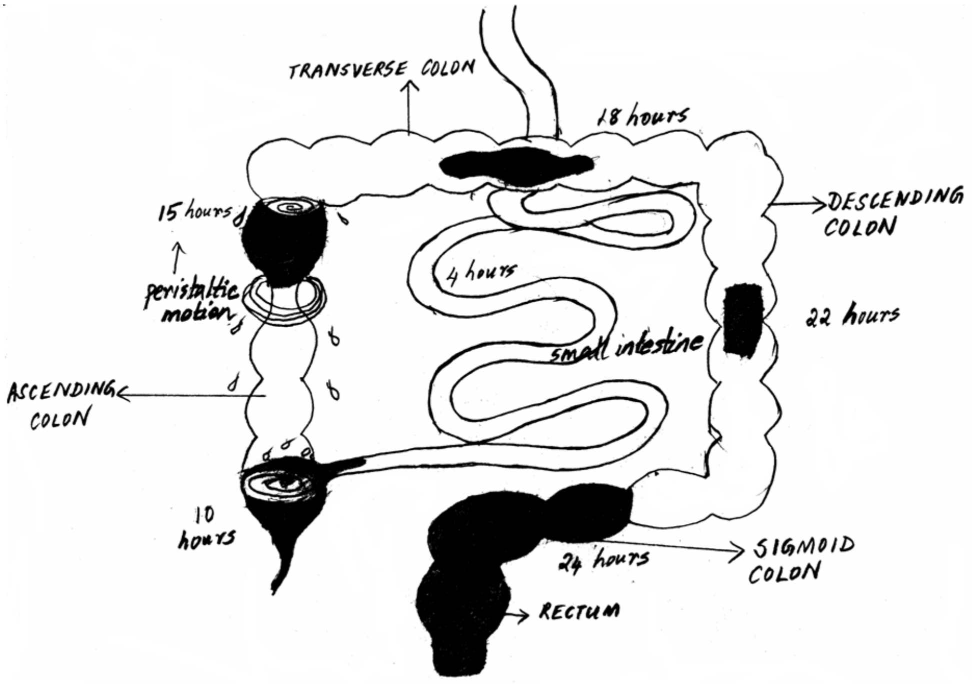
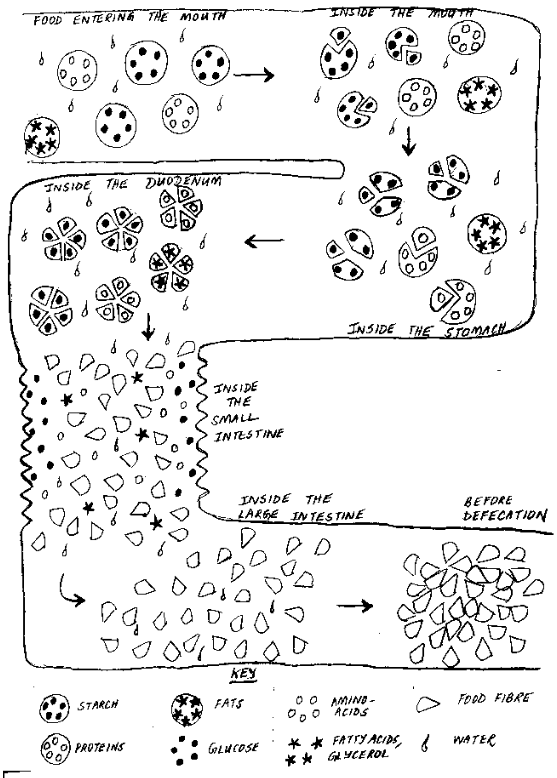


Figure 5.11: A 'function' diagram of digestion (Task 7)



Task 6 related to macroscopic aspects of function of the large intestines. It required students to comprehend a diagram of the large intestine (shown in Figure 5.10), which used annotations for time and condition of food at various points along its journey through this organ. Task 7 was more complex, depicting the chemical changes that take place during the entire process of digestion using symbols, which in turn had to be interpreted using a key (Figure 5.11).

The procedure for determining inter-rater reliability was the same as that described in Part 1 (Section 5.5.3). Inter-rater reliability estimated through Spearman's rho was 0.73 ($p<0.05$) for Part 3A and 0.82 ($p<0.01$) for Part 3B of the digestive system.

5.9.2 *Observations and results for Part 3 of the digestive system*

The criteria for Part 3 analysis is given in Appendix C.2.d.3A and C.2.d.3B. Table 5.21 and 5.22 show the mean scores, maximum scores, nature of question and what was tested for in each question for Parts 3A (Tasks 1-4) and 3B (Tasks 5-7) respectively.

Table 5.21: Digestive System Phase II Part 3A (predominantly structure diagrams): Mean scores, maximum scores, nature of questions and what was tested

Task	Q No	Mean score	Max. score	Nature of question	What was tested
1. Placement of teeth	1a*	0.88	1	drawing Divya's teeth from a top view	t, p, d
	1c*	0.70	4	describing shapes of different kinds of teeth, and how each is different from the other	pk
	1d*	0.70	4	function of each tooth	s→f, pk
	1b*	0.44	13	counting Divya's teeth, different kinds and their number	p, d
	1f*	0.44	1	how many teeth do you have?	e
	1e*	0.34	4	Structure-function relationships for each kind of tooth	s→f, pk
	1i*	0.34	2	teeth falling off in old age, reason	s→f, e, d
	1h*	0.31	2	why did we lose milk teeth? How are milk teeth diff from permanent ones?	s→f, e
	1g*	0.22	1	when will you get teeth you do not have?	e
2. Cross-section of wire	2c*	0.55	1	draw and label the cross section of the given wire	m, d
	2d*	0.47	1	example of CS from everyday life	m, a, e
	2e*	0.42	1	what more information from CS, compared to whole object	m
	2b*	0.40	1	why are cross sections drawn in diagrams	m
	2a*	0.29	1	what is a cross section	m
3. Trachea and oesophagus	3a*	0.31	3	another drawing of CS of trachea and oesophagus from normal breathing	d
	3b*	0.29	3	appearance of trachea and oesophagus while swallowing a mouthful of food	f→s, t, d
	3c*	0.23	1	diagram for choking while swallowing food	f→s, t, d
4. Small Intestine	4a*	0.07	1	cross-section of the small intestine	d

Key: s→f: structure to function, f→s: function to structure, inf: inference, t: transformational reasoning, a: analogy, p: perspective, m: model, e: experience, pk: prior knowledge, d: diagram

The questions accompanying each task are indicated in Table 5.21 and 5.22. The first column gives the task. The second column refers to the questions numbers within each task. The questions are arranged within each task from the lowest to the highest scoring ones as per the mean scores in the third column. The fourth column shows the maximum number of points which a student could get for each question depending on the number of aspects tested for. The final score is a proportion of the points obtained by the student and the maximum number of points on that question. This procedure is the same as that followed for scoring in Part 2.

As in Part 2, all the questions required inferences, most of which focused on relating of structure with function. In addition, the questions addressed aspects unique to diagram comprehension and production. There were five questions requiring diagram production, marked as 'd' in Table 5.21. Most of the questions involved comprehension and inferencing from the given diagrams, the exceptions being some questions in Task 1 (f-i), which related to students' everyday experiences (marked 'e'), and questions in Task 2, which required inferencing from a model (marked 'm' in Table 5.21). Questions in Tasks 1 and 3 (Table 5.21) required inferencing from the given 3d structural diagrams. In Tasks 6 and 7, the inferencing from diagrams, had to be done with the help of labels (Task 6) and key (Task 7) (Table 5.22).

Comparing the questions within Task 1, questions requiring change of perspective were the easiest, followed by questions requiring prior knowledge from the textbook. Thus, once the arrangement of teeth from a side-view was known, students were able to transform to a top view quite easily. The most difficult were the questions requiring inference from everyday experience which were not in the textbook. Questions relating to the shapes and function of each kind of tooth were relatively easy. This is not surprising since this is given in their textbooks. Predictions about function based on structure were more difficult.

Within Task 2, the relatively straightforward question about drawing and labeling the cross-section of the given wire was answered correctly by 55% of students. The later questions which needed more articulation were answered correctly by fewer students.

Only 29% students could say what is a cross-section. These results show that a large number of students had difficulty with understanding the concept of cross-sections.

All the three sub-questions within Task 3 required students to draw diagrams. For the first question, the majority of students did not realise that they could have copied the diagram that was already given. Although the caption of the diagram said that it showed the cross-section of the trachea and oesophagus during normal breathing, students did not pay attention to this information. The other two questions which required transformational reasoning (inferring structure from function) were found to be more difficult for students. The only question in Task 4 was difficult for students (mean score: 0.07) since they had to draw a cross-sectional diagram which they may not have encountered before, from a purely verbal description. Table 5.22 shows the scores for Part 3b (Tasks 5-7).

Table 5.22: Digestive system Phase II, Part 3B (predominantly function diagrams): Mean scores, maximum scores, nature of questions and what was tested for

Task	Q No	Mean Score	Max score	Nature of question	What was tested
Digested food in the small instestine	5*	0.93	3	Digestion and absorption in the SI, where does it go from SI	pk
Role of the large intestine	6a*	0.93	1	connection between SI and LI	f→s, pk
	6e*	0.81	1	In which part of LI would peristalsis occur?	f→s
	6d*	0.71	1	meaning of peristaltic motion	s→f
	6f*	0.70	11	state of food in each region of the large intestine, part reached after given pointers to time	f→s, pk
	6c*	0.62	1	meaning of time labels	l
	6j*	0.58	1	if peristaltic motion is faster, then what result?	t
	6g*	0.55	3	how does food material change in the large intestine, which parts get absorbed	f→s
	6h*	0.54	2	what is faeces composed of, how does LI help in faeces formation	s→f
	6l*	0.47	1	where else does peristalsis occur?	f→s, a
	6k*	0.37	2	how does peristaltic motion happen in the large intestine?	s→f, d
	6i*	0.32	1	if food stays in large intestine for	e

Task	Q No	Mean Score	Max score	Nature of question	What was tested
				longer than normal time, what result?	
	6b*	0.20	4	meanings of labels for the different regions of the LI	l
Schematic diagram of digestion	7a*	0.88	3	what components of food are shown being taken in through mouth?	s→f
	7b*	0.70	2	what changes are shown happening in the mouth? Why?	s→f
	7i*	0.68	1	what components are being excreted?	f→s
	7h*	0.55	1	what components absorbed in large intestine?	f→s
	7f*	0.40	2	what components absorbed in small intestine?	f→s
	7c*	0.38	2	what changes shown happening in the stomach? Why?	s→f
	7d*	0.34	2	what changes shown happening in the duodenum? Why?	s→f
	7e*	0.33	2	what changes in SI and why? Why?	s→f
	7g*	0.30	2	what changes in LI? Why?	s→f
	7j	0.08	1	draw an alternative diagram which may better represent what happens	d

Key: s→f: structure to function, f→s: function to structure, t: transformational reasoning, a: analogy, e: experience, pk: prior knowledge, d: diagram, l: label

Task 5 was based entirely on prior knowledge. It's aim was to check whether students knew about digestion in the small intestine and its connection with the large intestine. An overwhelming majority of students answered this question correctly. It is interesting that in Part 1, the same students were confused about the connection between the small and large intestine. Perhaps they resolved this confusion by looking at the diagram for Task 6 (Fig. 5.10) which was prominently given on the same page as Task 5.

Tasks 6 and 7 (Figures 5.10 and 5.11) were particularly interesting because they were meant to convey function. Within Task 6, questions on peristaltic motion which were directly connected to the given diagram and text were relatively easy. Recall that in Part 2, students had some difficulty with questions on peristaltic motion for the digestive system as well as the respiratory system. It seems that similar difficulties were encountered in Part 3 also for the questions which required analogical thinking and drawing diagrams. Of the two questions requiring understanding of labels, the one related to time labels was easier than the question on labels referring to regions of the large intestine (ascending, transverse, descending and sigmoid) which were found to be uninterpretable by the majority of students.

Task 7 (Figure 5.11) referred to 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 (question numbers: 7a, 7b and 7i) were comprehended better than the portions in the middle (stomach to large intestine). 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.

In all the Tasks, questions requiring prior knowledge from the textbook were easier compared to those on inference-making.

Table 5.23 gives a brief summary of each task, the number of questions included in each and the mean overall score for each Task. In calculating the mean overall score for Task 7, the question 7j alone was excluded since only one or two students even attempted that question. As before all the questions included in calculation of the overall mean scores are marked with a *.

Table 5.23: Summary of tasks in Parts 3A and 3B

Task no.	Description	Diagram given (Yes/No)	Number of sub-questions	Mean Score and (s.d.)
1	Orientation and arrangement of teeth in lateral (Figure 5.8) and top views of the jaw	Yes	9	0.48 (0.23)
2	Meaning of 'cross-section' and cross-sectional view of a given electric cable	No	5	0.42 (0.34)
3	Location and cross-sections of oesophagus and trachea (Figure 5.9)	Yes	3	0.23 (0.31)
4	Description of villi	No	1	0.07 (0.35)
5	Question about fate of food after digestion in stomach	No	1	0.93 (0.5)
6	Working of the large intestine (Figure 5.10)	Yes	11	0.46 (0.17)
7	Chemical action in the digestive tract (Figure 5.11)	Yes	9	0.41 (0.24)

The most difficult of the tasks in which diagrams were given was Task No.3 (Figure 5.9), involving comprehension of a magnified view. Part of this difficulty may have been in understanding of the idea of cross-section (Task 2) which was tested separately in Task 3. 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. Tasks 1, 2, 6 and 7 turned out to be of moderate difficulty.

In Part 3B, questions on comprehension of labels (Task 6) were clearly easier than those requiring comprehension of the key (Task 7). In particular questions dealing with comprehension of chemical digestion in the duodenum and facilitated by the liver and pancreas were particularly difficult confirming the result found earlier in Phase I and in Phase II, Part 1.

5.9.3 *Questionnaire for the respiratory system*

For the respiratory system, two tasks were prepared, both involving detailed diagrammatic representations. The first task contained predominantly structure diagrams, and the second task contained predominantly function diagrams. The tasks are detailed in the Appendix B.2.r.3.

The first task dealt with the structure of the respiratory system at three successive levels of detail (Figure 5.12). This task was composed of three diagrams. The first part of the diagram (showing the trachea, bronchi, bronchioles, lungs and alveoli) led to the second one (an enlarged cross-section of the alveolus) using the mechanism of zooming in. The second was a magnified diagram showing gas exchange in an alveolus and the point of contact between the oxygenated and deoxygenated blood in the capillaries. The third diagram showed an enlarged bronchiole with details of the alveolus.

The second task related to the changes which take place to the diaphragm and lungs during the processes of inspiration and expiration (Figure 5.13). Students had to infer about the role of each organ of the respiratory system in the process of gas exchange and tabulate it in the table.

Figure 5.12: Predominantly structure diagram showing gas exchange in an alveolus

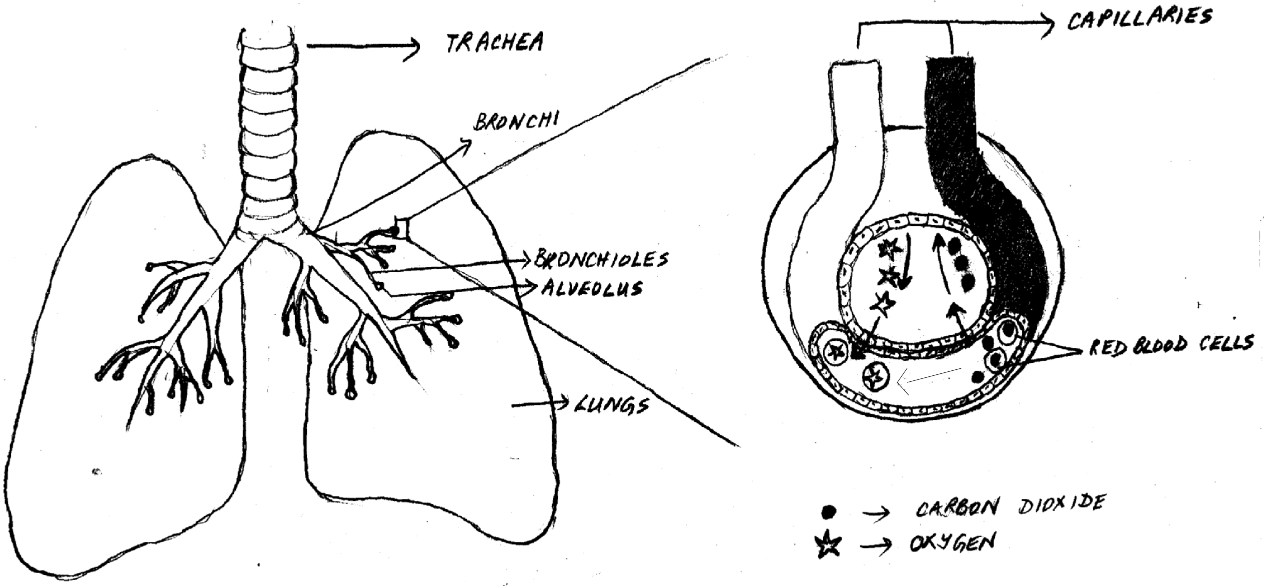


Fig 3 An enlarged bronchiole showing the alveoli

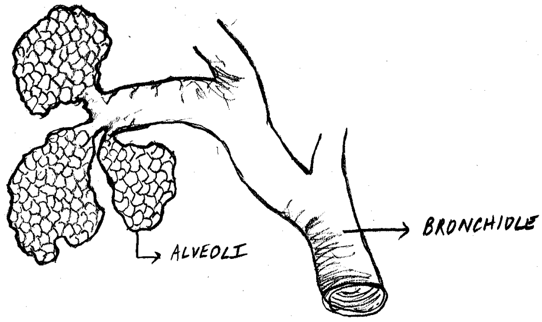
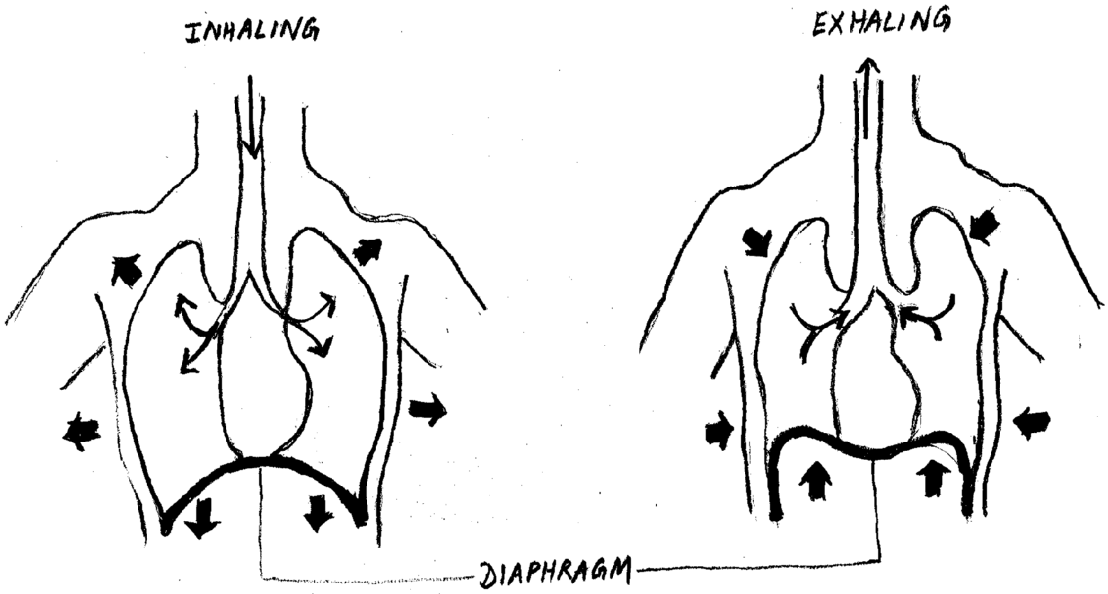


Figure 5.13: Predominantly function diagram showing mechanics of respiration

Fig 4 **Fig 5**



The procedure for determining inter-rater reliability was the same as that described in Part 1 (Section 5.5.3). Inter-rater reliability estimated through Spearman's rho was 0.98 ($p<0.01$) for Part 3 of the respiratory system.

5.9.4 *Observations and results for Part 3 of the respiratory system*

Table 5.24 gives the mean scores, maximum scores, nature of question and what was tested for each question.

Table 5.24: Mean scores, maximum scores, nature of question and what was tested for tasks in Part 3 of the respiratory system

Task	Q No	Mean Score	Max score	Nature of question	What was tested	Mean score (s.d.)
Structure of respiratory system, gas exchange in alveolus	1a*	0.74	15	location, structure and function of organs in the respiratory system	s→f, a	0.48 (0.26)
	1d*	0.54	2	role of Oxygen	s→f	
	1b*	0.48	1	meaning of term	s→f	

Task	Q No	Mean Score	Max score	Nature of question	What was tested	Mean score (s.d.)
				'exchange of gases'		
	1e*	0.45	2	role of Carbon dioxide	s→f	
	1c*	0.19	2	what is a capillary?	f→s, pk	
Mechanics of breathing	2a*	0.45	4	changes during inhalation, exhalation	s→f	0.37 (0.28)

Key: s→f: structure to function, f→s: function to structure, inf: inference, t: transformational reasoning, a: analogy, pk: prior knowledge

The structure of Table 5.24 is the same as the structure of (described earlier) Tables 5.21 and 5.22. The questions in the second column are arranged within each task, from the highest to the lowest scoring question as per the mean scores in the third column. The maximum number of points which the student could get is given in the third column. The score that the student could obtain is a proportion of the obtained points for that question and the maximum number of points. The last column gives the overall mean score for each task.

All the questions required comprehension and inferencing from the given diagrams. Most of these questions focused on relating of structure with function. The abbreviations for structure-function relationships (sf), prior knowledge (pk) and inference-making alone (inf) are as in the previous tables. All the questions were taken into account for calculation of overall mean scores for each task.

In the first task, question 1a involving predominantly structure diagrams of the respiratory system was the easiest. Questions 1b, 1d and 1e which related to chemical action were more difficult. The score on question 1c about the capillary was interesting. The capillary is explained in textbooks along with its difference from the artery and vein (the other two blood vessels). However from Phase I, we found that this was an area of conceptual difficulty for students. Question 1d about the role of Oxygen is easier compared to the role of Carbon dioxide. The second task had only two questions: 2a required interpretation of a diagram on the mechanics of respiration. This was easier compared to question 2b which required inference-making about the position of the heart.

Across the tasks, basic difficulties such as understanding the role of each organ involved in respiration, specially the alveolus and diaphragm, interfered with comprehension of diagrams dealing with them. The changes which take place in the diaphragm and lungs during inspiration and expiration are logically connected to each other: an error in one aspect leading to erroneous responses for others.

5.10 *Students' facility with diagrams*

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. As mentioned in Table 5.1, we did not give them an outline of the human body in order to encourage more variety in the kinds of depictions. However, contrary to what we expected, many of the students in Phase II did not draw diagrams or come up with a variety of diagrams, There weren't distinct structure and function diagrams, although a few students did make use of arrows and box diagrams linking concepts.

There was more variety in the diagrams drawn by students in Part 1 though overall about 36% students did not draw diagrams for the digestive system, and 32% students did not draw diagrams for the respiratory system. Part 1 tested for basic knowledge from prior understanding of mostly textbook content. Parts 2 and 3 had fewer diagrams since there were constraints and students were asked to draw in response to specific questions. In Part 3, where diagrams were given to them, some students made copies or slightly modified the given diagrams instead of producing anything new or different. Figures 5.14 to 5.16 are examples of diagrams drawn in Part 1, whereas Figures 5.17 to 5.19 are examples of diagrams drawn in Part 2.

As in Phase I, diagrams proved to be a useful tool in bringing out their alternative conceptions. Examples of such diagrams are shown in Figures: 5.14 to 5.16.

Figure 5.14: Student's diagram showing a structural connection from the stomach to the large intestine

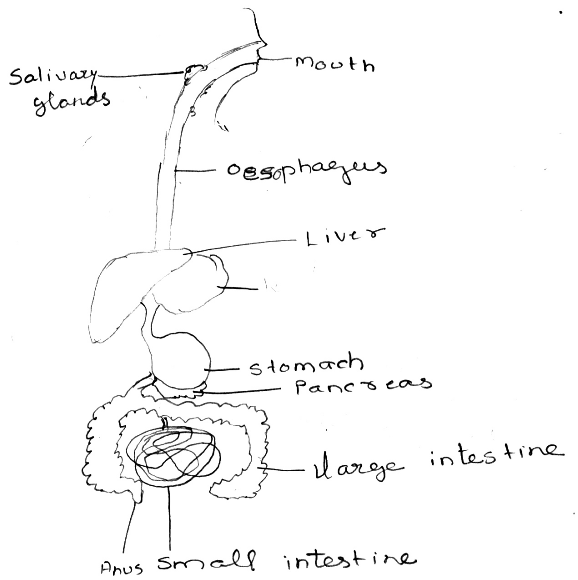


Figure 5.15: Student's representation of the structure of the respiratory system showing the important organs and a thick diaphragm unlike that shown in textbook diagrams, indicating his understanding of a plate-like structure of the diaphragm

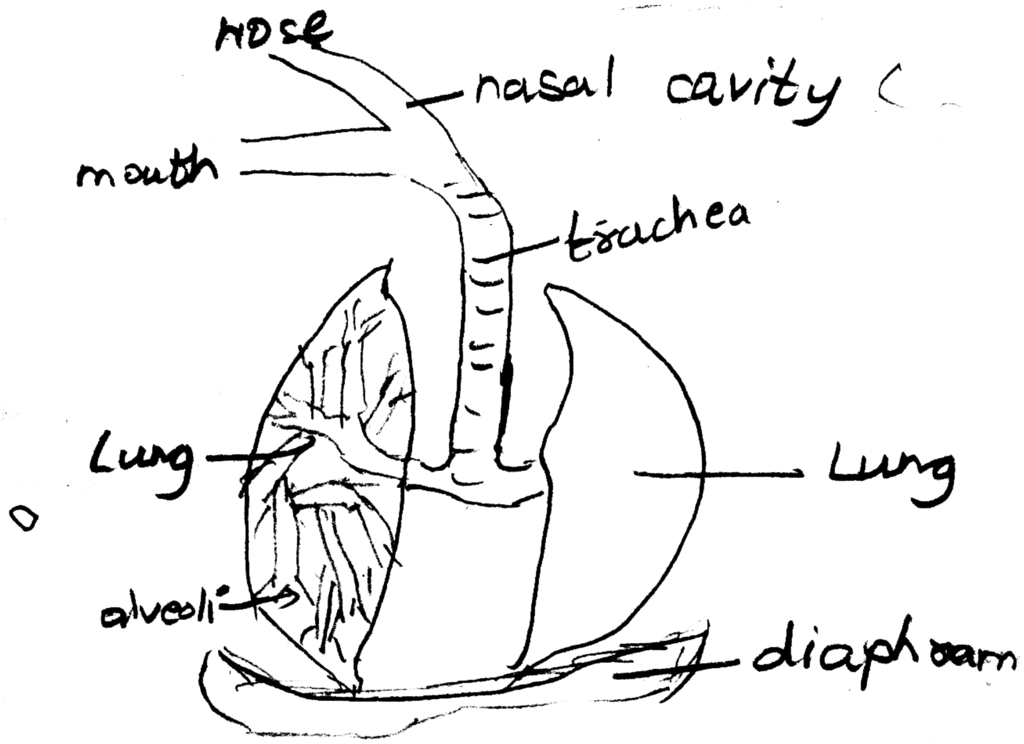
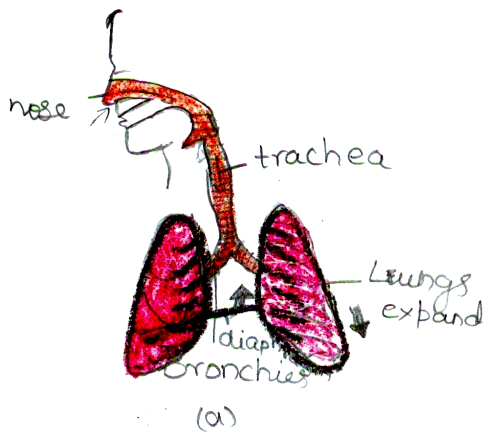


Figure 5.16: Student's representation of the processes of inspiration and expiration with corresponding changes in the lungs and diaphragm



There were also some interesting diagrams specially pertaining to the structure and function of various kinds of teeth. Examples are given in figures: 5.17 to 5.19.

Figure 5.17: Student's diagram showing different kinds of teeth and its location using a key

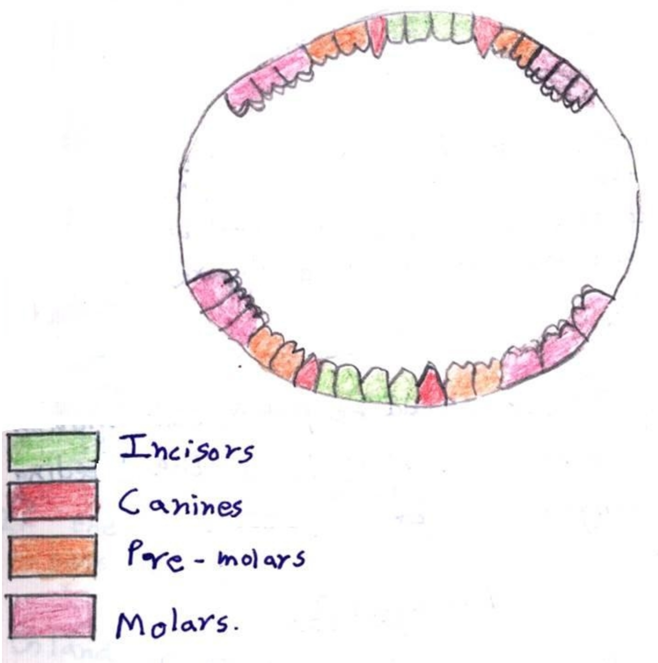


Figure 5.18: Student's diagram showing the condition of food after mastication by different kinds of teeth

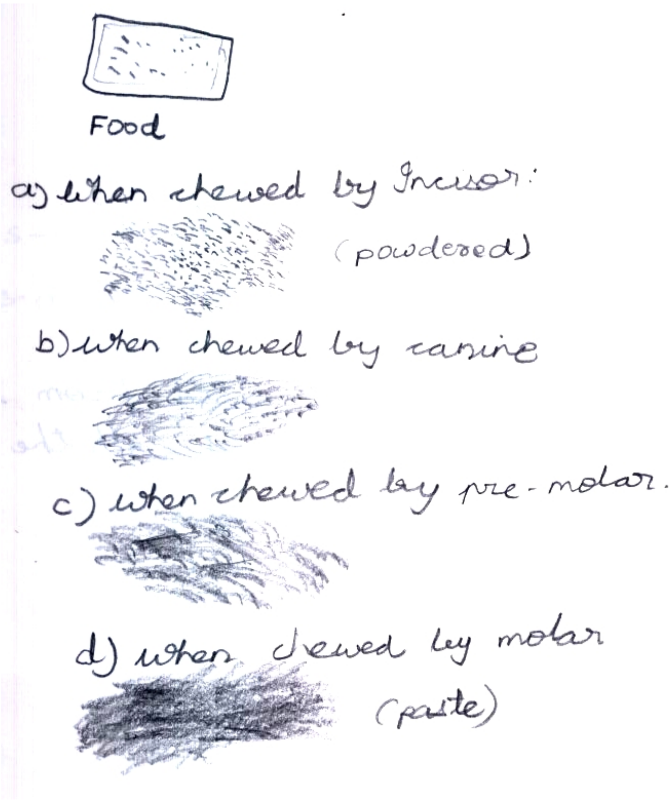
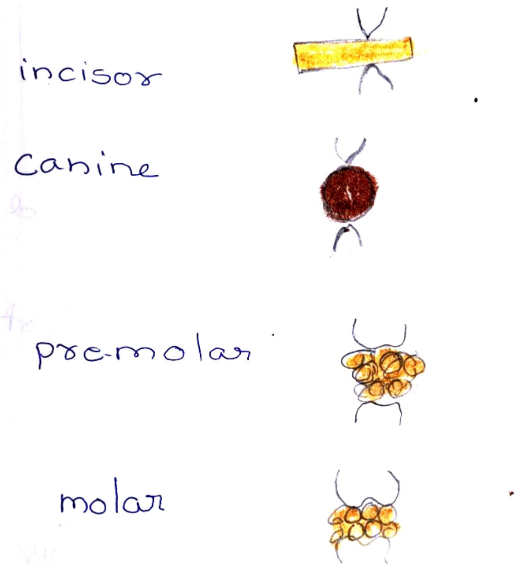


Figure 5.19: Student's diagram showing the relation between kind of food and teeth in the process of chewing. However there is no obvious difference between the incisors and canines and between the premolars and molars



5.11 *Overall observations on students' responses to the three Phase II questionnaires*

5.11.1 *Basic knowledge*

The majority of students possessed a reasonably good basic knowledge of the digestive system and a somewhat less adequate knowledge of the respiratory system. They expressed this knowledge mostly through text. A number of students did not draw diagrams. For those who did draw diagrams, there was a significant correspondence (i.e. high correlation) between their scores (on structure as well as function) expressed through text and through diagrams. Scores on structure were significantly higher than those on function except in the case of diagrams of the digestive system.

For Parts 2 and 3, questions involving inference making, and transformational reasoning, were relatively more difficult.

Frequency distributions of scores on the digestive system showed sub-populations of students who had different alternative conceptions depending on whether they had low, medium or high scores. For the respiratory system difficulties in understanding were homogenous across the student groups. The alternative conceptions seen in Phase I were also seen in Phase II.

5.11.2 *Visualisation*

Visualisation scores for the digestive system were significantly higher than for the respiratory system. Responses to the visualisation questions reflected basic difficulties in understanding of the systems.

5.11.3 *Comprehension of Structure-Function relationships from text*

We found that the content-related aspects predominantly influenced students' performance. Students were more competent at answering questions calling for prior knowledge from the textbook than those which were outside of the textbook. They found it relatively more difficult to answer questions requiring transformational reasoning.

5.11.4 *Comprehension of structure-function relationships from diagrams*

The most difficult tasks related to unfamiliar organs, cross-sections, microscopic or chemical processes and structure-function relationships. These difficulties were related to content knowledge as well as the conventions used in each of the diagrams which students had perhaps not encountered before at least in the context of biology.

5.11.5 *Qualitative characteristics of students' diagrams*

In the limited variety number and variety of diagrams from in the Phase II sample we found that most students did not distinguish between a structure and function diagram. Function was often represented as functional description or annotations accompanying a structure diagram or a sequence of parts along with a verbal description near it. A few students used arrows or schematic flow diagrams. Some diagrams proved to be useful in bringing out alternative conceptions.

5.12 *Comparison of students' performance in Phase I and the three Parts of Phase II*

Table 5.25 shows a comparison of mean scores between Phases I and II and further between the three Parts of Phase II. Phase I tested for understanding of basic knowledge alone. Part 1 of Phase II consisted of open-ended questions and spontaneous expression through diagrams or words as students wished. It also consisted of visualisation questions which required transformational reasoning and were assessed separately. Parts 2 and 3 required comprehension and inference-making slightly beyond the textbook content.

Table 5.25: Comparison of mean scores across Phase I and II

System	Phase I Exploratory Phase	Phase II			
		Part 1 Basic knowledge	Part 1 Visualisation	Part 2 Inference from text	Part 3 Inference from diagrams
Digestive	0.66	0.50	0.57	0.55	0.44
Respiratory	0.66	0.27	0.22	0.26	0.38
Circulatory	0.73	--			
Mean of Digestive and Respiratory systems	0.66	0.39	0.4	0.41	0.41

Table 5.25 shows that there were clearly high scores for Phase I compared to Phase II. The difference in the socio-economic background of the students in the two Phases could have led to this result (This aspect is further elaborated in Section 6.1.) Within Phase II, there were similar overall mean scores for the digestive and respiratory systems combined, across the three parts. The visualisation scores, inference from text and inference from diagrams tended to follow the basic knowledge scores, being higher for the digestive system. This result in turn is linked to more detail in the textbook content.

For the digestive system, about 32% of the students had similar scores across Parts 1, 2 and 3. A minority (5%) had all high scores: these were students who most successfully integrated structure with function through text and diagrams, in familiar as well as in new situations. About 11% students had all low scores while another 11% had high scores in Part 1 but low in Parts 2 and 3. Surprisingly there were some students (7%) who scored low in Part 1 but high in Parts 2 and 3. Perhaps these students were not good with their school learning, but given new content, they could work with it. It is also possible that some of these students worked with diagrams at a perceptual level without relating them to their conceptual understanding of the system as a whole.

We found that for the digestive system, five percent of the students had high verbal scores but relatively low drawing scores. These students showed a clearly higher ability for working with text over diagrams. They might be 'verbal' in their cognitive style. No corresponding group was found with a predominantly 'visual' style, i.e. good at diagrams rather than text.

Students found questions which required transformational reasoning (visualisation questions in Part 1, and a few questions in Parts 2 and 3) to be relatively more difficult. Prior knowledge of content was an important factor shaping students' responses to these questions. Unfamiliarity with handling new situations could be another factor which led to difficulty in answering such questions. Most outcomes of this reasoning process could be expressed adequately through verbal responses thereby giving students who were not skilled in diagram drawing a level of comfort in handling such questions, while also indicating that mental visualisation may not be dependent on drawing skill.

The results suggest quite overwhelmingly, the lack of visual or diagrammatic literacy among the large majority of students with a few exceptions. Even tasks requiring transformational reasoning show up in greater verbal than diagrammatic outcomes. Good understanding of the body system follows from an integrated knowledge of visual and propositional content as the high scorers in this study were able to achieve.

6 | *Chapter 6: Conclusions and discussion*

Table of Contents

In this chapter, we first place our findings within the overall socio-cultural context in India. Then we assess the contribution of this thesis to research on visualisation, in terms of our theoretical framework and the methodology that arose out of it, and then our results on students' understanding, inference, mental visualisation and facility with drawings. We discuss the textbook content for Classes 6, 7 and 8 with reference to the three human body systems and locate some of students' problems to the treatment of these topics in their textbooks. We end with pedagogical implications for the study of biology and development of visualisation abilities in school students.

6.1 *Socio cultural context*

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. Though the situation is changing somewhat, exposure to carefully designed, informative and educative visuals remains low. Through the mass media students are exposed to a large number of visuals, but perhaps in a passive manner, often serving the purpose of entertainment alone.

In Section 2.10 we reviewed some literature on the socio-cultural context of visuals. In oral cultures exposure to pictures comes about through schooling. A study by Liddell (1997) showed up the limitations faced by South African children due to lack of exposure to pictorial conventions in the early school years. South African children were found to use pictures in a passive form; labelling and linking associated with picture interpretation progressively decreased through the school years.

Students who participated in our study went to government-run schools on the same campus and following the same curriculum. 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. In Phase I, students' mean scores across all the criteria for analysis were high, and quantitative analyses did not indicate a distinct preference or facility with text or diagrams. Most students were apparently competent in both modes. A few of them even attempted schematic diagrams making use of conventions for function. They also appeared to be very competitive in their approach, tending to prepare ahead of our tests, after getting an initial feel of the kind of questions that were being asked. During the interviews, most of them were quite articulate and keen to receive feedback on their responses. [2]

In Phase II, though a few students were competent with both text and diagrams, more than a third preferred expression solely through text. Diagrams did not show the rich variety we obtained in Phase I. Students were also not as competitive or keen to understand their mistakes unlike the Phase I students. The better performance on the respiratory system in Phase I as compared to Phase II, was perhaps because of the Phase II sample who prepared ahead of the administration of the respiratory system questionnaire after getting an initial feel of the digestive system questionnaire.

One of the striking findings of this thesis was the low incidence of diagram use and low facility with diagrams found among the majority of middle school students. Our Phase I students, who came from literate, middle class families with an exposure to science at home, performed well on tasks that required knowledge from the textbook. Their scores on verbal expression and diagrams were comparable in most cases. On looking closely however, their diagrams were found to be mostly copies of textbook diagrams. The few diagrams which were innovative and departed from this norm are described in Section 4.13. The exceptionally low scores on the digestive system diagrams were also probably a reflection of inadequate treatment of the digestive system text and diagram in their textbooks (Section 6.4).

2 Though the sample in Phase I was drawn from Classes 6. 7 and 8, in terms of performance on human body systems, the three groups were equivalent.

6.2 *Methodological aspects*

6.2.1 *How to elicit and assess mental visualisation*

We probed students' understanding of structure, function and the relationships between them through their expression using text and diagrams. Tasks requiring analogical thinking and transformational reasoning served as principal tools to help students visualise the systems. Our work has not yielded definitive general notions on what constitutes visualisation since they were embedded in the content knowledge of human body systems. Prior knowledge of content was evidently a predominant factor in shaping students' responses. We feel that in science or in any other discipline, visualisation needs to be studied within the context in which it is embedded. However we have made use of general insights gained from previous literature to develop research tools to probe visualisation in science education, more particularly in biology education using a 'systems biology' outlook. This is a novel methodological aspect of this study. We can therefore say that a contribution of this thesis is the use of these research tools to probe visualisation in the context of body systems.

6.2.2 *Development of a coding scheme for analysis of diagrams and text based on systems criteria*

Adopting the structure-function approach and making use of three general aspects (segmentation, order and hierarchy, Section 3.4), our coding scheme was developed for assessment of diagrams and text. The analysis suggested by previous literature consists of noting and describing features such as: shape, colour, perspective, depth of field, etc. or to ask students to describe or explain what they have communicated through their drawings. Our coding scheme was particularly amenable to quantitative analysis of students' depictions. Also, it is generalisable to other biological systems. What is more, this was a common scheme to assess basic knowledge for both text and diagrams. It took into account domain general characteristics of diagrams and added to it context specific information that needed to be assessed about human body systems. Further, coding for structure-function relationships helped us to look at the system holistically rather than by artificially separating the two aspects.

6.2.3 *Interweaving qualitative and quantitative methods of analysis*

Both qualitative and quantitative data were collected, analysed and reported in this study. The data we obtained from students in the form of diagrams and verbal descriptions were used to code for basic knowledge in Phases I and II. In Phase I, the data was quantified by obtaining scores for the variables VrS, VrF, DS and DF. In Phase II, scores were determined for the variables TS, TF, DS, DF and V. These scores were statistically analysed and then further interpreted qualitatively in the light of textbook content on the systems. Quanitative analysis in Phase I and II could be interpreted qualitatively in terms of conceptual difficulties, and alternative conceptions. In Phase I, we were able to track the performance of students through scattergrams combined with case studies of two students: TT and GP.

In Phase II, Parts 2 and 3, scores on sub-questions in each passage and task helped us assess students' understanding of structure-function relationships, and some aspects unique to diagram comprehension. We were also able to point out specific conceptual difficulties by going back to qualitative analysis of the passage or task. Thus we moved between qualitative and quantitative analysis and used the results of one to interpret the other. This methodological tool helped us use the strengths of both methods of analysis to interpret the results.

6.3 *Main results of the thesis*

6.3.1 *The predominant role of content*

Our tasks which assessed students' understanding and comprehension of structure, function and structure-function relationships, closely reflected the content of human body systems. The coding schemes too were designed to extract content-relevant features of both text and drawn responses. Thus one might have expected already that the results would reflect the students' content knowledge. The results did conform to this expectation. But more interestingly we found that the assessment carried out in both the Phases and in all the parts of the study, showed up the places where prior content knowledge was affecting students' performance.

In Phase I we found, as expected, a significant correlation across all systems between structure and function scores. However this correlation was highest (positive) for the respiratory system, medium (non-significant) for the circulatory system and slightly negative (non-significant) for the digestive system. This result clued us to the fact that structure-function relationships were difficult to establish in the circulatory system, and for the digestive system there were some serious problems in students' understanding (Section 4.10). We were able to link these problems with some common alternative conceptions (Section 4.17) and further to some problem with the treatment of the content in the textbooks (Section 6.4).

In Phase II Part 1 we framed our tasks in a more systematic way rather than in the open-ended format used in Phase I. This change perhaps brought about the high structure-function correlations that we saw in Part 1. These high correlations further enabled us to separate the sample into groups of students who had low, medium or high scores on all the variables. To our surprise we found the same problems in understanding and the same alternative conceptions in Phase II that we had found in Phase I. In the digestive system we identified the alternative conceptions in the group of medium-scoring students, who had understood the system up to a certain (macro) level but had problems at the micro and chemical levels. The low-scoring students had problems even at the macro level. .

The visualisation tasks too were closely connected with prior content knowledge. These tasks required some component of manipulation, for which an essential requirement is correct and adequate basic knowledge of the organ or process to be manipulated. In consonance with students' overall performance, visualisation of the digestive system was more successfully done by students than visualisation of the respiratory system. The identification of visualisation with the structure-function relationship is discussed in Section 6.3.3.

In Part 2, scores for structure-function relationships indicated that questions dealing with mechanical action were comprehended better than those dealing with chemical action. On the other hand comprehension and inference from text on function was significantly better than a text on structure for a difficult passage on the oesophagus and epiglottis for the digestive system. For the respiratory system too comprehension and inference about structure-function relationships was closely tied to the familiarity and nature (macro / micro) the content tested.

Overall mean scores in Part 3 of the digestive system indicated that function diagrams (Part 3b) were comprehended better compared to structure diagrams (Part 3A). However across the tasks, diagrams depicting cross-sections were more difficult to comprehend since understanding cross-sections (a new concept) was difficult for students. In addition to the conceptual difficulties mentioned earlier, for comprehension of diagrams there were specific difficulties in understanding conventions i.e. perspective, use of key, labels and schematic representations.

6.3.2 *Use of multiple representations in tasks for probing understanding in students' responses*

In the literature, the term multiple external representations has been used to refer to diagrams, photographs, computer simulations, etc. We added verbal representations (including oral and text) to this list. Of these representations, line drawings and text have the advantage of being easy to produce, and reproduce through printing. Consequently they are the most easily accessible and hence the most widely used in school learning. Line drawings and text are also the ones which can be used most readily by students to express their understanding. Yet the potentialities of line drawings have not been systematically explored in science education research and development. Also, the relation between visuals and text is known to be a factor in students' comprehension of content (Section 2.6.4) but ways of bringing about the relationship have not been explored in previous research

In this thesis we have studied how students use the verbal (oral and text in Phase I and text only in Phase II), and diagram modes to express their understanding, and to comprehend and draw inferences about structure and function of human body systems. In assessment of basic knowledge, translation across text and diagram modes was found to occur in most cases, as seen from correlational analysis in Phase I (Section 4.11) and

Phase II (Section 5.7).

In Phase I a particular problem was detected with low text-diagram correlation for the digestive system, which reflected in low structure-function correlation and it could be interpreted in terms of students' conceptual difficulties with the system (Section 4.17). In Phase II through ordering of the questions, the students were able to connect structure with function, and the text-diagram correlation was also higher. Thus a well-ordered pedagogy linking structure with function may have enabled linking of text with diagrams.

Since the review of literature suggested an advantage for line drawings, we focused on line drawings for our study. In the tasks we developed in Phase II Part 3, we used a variety of line diagrams, i.e. multiple representations of structure-function relationships from more realistic and depictive representations to schematic ones. These diagrams were prepared keeping in mind the factors affecting their comprehension (discussed in Section 2.6) such as: cognitive interest by embedding the tasks in a relevant context such as a visit to a dentist in Task 1, use of pictorial conventions such as arrows (Task 7), labels (Task 6), key (Task 7), etc., and prior knowledge from the Class 6 textbook content.

In Section 2.2 we reviewed the literature comparing the visual and verbal indicating that a continuity exists between the depictive visual on one hand and the analytical text on the other. Though most students' diagrams tended to follow textbook diagrams, there were a few students who came up with alternative diagrams. This finally led to 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.. We did not see such a variety in Phase II diagrams though we tried to encourage more diagrams by not giving them an outline of the human body (Section 5.4.1).

In Phase I, students' mean scores across the variables was high and therefore there is no clear verdict about text or diagrammatic expression being preferred. Qualitatively the interviewer felt that expression through a verbal mode was better than expression through diagrams, but this was not substantiated by quantitative analysis for the two systems.

Students' stated preferences were also equally divided between text and diagrams. The case studies of two high performing students indicated that they were both adept at forming mental images and also expressing their understanding through text and drawings. But they differed in their style of representation. We have thus recommended use of variety of diagrams in pedagogy (Section 6.5.6).

In Phase II students were clearly more comfortable expressing understanding through text rather than through diagrams. There were a number of students who did not draw diagrams for both the digestive and respiratory systems. This clear statistical result from Phase II, and some qualitative observations which substantiated the same argument in Phase I, led us to conclude that the verbal mode was the preferred form of expression and communication among the large majority of students.

6.3.3 *Relationships between structure and function and its bearing on mental visualisation*

In Section 3.3, we discussed the need to understand the complex integration between structure and function in the human body, and to test for it in an appropriate manner. In Phase I, we saw this integration through correlational analysis. We also used open-ended questions requiring the use of analogies. In Phase II, Part 1, there were specific visualisation questions which were designed to specifically test for transformations of structure and relationships between structure and function. In Parts 2 and 3 we used a variety of questions testing for aspects of structure-function relationships. In Part 3 we introduced some diagram-related categories such as perspective, model, use of key, comprehension of labels etc.. These questions helped us paint a picture of students' visualisation of the body systems.

In any system of reasonable complexity, structural concepts cannot be adequately expressed through language alone. Drawings are necessary. On the other hand, function is generally difficult to express through drawings. In Phase I we found that more structure concepts were expressed through drawings than function concepts. In Phase II however, both structure and function concepts were expressed better through text than diagrams. The Phase II result seems to contradict what we saw in previous literature, as well as from our Phase I results.

6.3.3.1 *Assessing mental visualisation through analogical thinking*

Analogical thinking in the history of science as well as its use in pedagogical practice was discussed in Section 3.1. In Phase I, our questions probing analogical thinking were open-ended. However we obtained a variety of interesting responses. Students came up with a number of analogies pertaining to both structure and function and described without analogy too. The exercise of generating analogies helped students connect their real world knowledge with the new concepts in their textbooks. However, the pattern-matching which helped them arrive at these analogies led to several erroneous and often irrelevant responses which could have lead students' away from a correct understanding. As cautioned by Venville and Treagust (1997) greater teacher intervention and task constraints need to be imposed for it to be an effective pedagogical tool. In Phase II, we used these tasks with some constraints as discussed in Sections 5.8.1, 5.8.3, 5.9.1 and 5.9.3.

6.3.3.2 *Assessing mental visualisation through transformational reasoning*

As mentioned in Section 6.3.1, we found that good basic content knowledge would be an essential prerequisite to tackling the visualisation questions. 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 would depend on prior content knowledge.

Visualisation scores were more correlated with text scores than with diagram scores for the digestive system. Though this was not a statistically significant correlation and only one of degree, it is worth noting this interesting observation. This is especially since students tend to be dissuaded by diagrams in biology as a requirement of 'skill' or of passive copying rather than as a summary of the learning process. The scores for the digestive system were higher than for the respiratory system and followed a normal distribution. The digestive system is given more emphasis in the textbook. This also allowed us to test for more aspects compared to the respiratory system.

Tasks which required analogical thinking and transformational reasoning served mainly as research tools to probe students' conceptions of the human body, and also gave us an understanding of students' visualisation and its relationship with other variables tested for.

6.4 *Students' conceptual difficulties in the light of their textbook content*

The results on students' conceptual difficulties summarised in Section 6.3.1 should be seen in the context of the textbook content on human physiology. The presentation of content in the textbook can be seen as a source of some of the conceptual difficulties students encountered. The sample of students we tested in both Phases I and II followed the NCERT Science and Technology textbooks, first published in 2002. Students followed the third, fourth and fifth editions of the textbooks published in 2004, 2005 and 2006. The maximum content about the human body was found in the Class 6 textbook where the systems: digestive, respiratory, circulatory, excretory and nervous are explained at different levels of detail. In Phase I, our sample was drawn from classes 6, 7 and 8, and in the Class 6 textbook with some passages taken verbatim for comprehension. In Phase II too with students who had completed Class 6, we kept with the content in the Class 6 textbook when testing for basic knowledge. Passages and diagrams for comprehension were also framed keeping in mind the content of the textbooks.

Besides the Class 6 textbook, the Class 7 and 8 textbooks also had some details about the human body. In Class Seven, a chapter called the "Sustenance of the individual" compared the digestive, respiratory and excretory systems across plants and animals. Some details about chemical aspects of digestion were shown through a table. Digestive enzymes and their action received mention. There was also a diagram of the digestive system, which however did not clearly differentiate the path taken by the food and was rather similar to the diagram in the Class 6 textbook. Further in Class 7, the respiratory system in plants is compared with that in human beings. A diagram of the respiratory system showed the passage of air into the lungs, but did not show the processes which take place or what happens from there. The respiratory organs in lower organisms was mentioned, and some aspects of cellular respiration was explained such as the TCA cycle, respiratory enzymes and carriers. There was further another chapter called "Our Food" in which different components of the diet such as carbohydrates, proteins, fats, vitamins and minerals and their nutritive value was mentioned. In Class Eight, there was a chapter on "Common diseases" with mention of the organs which get affected. For example, cholera affects the gastro-intestinal tract, tuberculosis affects the lungs, typhoid affects the intestine, polio affects the central nervous system, etc..

Thus, in the Class 6 textbook all the systems were introduced and further details and applications were provided in Classes 7 and 8. However, it is not clear whether an integration of all the information relating to systems had been achieved through the curriculum. It would need teachers with a strong biology background to carry out integration across topics and years.

6.4.1 *Students' understanding of the digestive system*

Common difficulties pertaining to structure of the digestive system are with respect to organs which are unfamiliar or not given adequate emphasis in the textbook, such as the liver and pancreas. In the Class 6 Science and Technology textbook, the digestive system had the most level of detail compared with the other systems. Although all the digestive organs including the liver, pancreas and gall bladder, were introduced, their function was not made explicit. Also, the chemical aspects of digestion were not dealt with in detail in Class 6.

It is also clear from our empirical data that students had particular difficulty in understanding the connection between the small and large intestine.

The diagram of the digestive system, (shown in Figure 6.1) does not show a clear connection between the small and large intestine perhaps in an attempt to make it appear realistic with shades of red being used. Thus some of the students' difficulties do arise from problems with the textbook.

Figure 6.1. Diagram of the digestive system from the Class 6 NCERT Science and Technology textbook, 2002

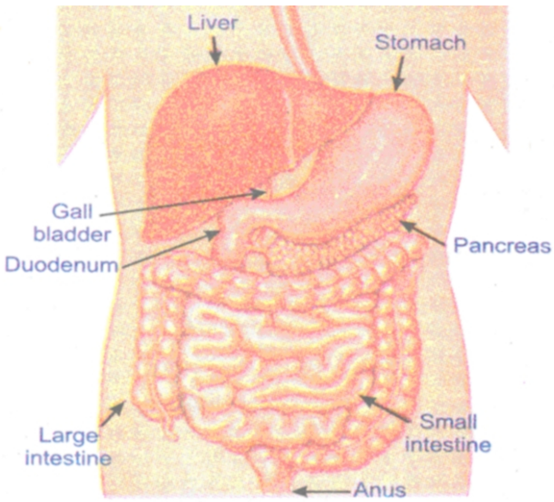


Figure 6.2. Diagram of the digestive system from a revised version of the NCERT 2002 textbook (5th edition: 2006)

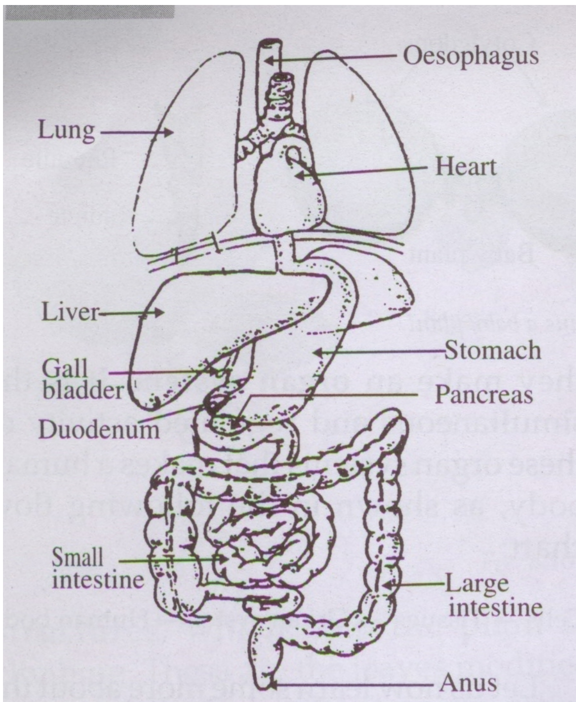


Fig.8.13 The digestive system

6.4.2 *Students' understanding of the respiratory system*

A positive aspect of students' understanding of the respiratory system was that there was a high correlation between the structure and function scores even in Phase I where the questions were more open-ended. However, in specific aspects of structure and function they did have problems.

The Class 6 Science and Technology textbook explains the mechanics of breathing. However, cellular respiration was not dealt with in detail, and is therefore a common source of alternative conceptions. The diaphragm and alveolus are not given much emphasis in the textbook. From students' responses it is evident that the structure of the diaphragm is an area of difficulty which translates into understanding the functional aspects such as the mechanics of respiration.

The location and structure of the alveolus, its role in gas exchange, and therefore the connection between the respiratory and circulatory systems are also areas of difficulty as seen from the results of both Phases I and II. For example, inadequate understanding of basic structural aspects of the alveolus translates into difficulty in understanding gas exchange and cellular respiration.

The textbook diagram of the structure of the respiratory system is reproduced in Figure 6.2. The diagram is quite clear with respect to structure except for the diaphragm which appears to be a part of the lungs.

Figure 6.3. Diagram of the respiratory system from the NCERT Science and Technology textbook for Class 6, 2002.

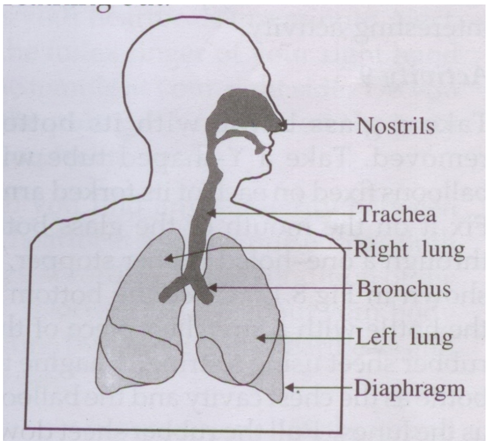


Fig.8.16 The respiratory system

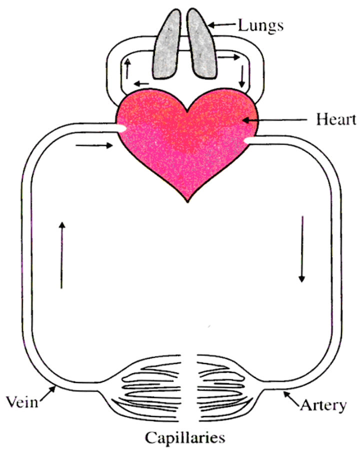
6.4.3 *Students' understanding of the circulatory system*

Most students had only a vague idea of the process of oxygenation of blood in the lungs, and the role of the heart and the lungs in facilitating the same. These processes are mainly explained through a schematic diagram in the textbook without adequate reference in the text. It may be recalled that in Phase I (Section 4.18.2.1), GP who made a copy of this diagram reversed the path of the oxygenated and deoxygenated blood. This is not surprising since the two processes and different directions taken by both are not explained in the textbook.

In the Class 6 Science and Technology textbook, the organs of the circulatory system (blood vessels and heart) received mention as well as their functions. Aspects of function such as the pulse rate, purification of blood in the lungs and heart-rate were explained through activities. However these aspects were not integrated with the overall functioning of the system and with an understanding of systemic and pulmonary circulation. For this system, the two levels of functional hierarchy are: systemic circulation and pulmonary circulation. Both of these aspects are illustrated through a diagram in the textbook, but are not complemented by adequate explanation through text. The textbook diagram is shown in Figure 6.3.

Unlike the other diagrams in the textbook, the diagram of the circulatory system is schematic and shows scant regard for structure with the heart being represented like a 'valentine'. It could have proved to be a good summary of the functioning of the system if the movement of blood and the process of oxygenation of blood in the lungs had been explained. Since this is not done, the diagram remains vague.

Figure 6.4. Diagram of the circulatory system from the NCERT Science and Technology textbook for Class 6, 2002.



6.5 *Pedagogical implications*

6.5.1 *Role of domain knowledge*

The questions, passages and tasks in our questionnaires are embedded in the context of human body systems. For questions requiring transformational reasoning, students needed to work with prior content knowledge in order to perform manipulations. Most cognitive strategies depend for use on prior knowledge of content, and visualisation is no exception. If prior knowledge can be relied upon then it frees up available resources for coordination within cognitive components (Pressley and Hilden, 2006). There is danger of circularity here when one is talking about the relationship between the use of visuals and effectiveness of learning. Our claim is that visuals and visualisation help in understanding of biology, but their use in turn is constrained by prior knowledge of biology content. We suggest that one would begin with familiar content to introduce new diagrammatic and discourse techniques which could in turn be used to tackle more difficult content (see Section 6.5.6).

6.5.2 *Visuals and visualisation*

Our research makes a distinction between mental 'visualisation', products of which could be expressed verbally, and external depictions or 'visuals', which, like text, could be learnt by rote. We found that the majority of the students' drawings (particularly in Phase II) were of the 'routine' kind. In Chapter 2, Section 2.8, we discussed two different kinds of cognitive pathways that have been proposed for processing of drawings: a non-visual pathway, sufficient for routine drawings, and a visual-imagery pathway for unfamiliar drawings (Guérin et al., 1999). We feel that pedagogy in schools may at times bypass the visual imagery pathway, leading to routine processing of drawings. The question then arises, how can we help students activate their visual imagery pathway? The first step may be (perhaps paradoxically) to use the text medium to help students make sense of the drawings.

Diagrams in Indian textbooks often inadequately supplement text-based information. Rarely is there any cross-referral between text and diagrams. Dual coding of content could be facilitated by linking text with diagrams within textbooks and through classroom discourse. Text should refer to and make use of the spatial information contained in diagrams, encouraging students to switch from one to the other in meaningful sequence. Finding connections between structure and function would be a particularly helpful technique in biology. The disconnect seen between internal 'visualisation' and external 'visuals' could be mended through these practices.

Interweaving flexibly between the verbal and visual is a skill that may help students activate their mental visualisation capabilities. This skill can be developed not only while reading text and diagrams but also while moving from dynamic visuals such as videos, to written or spoken description and back. Models, computer-aided 3D visualizations and animations could further activate multiple modes of representations.

6.5.3 *Development of visualisation abilities: practice helps*

In Phase I where we obtained a greater variety of diagrams, we could see the effect of practice in the students. There was better performance in the questionnaire on the digestive system compared to the respiratory system. Students prepared for content knowledge from their textbooks, and were also able to anticipate the kinds of questions that would be asked based on the questionnaire for the digestive system. Adequate exposure to and practice in comprehending and producing a variety of diagrams would therefore help in the development of visual thinking

6.5.4 *Use of analogies*

We had probed analogical thinking mainly through open-ended questions in Phase I and with some task constraints in Phase II. Though we did not assess responses to these questions quantitatively, we did obtain a rich variety of responses which gave us some insight into students' understanding of organs and processes and more importantly connected their real world understanding with content in their textbooks. School textbooks tend to routinely use analogies without adequately explaining them. Students tend to map the source and target randomly thereby developing alternative conceptions.

The Focus, Action and Reflection (FAR) guide was developed from the classroom practices of exemplary science teachers (Venville, 2008). In a nutshell, teachers using this model have to 'Focus' on the content, the analog and the student, take 'Action' by discussing with students the similarities and differences between the analog and the target, and finally 'Reflect' on the analogy to determine whether it was useful and how it could be improved.

Analogies therefore need to be used with some constraints and adequate teacher intervention to serve as useful pedagogical tools. Teachers need to map the relevant features of the source and target for the students, and also bring out the differences between them in order for it to be correctly understood.

6.5.5 *Transformational reasoning on an image and / or diagram*

In Phase II Part 1 of our empirical study we used specific questions probing transformational reasoning or 'visualisation' questions. Students could use words, diagrams or both according to their preference. In Parts 2 and 3 there were some questions on transformational reasoning requiring the use of words and diagrams. In these questions, students had to manipulate a generated mental image. Using this form of reasoning on a diagram will help students use the visual imagery pathway during diagram comprehension. As mentioned in Section 6.5.3, practice with using this form of reasoning develops the expertise required to use it in varied situations and contexts.

Subsequent to the publication of this research on transformational reasoning and on discussing the draft of this thesis, a physics colleague reported to us the motivational effect of this technique in trying to understand aspects of physics requiring visuospatial reasoning. We feel therefore that the technique of using transformational reasoning has much potential not only as a research tool but also as a tool for thinking and teaching.

6.5.6 *Design of diagrams*

We emphasise 2D line drawings for their low cost and accessibility in the Indian context and also for their power of simplification. Though overtly simplistic, line drawings abstract out relevant details and provide useful cues to understand complex situations.

Designing a good diagram depending on the context and the content to be communicated is a challenge especially in a discipline where transferring and translating across multiple levels of organisation and schematisation is a norm. Results from our diagram comprehension tasks in Phase II Part 3 allow us to make some recommendations pertaining to diagram design. We found that difficulties in comprehending diagrams related to understanding cross-sections, microscopic or chemical processes and structure-function relationships. But we also found that a well-designed diagram could convey aspects of function which are normally not understood by students. Based on results from the comprehension of Task 7 of the digestive system, we conclude that a good diagram should take into account working memory limitations in processing too much content especially when dealing with difficult concepts. On the other hand it is important to bring in variety in the design of such diagrams to familiarise students with conventions, perspective, use of key and other aspects regarding diagram comprehension.

It seems a worthwhile pedagogical exercise to design a wide variety of diagrams to convey structure and function in biology, while sensitising students to a range of visuals within the genre of line drawings. The range includes depictive, detailed drawings, more abstracted, schematised drawings with significant features highlighted, or without any depictive component at all (using only boxes, arrows, lines, etc.). Diagrams could be drawn from different orientations or viewpoints (as shown in Task 1), they might show relationships between external appearance and internal structure, as in various types of cross-sections (as shown in Task 3). One could have drawings that convey chemical processes, make use of a key and show dynamic processes using symbols (as shown in Tasks 7 and 6). Transformational reasoning on these diagrams would help students transfer from a two dimensional to a three dimensional image, and as mentioned in Section 6.5.5 help them use the visual imagery pathway while processing diagrams.

We need to encourage use of schematic diagrams especially since biology teaching in school tends to rely exclusively on depictive, exact representations. Schematic representations are less dependent on drawing skills, and at the same time provide affordances to convey structure-function relationships. Diagrams should be designed that can be used as tools for thinking through situations, and specifically promote inferences from structure to function and vice versa.

Comprehension of such diagrams is not a given. In designing diagrams for pedagogy one needs to introduce visual vocabulary in a gradual way, giving careful attention to symbols, conventions and complexity. Finally one needs to pre-test diagrams with the student populations with whom they are to be used.

6.6 *Some special features of this thesis*

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

- 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 unlike in previous research.

- 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.

6.7 *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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Appendices

Table of Contents

A. Information on students

A.1. List of students who attended Phase I of the study (May 2004)

S No	Code name	Class	Sex (B/G)	Rank in class
1	TT	6	G	4th
2	GP	6	B	6th
3	SRM	6	B	17th
4	AV	7	B	4th
5	SK	7	B	7th
6	NS	7	G	13th
7	PA	7	G	13th
8	AA	7	B	15th
9	PS	7	B	23rd
10	UA	8	B	2nd
11	NT	8	G	3rd
12	JS	8	G	3rd
13	PM	8	G	16th

6.7.1 *A.2. Students who attended Phase II of the study*

No. of students	Girls	Boys
87	46	41

B. Questionnaires

B.1. Questionnaires for Phase I

B.1.1. Questionnaire for the Digestive system (Phase I)

Homi Bhabha Centre for Science Education,

Tata Institute of Fundamental Research

Mankhurd, Mumbai- 400088

Some questions about the structure and functioning of our body

The Human Body

1. Draw an outline of the human body in the blank sheet given to you. In the drawing, show what is inside the body including the organs within it. Colour your diagram.

The Digestive System:

2. Draw the organs involved in digestion within the outline of the human body given to you. Colour your diagram.

3. Read the paragraph below. Then draw a diagram of the digestive system within the given outline of the human body. Show in which parts of the body the actions given in **bold** letters are carried out.

All animals including human beings need nutrients to grow and function properly. They obtain them from food. This purpose is served by the **digestive system.** It includes feeding, digestion, absorption and defecation. When we eat food **(feeding)**, it gets broken down into smaller particles. These particles then get changed into absorbable forms in the body **(digestion)**. The digested food is then absorbed and used in the body **(absorption)**. The unabsorbed food is thrown out of the body in the form of faeces **(defecation).**

4. Imagine you are eating _________________. Draw diagrams to describe what happens to the food in your body from the time you eat it to when it gets completely digested.

5. Can you think of another process which is similar to or reminds you of the process of digestion, or of anything related to digestion.

6. Describe the images that come to your mind when you think of the following digestive organs:

The food pipe reminds me of________________________________.

The intestine reminds me of ______________________________________.

The stomach reminds me of______________________________________.

The liver reminds me of____.

B.1.2. Questionnaire for the Respiratory system (Phase I)

Homi Bhabha Centre for Science Education

Tata Institute of Fundamental Research

Mankhurd, Mumbai- 400088

1. Draw the organs involved in respiration within the outline of the human body given to you. Colour your diagram.

2. Read the paragraph below. Draw a diagram to show what this paragraph says in words .

When a person breathes in, oxygen containing air enters the body and goes to the lungs. Here, oxygen enters the blood and goes to the different parts of the body. Water vapour and carbon-dioxide are released from the blood into the lungs. When we breathe out, these are removed from the lungs.

3. Can you think of another process which is similar to or reminds you of the process of respiration, or of any step during the process of respiration (such as: breathing in and breathing out..)? Make a drawing or describe what you have thought of.

4. Draw the respiratory system when you breathe in air, and when you breathe out (inhale and exhale).

5. Imagine that you are walking through a very dusty place. You can feel the dust entering your body as you breathe in air. Describe using words and diagrams what would happen to the dust from the moment it enters your nose. Use the following keywords to help you draw your diagram: nose, windpipe, diaphragm, lungs, blood, oxygen, carbon-dioxide.

6. Complete these sentences using the images which come to your mind when you think of the following:

The respiratory system reminds me of ____________________________________.

The action of the lungs remind me of ___________________________________.

The diaphragm reminds me of ____.

B.1.3. Questionnaire on the Circulatory system (Phase I)

Homi Bhabha Centre for Science Education

Tata Institute of Fundamental Research

Mankhurd, Mumbai- 400088

1. Draw the organs associated with the circulatory system within the outline of the human body given to you.

2. Can you think of another process which is similar to or reminds you of the process of circulation? Make a drawing or describe what you have thought of.

3. Represent diagrammatically the working of the heart using the following points to guide you (with more additions if you wish):

The lungs receive oxygen from the air. This oxygen combines with the blood and goes to the heart. From the heart the oxygen-filled blood goes to the different parts of the body. The heart also receives impure, carbon-dioxide filled blood from the various parts of the body and sends it to the lungs. The lungs filter the carbon-dioxide from the blood and expels or sends it out when we breathe out (exhale).

6. Complete these sentences using the images which come to your mind when you think of the following:

The circulatory system reminds me of ______________________________________.

The movements and function of the heart reminds me of ______________________.

Blood reminds me of ____.

B.2 Questionnaires for Phase II

B.2.d Questionnaires for the digestive system

B.2.d.1. Questionnaire for digestive system: Part 1 (Phase II)

Homi Bhabha Centre for Science Education
Tata Institute of Fundamental Research
V.N. Purav Marg, Mankhurd, Mumbai- 400088

Please fill up the following details

Your name:
Class:
School:
Today's date:

To answer these questions you may use words and drawings in any way that you wish.

1. Describe your digestive system.

2. 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?

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

4. Describe the food-pipe. How does the food-pipe help in digestion?

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

6. Describe the stomach. How does the stomach help in digestion?

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

8. Describe the small intestine. How does the small intestine help in digestion?

9. Suppose the small intestine was much shorter. What difference would it make? Would it affect digestion of food? If so, how?

10. Describe the large intestine. How does the large intestine help in digestion?

11. Think of another shape for the large intestine. Would that different shape have any effect on the working of the large intestine?

12. Imagine that you are eating a piece of bread toast. What changes does the toast go through in each digestive organ while it is being digested? Answer using the table given below. Use more paper if you wish.

Digestive Organ	**Changes that happen to the food while in this organ (use more paper to answer if you wish)**	**Condition of toast after it has passed through this organ (put a √ in the appropriate column)**		
		Liquid	**Semi -solid**	**Solid**
Mouth				
Oesophagus				
Stomach				
Small Intestine				
Large Intestine				

13. Try to show through a drawing what happens to the toast at each stage of the process of digestion.

B.2.d.2A. Digestive system Part 2A (Phase II)

Homi Bhabha Centre for Science Education
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Summer camp on "Visualisation in Biology"

Questions on the digestive system: Part 2A (010505)

Please fill up the following details

Your name:
Class:
School:

Today's date:

Read the passages given below and answer the questions given below each of them. To answer the questions you may use words or drawings as you wish.

Passage 1

The mouth contains many teeth, one tongue and some salivary glands. We have four kinds of teeth: incisors, canines, pre-molars and molars. Incisors are the front teeth, which are flat in shape. On both sides of the incisors are the long and pointed canine teeth. Any food first comes into contact with the incisors and the canines.

Deeper in the jaw, behind the canines, are the pre-molars. The pre-molars have two points, or cusps, and are therefore called "bicuspids". Further deep inside, behind the pre-molars, are a few teeth which are the last to develop. These special teeth, called molars, have four or five points, or cusps.

The walls of the mouth cavity carry three pairs of salivary glands. Saliva secreted by these glands contains some active proteins, called enzymes. Some enzymes can convert starch into sugar. Other enzymes can kill bacteria. The saliva contains a lot of water and some slimy mucus.

The tongue is a muscular organ. It has on its surface thousands of special structures called taste-buds. There are different kinds of taste-buds for sweet, salty, sour and bitter tastes. Each of these four kinds of taste-buds are located in a specific region of the tongue.

a. Draw what you imagine could be the shapes of an incisor, a canine, a pre-molar and a molar tooth.

b. Draw a diagram to illustrate the position of the different kinds of teeth.

c. From the shape and location of each kind of tooth, what can you say about its function? Answer in the table given below. Draw diagrams if necessary.

Type of tooth	**Shape of tooth**	**Where it is located in the mouth**	**Probable function of this tooth**
Incisor			
Canine			
Pre-molar			
Molar			

d. What could be the use of water and mucus in the saliva? Explain.

e. How does it help that the tongue is a muscular organ? What if the tongue were hard and bony?

f. A piece of roti, when chewed well, tastes sweet. Why?

g. Can you taste all foods in all parts of the tongue? Why or why not?

h. Give examples of foods which have a taste that is a combination of two or more tastes. How could you detect such a taste?

i. If you cut your finger by mistake with a knife, and blood comes out of the cut, you are sometimes asked to put your finger in your mouth. Why do you think that is done?

Passage 2

The oesophagus is a flexible tube. This tube begins at the back of the mouth. The walls of the tube can repeatedly relax and contract to push the food along the oesophagus.

The opening to the trachea lies close to the opening of the oesophagus. A flap of tissue called the epiglottis covers the trachea like a lid.

The oesophagus connects the mouth with the stomach. The walls of the stomach contain glands which secrete gastric juices, which are strongly acidic and act on the proteins. The inside of the stomach is lined with a thick layer of mucus which protects it from the action of these juices.

a. Which of these words might describe the walls of the oesophagus: soft, hard, strong, flexible, bony?

b. How do you think the food is pushed from the mouth to the stomach through the food-pipe? Make a drawing of it.

c. Where else can you see a similar process in the human body itself?

d. How might the epiglottis look like? Draw the trachea and oesophagus and show also the epiglottis in the drawing.

e. What would happen if the epiglottis were not there?

f. What do we do if food accidently lands on the epiglottis or enters the trachea?

g. After reading Passage 1 and Passage 2, what is your idea of a "gland"? About how big might be the glands mentioned in Passage 1 and Passage 2?

h. After reading Passage 1 and Passage 2, what is your idea of "mucus"?

i. What would happen if there were no layer of mucus on the inside of the stomach?

j. Draw diagrams to show what the stomach looks like and what happens inside it during digestion

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Summer camp on "Visualisation in Biology"

Questions on the digestive system: Part 2B (010505)

Please fill up the following details

Your name:
Class:
School:
Today's date:

Read the passages given below and answer the questions given below each of them. To answer the questions you may use words or drawings as you wish.

Passage 1

Digestion of food begins in the mouth. In our mouth we have four kinds of teeth: incisors, canines, pre-molars and molars. The teeth chew the food in the following way. First the incisors break off a piece of the food. Tough foods are torn up by the canines. Next the pre-molars and molars grind the food. This is how our teeth break up the food material into tiny pieces.

Three pairs of salivary glands in the mouth secrete saliva. Saliva mixes with the tiny pieces of food. Active proteins, or enzymes in the saliva, help convert some starch in the food into sugar. Other enzymes in the saliva kill bacteria. Mucus and water in the saliva helps us to smoothly swallow the chewed-up food.

The tongue moves the food around in the mouth to mix it with the saliva. The tongue also detects the taste of the food. Taste buds in specific regions of the tongue can detect one of four different kinds of tastes: sweet, salty, sour and bitter.

a. Draw what you imagine could be the shapes of an incisor, a canine, a pre-molar and a molar tooth.

b. Draw a diagram to illustrate the action of the different kinds of teeth.

c. From the function of each kind of tooth, can you guess its shape and location? Answer in the table given in the next page. Draw diagrams if necessary.

Type of tooth	Function of tooth	Probable shape of this tooth	Where it might be located in the mouth
Incisor			
Canine			
Pre-molar			
Molar			

d. What could be the use of water and mucus in the saliva? Explain.

e. What do you think the tongue is made of? Could the tongue have bones in it? Could it have blood vessels? Or muscle tissue?

f. A piece of roti, when chewed well, tastes sweet. Why?

g. Can you taste all foods in all parts of the tongue? Why or why not?

h. Give examples of foods which have a taste that is a combination of two or more tastes. How could you detect such a taste?

i. If you cut your finger by mistake with a knife, and blood comes out of the cut, you are sometimes asked to put your finger in your mouth. Why do you think that is done?

Passage 2

When food is swallowed, it goes from the mouth into the oesophagus. The food is pushed along with the help of repeated contractions and relaxations of the oesophagus.

The opening to the trachea lies close the opening of the oesophagus. As we swallow, a flap of tissue called the epiglottis closes over the top of the trachea.

The food passes from the oesophagus to the stomach. Here, proteins are acted on by strong acids known as gastric juices, which are secreted by glands in the walls of the stomach. The mucus lining inside the stomach protects it from the action of these juices.

a. Which of these words might describe the walls of the oesophagus: soft, hard, strong, flexible, bony?

b. How do you think the food is pushed from the mouth to the stomach through the food-pipe? Make a drawing of it.

c. Where else can you see a similar process in the human body itself?

d. How might the epiglottis look like? Draw the trachea and oesophagus and show also the epiglottis in the drawing.

e. What would happen if the epiglottis were not there?

f. What do we do if food accidently lands on the epiglottis or enters the trachea?

g. After reading Passage 1 and Passage 2, what is your idea of a "gland"? About how big might be the glands mentioned in Passage 1 and Passage 2?

h. After reading Passage 1 and Passage 2, what is your idea of "mucus"?

i. What would happen if there were no layer of mucus on the inside of the stomach?

j. Draw diagrams to show what the stomach looks like and what happens inside it during digestion.

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Summer camp on "Visualisation in Biology"

Questions on the digestive system: Part 3A (040505)

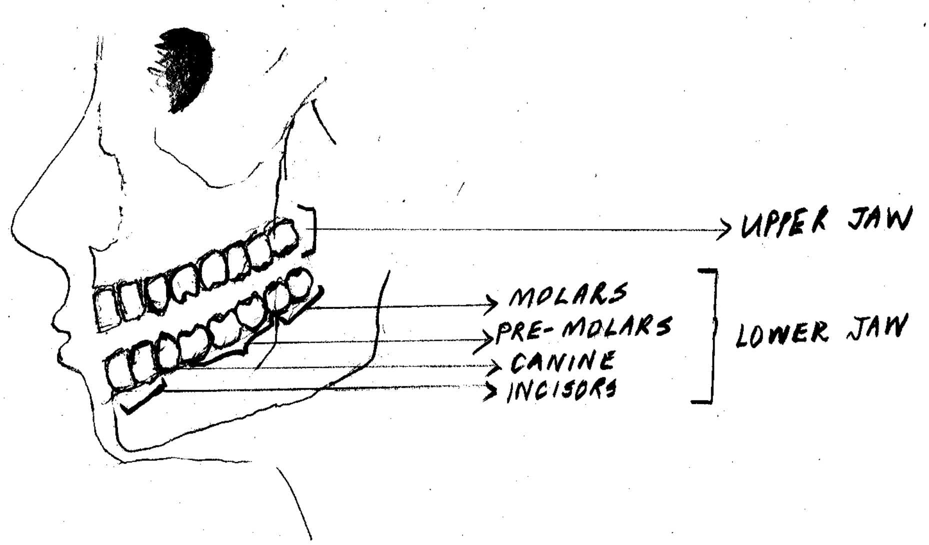
Please fill up the following details

Your name:
Class:
School:
Today's date:

Task 1

Fig. 1 shows the side-view of Divya's upper and lower set of teeth (that is one half of her full set of teeth). Her lower teeth are labelled. The corresponding upper teeth have exactly the same names.

Fig. 1

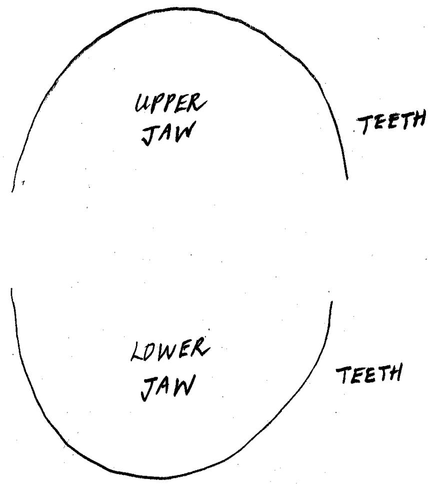


Now imagine that Divya is sitting in a dentist's clinic. The dentist says to her:

Dentist: Divya, please open your mouth wide.
(Divya opens her mouth as wide as possible.)
Dentist: A little wider ... Aah! Now I can see all your teeth.

1a. Show in a diagram how the dentist might see Divya's teeth when he looks into her mouth. Label the teeth in this diagram. Clue: use the format shown in Fig. 2 given below.

Fig. 2



1b. Now count Divya's teeth. Give the number of teeth in the table below.

Type of tooth	**Number in the upper jaw**	**Number in the lower jaw**	**Total number of teeth of this kind**
Incisor			
Canine			
Pre-molar			
Molar			
Total number of teeth altogether:			

1c. Describe the shapes of each kind of tooth: an incisor, a canine, a pre-molar and a molar. Mention how they are different from each other.

1d. How does each kind of tooth help in the process of chewing?

1e. Is the shape of each tooth related to its function? How?

1f. How many teeth do you have?

1g. Are there any teeth you do not have? If so, when will you get them?

1h. Why do you think you lost several teeth when you were about five-six years old? Are the teeth that you have now different from those teeth that you lost? How?

1i. How do you think teeth fall off in old-age? Guess and explain through diagrams and words how this might happen.

Task 2

2a. What is a cross-section?

2b. Why do we draw cross-sections in diagrams?

2c. Draw and label the cross-section of the wire that is given to you.

2d. Give another example from everyday life where you saw a cross-section of something.

2e. What more information was the cross-section able to give you which the whole object could not?

Task 3

The diagram below shows the trachea (wind-pipe) and the oesophagus (food-pipe), which are located close to each-other. Fig. 3 shows the structure of the trachea and the oesophagus and its location in the body. Fig. 4 shows the cross-section of the two organs. The cross-section shows us that the trachea is a hard, rigid tube compared to the oesophagus which is softer and less rigid.

Fig. 3 Location of the trachea and the oesophagus in the body

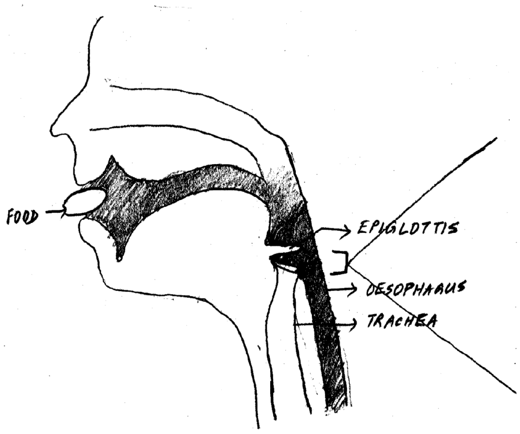
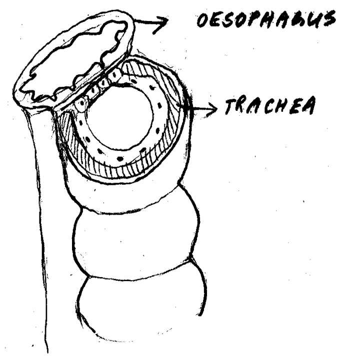


Fig. 4 Cross-section of the trachea and the oesophagus during normal breathing



3a. Make another drawing of the cross-section of the trachea and the oesophagus during normal breathing. Show the position of the epiglottis in your diagram.

3b. Show how the trachea and the oesophagus would look like when you're swallowing a mouthful of food. Show a piece of food and the epiglottis in your diagram.

3c. Supposing you choke while swallowing food, how will your previous diagram change? Show the changes that happen in another diagram.

Task 4

Read the passage given below

The small intestine is a long tube which has the task of absorbing nutrients after they have been broken down by juices from the stomach and pancreas. To absorb the nutrients effectively, the inner surface of the small intestine is compressed into hundreds of folds and lined with thousands of finger-like protrusions called villi.

4a. Draw how you imagine the cross-section of the small intestine might look. (You need not show hundreds or thousands of folds or villi. A few will be sufficient for illustration.)

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Tata Institute of Fundamental Research
V.N. Purav Marg, Mankhurd, Mumbai- 400088

Summer camp on "Visualisation in Biology"

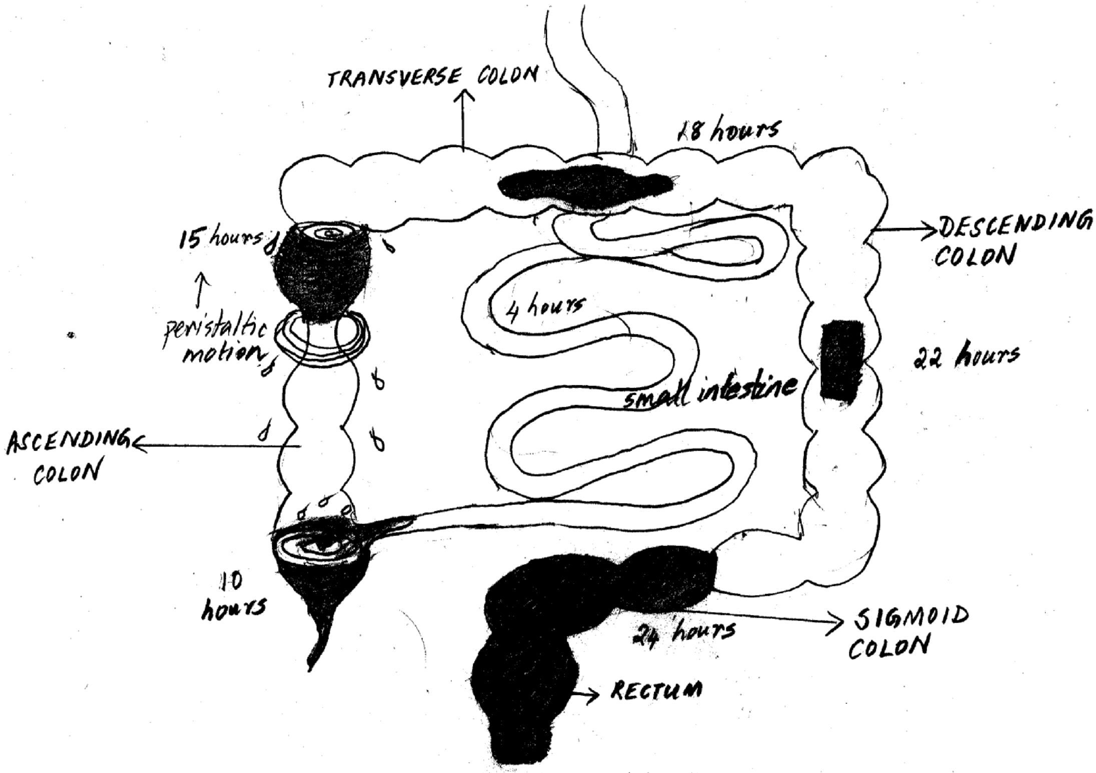
Questions on the digestive system: Part 3B (050505)

Please fill up the following details

Your name:
Class:
School:
Today's date:

Task 5. Where does the food go after it is digested in the stomach? What happens to it in the small intestine? Where does it go from there?

Task 6. Only the undigested part of the food goes into the large intestine. The diagram below illustrates the working of the large intestine. Go through the diagram carefully, then answer the following questions:



6a. Where is the food just before it enters the large intestine?

6b. In the diagram you see the labels "ascending colon", "transverse colon", "descending colon" and "sigmoid colon". Explain what these labels indicate.

6c. You also see the labels "10 hours", "15 hours", "18 hours", "22 hours" and "24 hours". Explain what these times indicate.

6d. You see a ring drawn around the part which is labelled "peristaltic motion". This ring shows that, in that place, the walls of the large intestine are contracting. Due to this contraction, the food material moves further ahead. Once the material has moved further, the walls relax to their normal position. This successive contraction and relaxation is called peristaltic movement.
How is peristaltic movement useful to us?

6e. In which parts of the large intestine would you expect peristaltic movement to happen?

6f. How much time after eating the food does it enter the large intestine? How long does it stay in the large intestine? Describe in the following Table how the food material looks - either liquid, semi-solid or solid, in different parts of the large intestine.

Time	Which part of the large intestine has it reached after this many hours?	State of the food		
		Solid	Semi-solid	Liquid
10 hours				
15 hours				
18 hours				
22 hours				
24 hours				

6g. How does the food material change as it goes through the large intestine? Why does it change? What parts get absorbed in the large intestine?

6h. What is faeces composed of? How does the large intestine help in the formation of faeces?

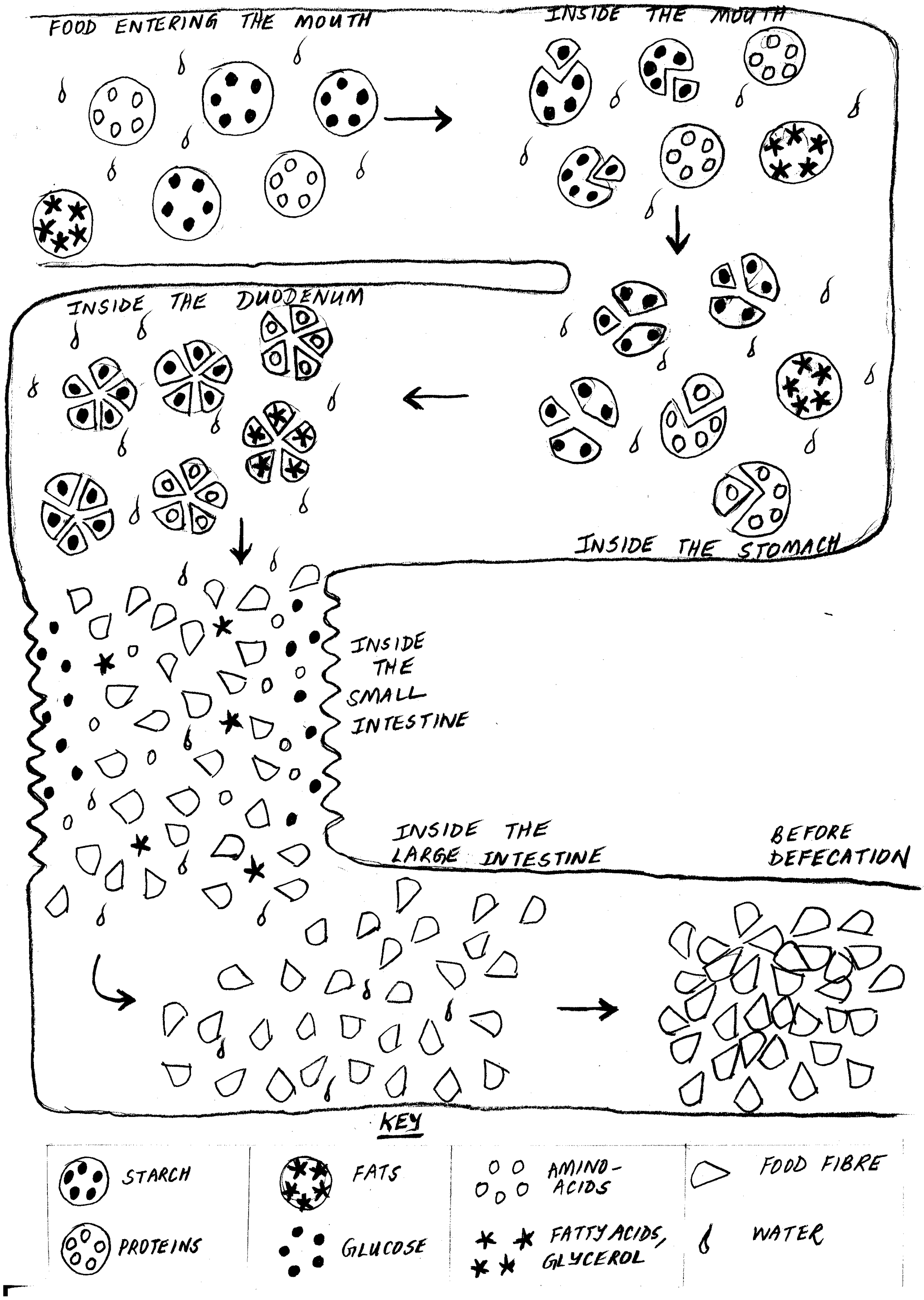
6i. Suppose that food stayed in the large intestine for longer than the normal time. What would be the result?

6j. Suppose peristaltic motion happened faster than normal. What would be the result?

6k. Explain step by step through words and drawings how peristaltic motion happens in the large intestine. Take a clue from the given drawing.

6l. Where else in the body do you see peristaltic motion?

Task 7. The drawing below illustrates the process of digestion in the human body. Look through the diagram carefully and answer the questions below.



7a. What components of food are shown being taken in through the mouth?

7b. What changes are shown happening in the mouth? Why do these changes happen?

7c. What changes are shown happening in the stomach? Why do these changes happen?

7d. What changes are shown happening in the duodenum? Why do these changes happen?

7e. What changes are shown happening in the small intestine? Why do these changes happen?

7f. What components are shown being absorbed in the small intestine?

7g. What changes are shown happening in the large intestine? Why do these changes happen?

7h. What components are shown being absorbed in the large intestine?

7i. What are the components that are shown being excreted?

7j. Do you think that this diagram shows well what happens to food during digestion? Can you think of a better way of showing this?

B.2. Questionnaires for the Respiratory system (Phase II) B.2.r. Respiratory system (Phase II)

B.2.r.1. Respiratory system Part 1 (Phase II)

Homi Bhabha Centre for Science Education
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Summer camp on "Visualisation in Biology"

Questions on the respiratory system: Part 1 (080505)

Please fill up the following details

Your name:
Class:
School:
Today's date:

To answer these questions you may use words or drawings as you wish.

1. What do you understand by "respiration"?

2. Describe your respiratory system.

3. 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

4. What is the role of the nose in respiration? Does it have other functions also?

5. Describe the trachea. What is its role in respiration?

6. The trachea is quite strong and rigid compared to the oesophagus or food pipe. Why is it that way?

7. What would happen if the trachea was a smooth, flexible structure?

8. Describe your lungs.

9. How do your lungs help in respiration?

10. Describe the alveoli. Think of another shape for the alveoli. What is the difference between the two shapes?

11. What is the function of the alveoli?

12. Describe the diaphragm. What is the function of the diaphragm? Can you think of another shape for the diaphragm?

13. What do you understand by the word "breathing"?

14. What are the changes that take place to the respiratory organs when we breathe in and breathe out? Answer using the table given below.

Organ	**Changes that happen while breathing in**	**Changes that happen while breathing out**
Lungs		
Diaphragm		

15. Draw and explain the changes that take place to the lungs and diaphragm while:
a) you breathe in
b) you breathe out

16. Where does the Oxygen taken into the body go to?

17. Where does the Carbon dioxide we breathe out come from?

18. How do you think Oxygen is always taken in, and carbon dioxide sent out of the body? Do you think carbon-dioxide could be taken in and Oxygen sent out?

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

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

21. What are the changes that you experience when you have a common cold? What are the reasons for these changes?

B.2.r.2. Respiratory system Part 2 (Phase II)

Homi Bhabha Centre for Science Education
Tata Institute of Fundamental Research
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Summer camp on "Visualisation in Biology"

Questions on the respiratory system: Part 2 (100505)

Please fill up the following details

Your name:
Class:
School:
Today's date:

Read the passages and answer the questions given below each of them. To answer the questions you may use words or drawings as you wish.

Passage 1

The nasal cavities are passages for air to go into the lungs, and to be sent out from the lungs. These cavities also have special receptors for smell. The pharynx is a short, common passageway for both air and food. It also carries air from the mouth. The pharynx leads to the larynx. This organ is involved in voice production. The larynx is followed by the trachea. The trachea is a cylindrical tube. Its wall is composed of soft tissue as well as rings of tough tissue called cartilage. It is lined with mucous membrane. The mucous membrane has hair-like structures called cilia. The trachea divides into two bronchi. The two bronchi lead to two lungs on each side. The lungs are divided into the right and the left lung. The left lung is smaller to accommodate the heart. The bronchi further divide into tubes which are smaller in diameter and are called bronchioles. The bronchioles end in tiny air-sacs called alveoli. Each alveolus has a thin wall lined with a fine network of capillaries.

Questions

a. Draw the respiratory organs mentioned in the passage and the location of each of them with respect to each other.

b. What would happen if there was no pharynx, or a common passage, before it divides into the trachea and oesophagus?

c. Why do you think the larynx or "voice-box" is located at the opening of the trachea? Do you think it could be located elsewhere?

d. Why does the trachea have both soft as well as tough tissue?

e. Why does the trachea divide further and further into smaller and smaller passages till it ends in the air-sacs or alveoli?

f. What is a capillary?
Why are the alveoli lined with a network of capillaries?

Passage 2

Three mechanisms help in the removal of foreign materials from the respiratory passage:

i) ciliary action
ii) peristaltic motion of the bronchioles
iii) cough reflex

The respiratory passage from the nasal cavities to the bronchi is lined by a layer of sticky mucus. Particles which come in with the inhaled air get trapped in this mucus. They get stuck mainly because of two reasons:

i) To trap the larger particles in the mucus, the direction of movement of air in the throat changes.
ii) To trap the smaller particles, there is a random or unplanned movement of particles in the same direction as the air.

Once the particles get stuck, they have to be removed along with the mucus in which they have been trapped. This is carried out by the cilia lining the inner wall of the trachea, which move the mucus towards the nose and mouth. The cilia in the nose beat downwards, while those in the trachea and the passages below it beat upwards.

A cough is a result of the irritation of the larynx, trachea and bronchi. A sneeze happens because of the irritation of the nasal passages. The outward movement of air sweeps the foreign particles out of the respiratory passages.

Irritation of the respiratory passages and the organs beyond the nose, results in a cough. Excessive irritation of the external respiratory organs results in a sneeze.

Questions

a. Draw diagrams and explain how small and large particles get trapped or stuck in the mucus lining the respiratory passage.

b. Draw diagrams and explain what is meant by “ciliary action”.

c. Taking a clue from what we have seen in the case of the digestive system, what do you understand by the "peristaltic motion of the bronchioles"?

d. How do you think peristaltic motion could help in removing the foreign particles from the respiratory passage?

e. Explain the difference between a cough and a sneeze in your own words or using diagrams.

Passage 3

Breathing happens in two parts or phases: inspiration or taking in air and expiration or giving out air. When we take in air, the size of the thorax is increased by the contraction of the diaphragm. This causes the elastic tissue of the lungs to expand and fill up the entire region enclosed by the ribs. When we breathe out, the ribs and diaphragm return to their normal positions and the lungs return to their normal size.

Questions

a. How do you think a cross-section of the lung would look like?

b. Can you think of another object or process in your daily life which you think is similar to the appearance or functioning of the lungs.

c. What would happen if there was no diaphragm in the respiratory system?

d. Draw diagrams to show the differences between inspiration and expiration.

B.2.r.3. Respiratory system Part 3 (Phase II)

Homi Bhabha Centre for Science Education
Tata Institute of Fundamental Research
V.N. Purav Marg, Mankhurd, Mumbai- 400088

Summer camp on "Visualisation in Biology"

Questions on the respiratory system: Part 3 (120505)

Please fill up the following details

Your name:
Class:
School:
Today's date:

Task 1

Go through the diagrams (Fig. 1, 2 and 3) carefully and answer the questions given below them.

Fig 1 The trachea, bronchi, bronchioles, alveoli and the lungs

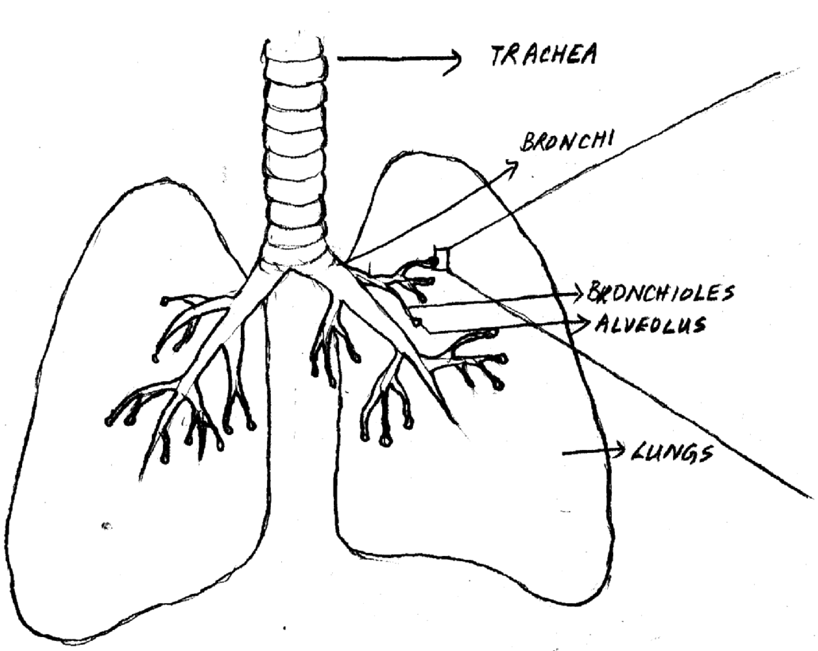


Fig 2 Exchange of gases between an alveolus and a blood capillary

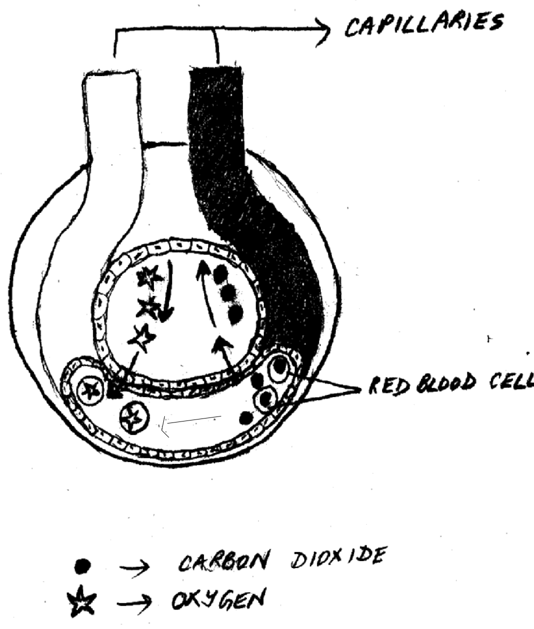
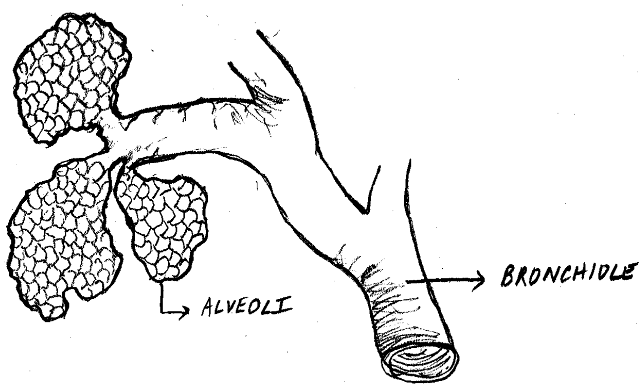


Fig 3 An enlarged bronchiole showing the alveoli



Questions

1a. Fill up the table given below using the information given in Fig. 1, 2 and 3. Use more paper if you wish.

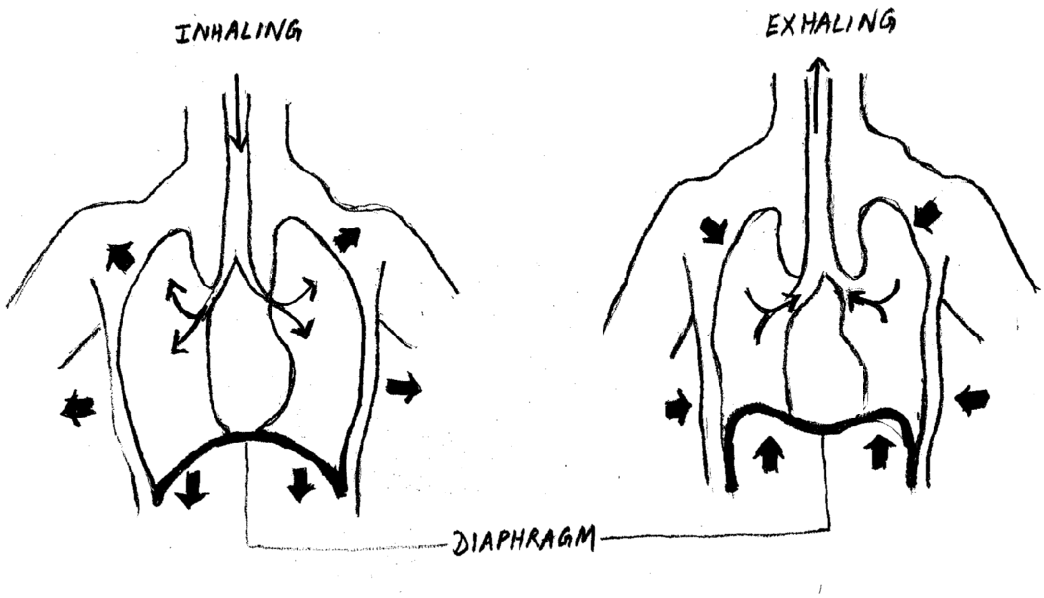
Organ	**Its location in the respiratory system**	**Its structure (its appearance, similarity to a familiar everyday object or geometric shape, etc.)**	**Its role or function in the respiratory system**
Trachea			
Bronchi			
Bronchioles			
Alveoli			
Lungs			

Fig.2 shows an enlarged alveolus, with its cross-section showing the exchange of gases between a capillary and an alveolus. From the figure:

1b. What do you understand by the term "exchange of gases"?
1c. What is a capillary? Why is it present in the alveolus?
1d. Where is the Oxygen shown in the figure coming from? Where is it going to?
1e. Where is the Carbon-dioxide coming from? Where is it going to?

Task 2
Fig. 4 and Fig. 5 show the processes of inhalation and exhalation.

Fig 4 **Fig 5**



2a. What are the changes that take place during both the processes. Use the table below for your answers. Use more paper if you wish.

Organ	Changes that happen while breathing in (inhalation)	Changes that happen while breathing out (exhalation)
Lungs		
Diaphragm		

2b. Why do you think there is a curved region in the lower part of the left lung in both Fig. 4 and Fig. 5 (the region marked ‘X’)?

C. Analysis criteria

C.1. Analysis criteria for Phase I

C.1.1. Coding scheme for the Digestive system (Phase I)

Comprehension of Verbal Structure (VrS)

I. Organs of the system

1. Mouth (comprising of 2. teeth, 3. tongue, 4. salivary glands), 5. oesophagus, 6. stomach,

7. duodenum, 8. liver, 9.pancreas, 10. small intestine, 11. large intestine, 12. anus

II. Order of location

1. mouth-oesophagus
2. oesophagus-stomach
3. stomach-duodenum
4. liver and pancreas connected to duodenum
5. duodenum-small intestine
6. small intestine-large intestine
7. large intestine-anus

Propositions from Std. 6 textbook (PS)

1. The tongue is a muscular organ.
2. There are four types of teeth in our mouth: incisors, canines, pre-molars and molars.
3. The oesophagus is also called food pipe.
4. The foodpipe is a passage.
5. The stomach is a bag-like structure.
6. The small intestine is a long tubular structure arranged in the form of a coil.

Comprehension of Verbal Function (VrF)

I. Order of function

1. mouth-oesophagus

2. oesophagus-stomach

3. stomach-duodenum

4. liver and pancreas connected to duodenum

5. duodenum-small intestine

6. small intestine-large intestine

7. large intestine-anus

II. Hierarchy

1. alimentary canal

2. liver and pancreas

Propositions from the 6 Std. Textbook (PF)

1. Different regions of the tongue carry different taste sensations.
2. Teeth are used to chew food during the process of mastication.
3. The incisors are used for biting.
4. The canines are used for biting and tearing.
5. The pre-molars and molars are used for grinding.
6. Food particles are mixed with saliva.
7. Saliva is secreted by the salivary glands.
8. Tongue helps in mixing saliva with the food.
9. Tongue helps in swallowing.
10. The foodpipe takes food from the mouth to the stomach.
11. The stomach contains an acidic juice.
12. Acids help in the digestion of proteins.
13. Food goes to the duodenum (first part of the small intestine) from the stomach.
14. Absorption of digested food takes place in the small intestine.
15. Digestion of food is completed in the duodenum and small intestine.
16. The waste material left after absorption of food moves to the large intestine.
17. The large intestine absorbs water.
18. The large intestine removes undigested food through the anus.

Comprehension of Diagram Structure (DS)

I. Segmentation

1. Mouth (comprising of 2. teeth, 3. tongue, 4. salivary glands), 5. oesophagus, 6. stomach, 7. duodenum, 8. liver, 9.pancreas, 10. small intestine, 11. large intestine, 12. anus.

II. Order of location

1. mouth-oesophagus
2. oesophagus-stomach
3. stomach-duodenum
4. liver and pancreas connected to duodenum
5. duodenum-small intestine
6. small intestine-large intestine
7. large intestine-anus

Comprehension of Diagram Function (DF)

I. Order of action

1. mouth-oesophagus
2. oesophagus-stomach
3. stomach-duodenum
4. liver and pancreas connected to duodenum
5. duodenum-small intestine
6. small intestine-large intestine
7. large intestine-anus

II. Hierarchy

1. alimentary canal
2. liver and pancreas

C.1.2. Coding scheme for the Respiratory system (Phase I)

Comprehension of Structure (VrS / DS)

I. Segmentation / Organs of the system

1. Nostrils (Nose)
2. pharynx

3. trachea

4. bronchi

5. bronchioles

6. alveoli

7. lungs

II. Order of location

1. nostrils-pharynx

2. pharynx-trachea

3. trachea-bronchi

4. bronchi-bronchioles

5. bronchioles-alveoli (in lungs)

6. alveoli-bloodstream

7. bloodstream- (cells)organs of the body

Propositions from the 6 Std. Textbook (PS)

1. Hair and mucus is present inside the nose.

2. Mucus is a sticky fluid present in the nose.

3. Lungs lie in the chest cavity bound by the ribs and the diaphragm.

4. The chest and diaphragm is made up of muscles.

5. The diaphragm is a powerful muscle situated inside the chest cavity below the lungs.

Comprehension of Function (VrF / DF)

I. Order of action

1. nostrils-pharynx

2. pharynx-trachea

3. trachea-bronchi

4. bronchi-bronchioles

5. bronchioles-alveoli (in lungs)

6. alveoli-bloodstream

7. bloodstream- (cells)organs of the body

II. Hierarchy

1. movement of air from the nose to the alveoli and gas exchange; mechanics of

respiration (external respiration)

2. internal / cellular respiration

Propositions from 6 Std. Textbook (PF)

1. Respiration involves exchange of gases: intake of Oxygen and release of carbon dioxide. This process is called breathing.

2. Energy released by the breakdown of digested foodstuff is called respiration.

3. Air enters the respiratory system through the nostrils during breathing.

4. The hair and mucus present inside the nose prevent dirt, dust and germs from entering the respiratory system.

5. Air that is rich in Oxygen is inhaled during breathing.

6. Oxygen containing air reaches the lungs, and then it enters the blood.

7. Blood transports Oxygen to different parts of the body.

8. Blood collects carbon dioxide with the help of the pigment haemoglobin present in it.

9. Carbon dioxide is formed as a waste product during respiration.

10. Water vapour and carbon dioxide are released from the blood into the lungs.

11. When we breathe out, water vapour and carbon dioxide are removed from the lungs.

12. Muscles of the chest and diaphragm help in breathing in and breathing out.

13. During inhalation, the diaphragm is pulled down (it appears flattened).

14. The lungs and chest cavity expand during inhalation of air.

15. During exhalation, the diaphragm moves up to its normal, curved position.

16. During exhalation, the lungs deflate or relax by pushing air out.

Respiratory system

Comprehension of Structure (VrS / DS)

I. Segmentation / Names of Organs

1. Nose

2. pharynx

3. trachea

4. bronchi

5. bronchioles

6. alveoli

7. lungs

II. Order of location

1. nose-pharynx
2. pharynx-trachea
3. trachea-bronchi
4. bronchi-bronchioles
5. bronchioles-alveoli
6. alveoli-bloodstream
7. bloodstream- (cells)organs of the body

Comprehension of Function (VrF / DF)

I. Order of action

1. nose-pharynx
2. pharynx-trachea
3. trachea-bronchi
4. bronchi-bronchioles
5. bronchioles-alveoli
6. alveoli-bloodstream
7. bloodstream- (cells)organs of the body

II. Hierarchy

1. movement of air from the nose to the alveoli and gas exchange; mechanics of respiration
2. internal/ cellular respiration

C.1.3. Coding scheme for the Circulatory system (Phase I)

Comprehension of Structure (VrS / DS)

I. Segmentation / Organs of the system

1. Heart
2. Arteries
3. Veins
4. Capillaries
5. Lungs

II. Order of location

Pulmonary circulation

1. heart-pulmonary artery
2. pulmonary artery-lungs
3. lungs-capillary bed in alveolus
4. alveolus-pulmonary vein

Systemic circulation

1. pulmonary vein-heart
2. heart-aorta
3. aorta-different parts of the body

Propositions from 6 Std. textbook

1. The circulatory system is composed of the heart and blood vessels.
2. The system of organs which circulate blood through our body is called the circulatory system.
3. The blood vessels are the arteries, veins and capillaries.
4. The heart is located in the chest cavity with its lower tip slightly towards the left.
5. Veins lie just below the skin and can be easily seen.
6. Arteries lie a little deeper under the skin and so cannot be seen easily.
7. A network of capillaries forms the connection between the arteries and veins.

Comprehension of Diagram structure

Comprehension of function (VrF / DF)

I. Order of action

Pulmonary circulation

1. heart-pulmonary artery
2. pulmonary artery-lungs
3. lungs-capillary bed in alveolus
4. alveolus-pulmonary vein

Systemic circulation

1. pulmonary vein-heart
2. heart-aorta
3. aorta-different parts of the body

II. Hierarchy

1. Systemic circulation

2. Pulmonary circulation

Propositions from 6 Std. textbook

1. The circulatory system makes food and Oxygen available to every cell of the body through blood.

2. The circulatory system helps in the removal of waste material from the cells.

3. The circulatory system maintains a uniform body temperature.

4. The veins carry blood from all the organs of the body back to the heart.

5. Veins (with the exception of the pulmonary vein) carry impure blood.

6. Arteries carry blood from the heart to all parts of the body.

7. Arteries (with the exception of the pulmonary artery) carry pure blood.

8. Before re-entering the heart, the blood carrying waste materials is purified by the lungs.

9. Blood is thus again enriched with Oxygen in the lungs.

10. During physical exercise the heartbeat generally increases.

11. The pressure of movement of blood through the artery is due to the beating of the heart. This is called the pulse.

12. The heartbeat and pulse rate change according to the condition of the body.

13. A physician uses a stethoscope to hear the sound of thumping of the heart.

Common questions to be asked to all the students during the clinical interviews:

You have left the spaces between the organs empty. Do you think there is anything in between the spaces? How are the various organs kept in their place?

1. What does it mean to represent something through a diagram as opposed to words?

2. Can you think of some other way of drawing the diagrams which you have shown?

(We could just ask them to suggest or describe various other ways of drawing the diagrams).

C.2. Criteria for analysis for Phase II

C.2.d. Digestive system

C.2.d.1. Digestive system Part 1

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Digestive system Phase II Part 1: Coding Scheme for Basic Knowledge and Visualisation

Basic Knowledge was derived from performance on Questions 1, 4, 6, 8, 10 and 12 of the Questionnaire above. The responses were coded based on the criteria of Segmentation, Order and Hierarchy. The scheme is summarized in the first four columns of the Table below, followed by the criteria for coding, which show the break-up of the scores.

Coding scheme for Phase II Part 1

Basic knowledge				**Visualisation**
Text responses (T)		**Drawn responses (D)**		**Generation and transformation of images (Text and Diagrams)**
Structure (TS)	**Function (TF)**	**Structure (DS)**	**Function (DF)**	
Names of Organs	-	Segmentation (depiction of organs)	-	
Order (location of organs)	Order of action	Order (location of organs)	Order of action	
-	Hierarchy	-	Hierarchy	

Criteria for coding

Numbers within brackets refer to the total score for the criterion

Basic knowledge: Comprehension of structure

Variables: Structure expressed through Text (TS) and Structure expressed through Diagrams (DS)

I. Segmentation = Names (text) or Depiction (diagrams) of the organs of the system (12):
1. Mouth (comprising of 2. teeth, 3. tongue, 4. salivary glands), 5. oesophagus, 6. stomach, 7. duodenum, 8. liver, 9.pancreas, 10. small intestine, 11. large intestine, 12. anus

II. Order of passage of food to the various organs expressed through text or diagrams (the same criterion is used for understanding function too) (7):

1. mouth-oesophagus
2. oesophagus-stomach
3. stomach-duodenum
4. liver and pancreas connected to duodenum
5. duodenum-small intestine
6. small intestine-large intestine
7. large intestine-anus

Total Score on TS / DS was calculated by adding the scores on Segmentation and Order and normalising to a maximum score of 1.

Basic knowledge: Comprehension of function

Variables: Function expressed through Text (TF) and Function expressed through Diagrams (DF)

I. Order of function expressed through text or diagrams (same as that given for structure) (7)

II. Hierarchy (2)

1. alimentary canal
2. liver and pancreas

Total Score on TF / DF was calculated by adding the scores on Order and Hierarchy and normalising to a maximum score of 1.

Visualisation was derived from performance on Questions 2, 3, 5, 7, 9, 11, 12 and 13.

*Four criteria for visualisation (holistically from both text and drawings), c*oded for each question requiring visualisation:

1. Generation of an image
2. Correctness / feasibility of the generated image
3. Ability to manipulate the generated image
4. Correct manipulation of generated image

These criteria were applied to the questions below. Assigning one point per criterion the maximum score was as given in brackets after each question. The question numbers are as per the numbering in the questionnaire:

2. 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? (4)

3. Draw the inside of your friend's mouth as it might have appeared to you. (4)

5. Suppose the food-pipe was longer or shorter. What difference would it make? Would it affect digestion of food? If so, how? (4)

7. Suppose the stomach was in the shape of a pipe. What difference would it make? Would it affect digestion of food? If so, how? (4)

9. Suppose the small intestine was much shorter. What difference would it make? Would it affect digestion of food? If so, how? (4)

11. Think of another shape for the large intestine. Would that different shape have any effect on the working of the large intestine? (4)

12. Imagine that you are eating a piece of bread toast. What changes does the toast go through in each digestive organ while it is being digested? Answer using the table given below. Use more paper if you wish.

Digestive Organ	**Changes that happen to the food while in this organ (use more paper to answer if you wish)**	**Condition of toast after it has passed through this organ (put a √ in the appropriate column)**		
		Liquid	**Semi-solid**	**Solid**
Mouth				
Oesophagus				
Stomach				

Small Intestine				
Large Intestine				

13. Try to show through a drawing what happens to the toast at each stage of the process of digestion. (20 points for both 12 and 13 taken together)

Summary of scores assigned to Part 1 variables for the digestive system
(S: Structure, F: Function, S-F: Structure-Function relationship)

Part I: Part 1 was scored overall for students' responses and not for each question individually except for the questions on visualisation

1. Text-structure

- Organs: 12
- Order: 7

Total score: 19

- Propositions: 6

2. Text-function

-Order of action: 7
- Hierarchy: 2

Total score: 9

- Propositions: 18

3. Diagrams-structure

- Segmentation: 12
- Order: 7

Total score: 19

4. Diagrams-function

- Order: 7
- Hierarchy: 2

Total score: 9

5. Visualisation

Question nos. with score for each question within brackets: 2 (4), 3 (4), 5 (4), 7 (4), 9 (4), 11 (4), 12/13 (20)

Total score: 44

Scores on Textbook knowledge

In addition, comparison with standard propositions from the Std. 6 Science textbook was used as a separate criterion to compare propositions in students' responses with standard propositions in the textbook.

Structure propositions (PS)

1. The tongue is a muscular organ.
2. There are four types of teeth in our mouth: incisors, canines, pre-molars and molars.
3. The oesophagus is also called food pipe.
4. The foodpipe is a passage.
5. The stomach is a bag-like structure.
6. The small intestine is a long tubular structure arranged in the form of a coil.

Function propositions (PF)

1. Different regions of the tongue carry different taste sensations.
2. Teeth are used to chew food during the process of mastication.
3. The incisors are used for biting.
4. The canines are used for biting and tearing.
5. The pre-molars and molars are used for grinding.
6. Food particles are mixed with saliva.
7. Saliva is secreted by the salivary glands.
8. Tongue helps in mixing saliva with the food.
9. Tongue helps in swallowing.
10. The foodpipe takes food from the mouth to the stomach.
11. The stomach contains an acidic juice.
12. Acids help in the digestion of proteins.
13. Food goes to the duodenum (first part of the small intestine) from the stomach.
14. Absorption of digested food takes place in the small intestine.
15. Digestion of food is completed in the duodenum and small intestine.
16. The waste material left after absorption of food moves to the large intestine.
17. The large intestine absorbs water.
18. The large intestine removes undigested food through the anus.

C.2.d.2A. Digestive system Part 2A (Phase II)

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Digestive System Phase II Part 2: Questionnaires with Scores Assignation

Part 2A – Comprehension of Structure Passages

Each question carries a certain number of points which are given within brackets. Questions numbers considered in the calculation of comprehension scores are marked with *. A summary of the questions considered and the total points they carry is given after the two questionnaires.

Read the passages given below and answer the questions given below each of them. To answer the questions you may use words or drawings as you wish.

Passage 1 (Mouth: Description of structure)
Understanding of function from a structural description (therefore understanding of function)

The mouth contains many teeth, one tongue and some salivary glands. We have four kinds of teeth: incisors, canines, pre-molars and molars. Incisors are the front teeth, which are flat in shape. On both sides of the incisors are the long and pointed canine teeth. Any food first comes into contact with the incisors and the canines.

Deeper in the jaw, behind the canines, are the pre-molars. The pre-molars have two points, or cusps, and are therefore called "bicuspids". Further deep inside, behind the pre-molars, are a few teeth which are the last to develop. These special teeth, called molars, have four or five points, or cusps.

The walls of the mouth cavity carry three pairs of salivary glands. Saliva secreted by these glands contains some active proteins, called enzymes. Some enzymes can convert starch into sugar. Other enzymes can kill bacteria. The saliva contains a lot of water and some slimy mucus.

The tongue is a muscular organ. It has on its surface thousands of special structures called taste-buds. There are different kinds of taste-buds for sweet, salty, sour and bitter tastes. Each of these four kinds of taste-buds are located in a specific region of the tongue.

a. Draw what you imagine could be the shapes of an incisor, a canine, a pre-molar and a molar tooth (4)

b. Draw a diagram to illustrate the position of the different kinds of teeth (1).

c. From the shape and location of each kind of tooth, what can you say about its function? Answer in the table given below. Draw diagrams if necessary (12). *

Type of tooth	**Shape of tooth**	**Where it is located in the mouth**	**Probable function of this tooth**
Incisor			
Canine			
Pre-molar			
Molar			

d. What could be the use of water and mucus in the saliva? Explain. (1) *

e. How does it help that the tongue is a muscular organ? What if the tongue were hard and bony? (1) *

f. A piece of roti, when chewed well, tastes sweet. Why? (1)

g. Can you taste all foods in all parts of the tongue? Why or why not? (1) *

h. Give examples of foods which have a taste that is a combination of two or more tastes. How could you detect such a taste? (1) *

i. If you cut your finger by mistake with a knife, and blood comes out of the cut, you are sometimes asked to put your finger in your mouth. Why do you think that is done? (1)

Passage 2 (Oesophagus and stomach: description of structure)

The oesophagus is a flexible tube. This tube begins at the back of the mouth. The walls of the tube can repeatedly relax and contract to push the food along the oesophagus.

The opening to the trachea lies close to the opening of the oesophagus. A flap of tissue called the epiglottis covers the trachea like a lid.

The oesophagus connects the mouth with the stomach. The walls of the stomach contain glands which secrete gastric juices, which are strongly acidic and act on the proteins. The inside of the stomach is lined with a thick layer of mucus which protects it from the action of these juices.

a. Which of these words might describe the walls of the oesophagus: soft, hard, strong, flexible, bony? (2) *

b. How do you think the food is pushed from the mouth to the stomach through the food-pipe? Make a drawing of it. (1) *

c. Where else can you see a similar process in the human body itself? (1) *

d. How might the epiglottis look like? Draw the trachea and oesophagus and show also the epiglottis in the drawing (1).

e. What would happen if the epiglottis were not there? (1) *

f. What do we do if food accidently lands on the epiglottis or enters the trachea? (1) *

g. After reading Passage 1 and Passage 2, what is your idea of a "gland"? About how big might be the glands mentioned in Passage 1 and Passage 2? (2) *

h. After reading Passage 1 and Passage 2, what is your idea of "mucus"? (1) *

i. What would happen if there were no layer of mucus on the inside of the stomach? (1) *

j. Draw diagrams to show what the stomach looks like and what happens inside it during digestion. (2) *

C.2.d.2B: Digestive system Part 2B (Phase II)

Part 2B – Comprehension of Function Passages

Each question carries a certain number of points which are given within brackets. Questions numbers …. only were considered in the calculation of comprehension scores. These questions are marked with *.

Read the passages given below and answer the questions given below each of them. To answer the questions you may use words or drawings as you wish.

Passage 1 (Mouth – description of function)

Digestion of food begins in the mouth. In our mouth we have four kinds of teeth: incisors, canines, pre-molars and molars. The teeth chew the food in the following way. First the incisors break off a piece of the food. Tough foods are torn up by the canines. Next the pre-molars and molars grind the food. This is how our teeth break up the food material into tiny pieces.

Three pairs of salivary glands in the mouth secrete saliva. Saliva mixes with the tiny pieces of food. Active proteins, or enzymes in the saliva, help convert some starch in the food into sugar. Other enzymes in the saliva kill bacteria. Mucus and water in the saliva helps us to smoothly swallow the chewed-up food.

The tongue moves the food around in the mouth to mix it with the saliva. The tongue also detects the taste of the food. Taste buds in specific regions of the tongue can detect one of four different kinds of tastes: sweet, salty, sour and bitter.

a. Draw what you imagine could be the shapes of an incisor, a canine, a pre-molar and a molar tooth (4). *

b. Draw a diagram to illustrate the action of the different kinds of teeth (4). *

c. From the function of each kind of tooth, can you guess its shape and location? Answer in the table given in the next page. Draw diagrams if necessary (12). *

Type of tooth	Function of tooth	Probable shape of this tooth	Where it might be located in the mouth
Incisor			
Canine			

Type of tooth	Function of tooth	Probable shape of this tooth	Where it might be located in the mouth
Pre-molar			
Molar			

d. What could be the use of water and mucus in the saliva? Explain. (1)

e. What do you think the tongue is made of? Could the tongue have bones in it? Could it have blood vessels? Or muscle tissue? (1) *

f. A piece of roti, when chewed well, tastes sweet. Why? (1)

g. Can you taste all foods in all parts of the tongue? Why or why not? (1) *

h. Give examples of foods which have a taste that is a combination of two or more tastes. How could you detect such a taste? (1)

i. If you cut your finger by mistake with a knife, and blood comes out of the cut, you are sometimes asked to put your finger in your mouth. Why do you think that is done? (1)

Passage 2 (Oesophagus and stomach – description of function)

When food is swallowed, it goes from the mouth into the oesophagus. The food is pushed along with the help of repeated contractions and relaxations of the oesophagus.

The opening to the trachea lies close the opening of the oesophagus. As we swallow, a flap of tissue called the epiglottis closes over the top of the trachea.

The food passes from the oesophagus to the stomach. Here, proteins are acted on by strong acids known as gastric juices, which are secreted by glands in the walls of the stomach. The mucus lining inside the stomach protects it from the action of these juices.

a. Which of these words might describe the walls of the oesophagus: soft, hard, strong, flexible, bony? (2) *

b. How do you think the food is pushed from the mouth to the stomach through the food-pipe? Make a drawing of it. (1) *

c. Where else can you see a similar process in the human body itself? (1) *

d. How might the epiglottis look like? Draw the trachea and oesophagus and show also the epiglottis in the drawing. (1) *

e. What would happen if the epiglottis were not there? (1) *

f. What do we do if food accidently lands on the epiglottis or enters the trachea (1)?

g. After reading Passage 1 and Passage 2, what is your idea of a "gland"? About how big might be the glands mentioned in Passage 1 and Passage 2? (2) *

h. After reading Passage 1 and Passage 2, what is your idea of "mucus"? (1) *

i. What would happen if there were no layer of mucus on the inside of the stomach? (1) *

j. Draw diagrams to show what the stomach looks like and what happens inside it during digestion. (2) *

Questions which probed understanding of Structure-Function relationships for the digestive system: Only the average of these questions was taken into account while calculating mean scores for Part II:

Part 2a

Question nos: 1c (12), 1d (1), 1e (1), 1g (1), 1h (1), 2a (2), 2b (1), 2c (1), 2e (1), 2f (1), 2g (2), 2h (1), 2i (1), 2j (2)
Total: 28

Part 2b

Question nos: 1a (4), 1b (1), 1c (12), 1e (1), 1g (1), 2a (2), 2b (1), 2c (1), 2d (1), 2e (1), 2g (2), 2h (1), 2i (1), 2j (2)
Total: 31

C.2.d.3A. Digestive system Part 3A

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Questionnaires, coding schemes, analysis and results

Digestive System Phase II Part 3: Questionnaires with Scores Assignation

Part 3A – Comprehension of Structure Diagrams

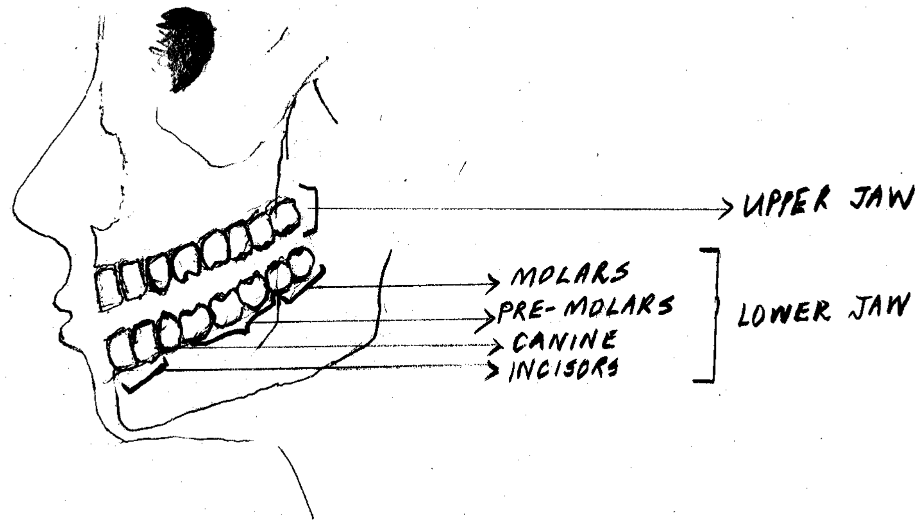
Each question carries a certain number of points which are given within brackets. Mean score for each passage was calculated by putting together scores obtained from all questions for Part 3a. However for Part 3b, three questions: 1, 3j and 2l were not taken into account in calculating the mean scores. All other questions were considered, and are marked with *.

Diagrams were adapted (simplified and converted to black and white line drawings) from: Broderick, M. (Ed.) (1994). The Human Body. Time Life's Illustrated World of Science. Hong Kong: Time Life Inc.

Task 1

Fig. 1 shows the side-view of Divya's upper and lower set of teeth (that is one half of her full set of teeth). Her lower teeth are labelled. The corresponding upper teeth have exactly the same names.

Fig. 1

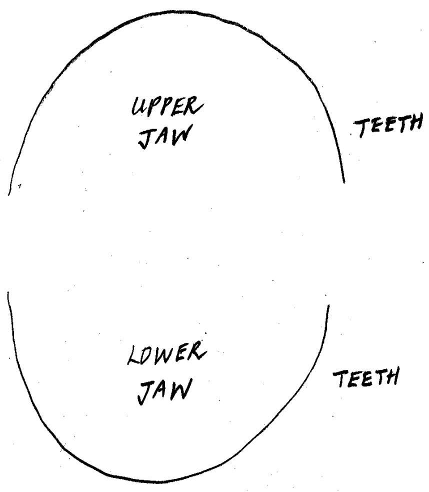


Now imagine that Divya is sitting in a dentist's clinic. The dentist says to her:

Dentist: Divya, please open your mouth wide.
(Divya opens her mouth as wide as possible.)
Dentist: A little wider ... Aah! Now I can see all your teeth.

1a. Show in a diagram how the dentist might see Divya's teeth when he looks into her mouth. Label the teeth in this diagram. Clue: use the format shown in Fig. 2 given below (1).

Fig. 2



1b. Now count Divya's teeth. Give the number of teeth in the table below. (13)

Type of tooth	Number in the upper jaw	Number in the lower jaw	Total number of teeth of this kind
Incisor			
Canine			
Pre-molar			
Molar			
Total number of teeth altogether:			

1c. Describe the shapes of each kind of tooth: an incisor, a canine, a pre-molar and a molar. Mention how they are different from each other. (4)

1d. How does each kind of tooth help in the process of chewing? (4)

1e. Is the shape of each tooth related to its function? How? (4)

1f. How many teeth do you have? (1)

1g. Are there any teeth you do not have? If so, when will you get them? (1)

1h. Why do you think you lost several teeth when you were about five-six years old? Are the teeth that you have now different from those teeth that you lost? How? (2)

1i. How do you think teeth fall off in old-age? Guess and explain through diagrams and words how this might happen. (2)

Task 2

2a. What is a cross-section? (1)

2b. Why do we draw cross-sections in diagrams? (1)

2c. Draw and label the cross-section of the wire that is given to you. (1)

2d. Give another example from everyday life where you saw a cross-section of something. (1)

2e. What more information was the cross-section able to give you which the whole object could not? (1)

Task 3

The diagram below shows the trachea (wind-pipe) and the oesophagus (food-pipe), which are located close to each-other. Fig. 3 shows the structure of the trachea and the oesophagus and its location in the body. Fig. 4 shows the cross-section of the two organs. The cross-section shows us that the trachea is a hard, rigid tube compared to the oesophagus which is softer and less rigid.

Fig. 3 Location of the trachea and the oesophagus in the body

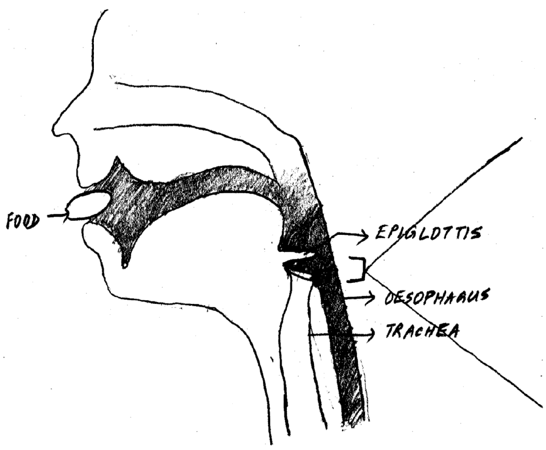
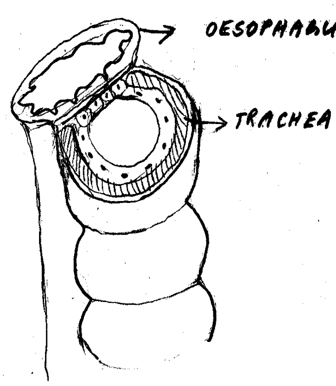


Fig. 4 Cross-section of the trachea and the oesophagus during normal breathing



3a. Make another drawing of the cross-section of the trachea and the oesophagus during normal breathing. Show the position of the epiglottis in your diagram. (3)

3b. Show how the trachea and the oesophagus would look like when you're swallowing a mouthful of food. Show a piece of food and the epiglottis in your diagram.

(4)

3c. Supposing you choke while swallowing food, how will your previous diagram change? Show the changes that happen in another diagram (1).

Task 4

Read the passage given below

The small intestine is a long tube which has the task of absorbing nutrients after they have been broken down by juices from the stomach and pancreas. To absorb the nutrients effectively, the inner surface of the small intestine is compressed into hundreds of folds and lined with thousands of finger-like protrusions called villi.

4a. Draw how you imagine the cross-section of the small intestine might look. (You need not show hundreds or thousands of folds or villi. A few will be sufficient for illustration.) (1)

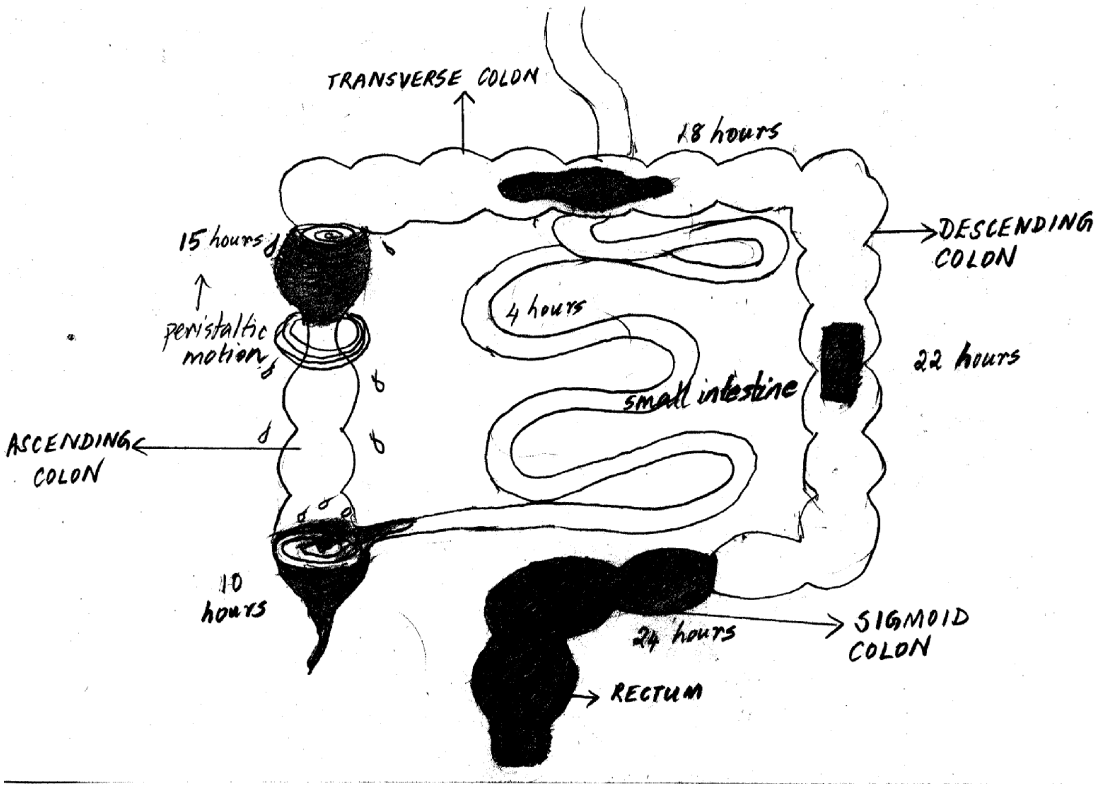
C.2.d.3B. Digestive system Part 3B (Phase II)

Part 3B – Comprehension of Function Diagrams

Each question carries a certain number of points which are given within brackets. Questions numbers 2a – 2k and 3a to 3i. only were considered in the calculation of comprehension scores. These questions are marked with *.

Task 5. Where does the food go after it is digested in the stomach? What happens to it in the small intestine? Where does it go from there? (3) *

Task 6. Only the undigested part of the food goes into the large intestine. The diagram below illustrates the working of the large intestine. Go through the diagram carefully, then answer the following questions:



6a. Where is the food just before it enters the large intestine? (1) *

6b. In the diagram you see the labels "ascending colon", "transverse colon", "descending colon" and "sigmoid colon". Explain what these labels indicate. (4) *

6c. You also see the labels "10 hours", "15 hours", "18 hours", "22 hours" and "24 hours". Explain what these times indicate. (5) *

6d. You see a ring drawn around the part which is labelled "peristaltic motion". This ring shows that, in that place, the walls of the large intestine are contracting. Due to this contraction, the food material moves further ahead. Once the material has moved further, the walls relax to their normal position. This successive contraction and relaxation is called peristaltic movement.

How is peristaltic movement useful to us? (1) *

6e. In which parts of the large intestine would you expect peristaltic movement to happen? (1) *

6f. How much time after eating the food does it enter the large intestine? How long does it stay in the large intestine? Describe in the following Table how the food material looks - either liquid, semi-solid or solid, in different parts of the large intestine. (10) *

Time	**Which part of the large intestine has it reached after this many hours?**	**State of the food**		
		Solid	**Semi-solid**	**Liquid**
10 hours				
15 hours				
18 hours				
22 hours				
24 hours				

6g. How does the food material change as it goes through the large intestine? Why does it change? What parts get absorbed in the large intestine? (3) *

6h. What is faeces composed of? How does the large intestine help in the formation of faeces? (2) *

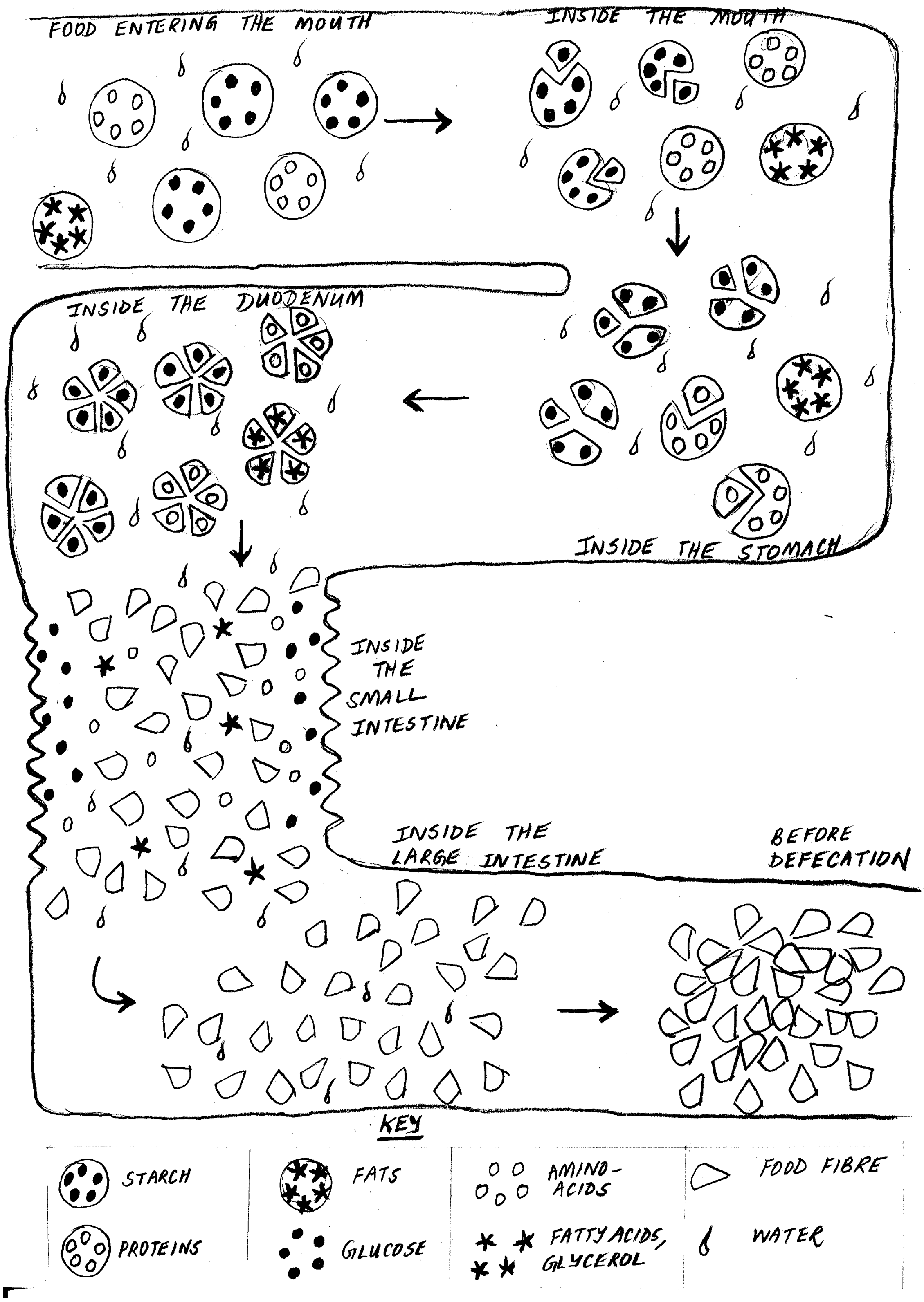
6i. Suppose that food stayed in the large intestine for longer than the normal time. What would be the result? (1) *

6j. Suppose peristaltic motion happened faster than normal. What would be the result? (1) *

6k. Explain step by step through words and drawings how peristaltic motion happens in the large intestine. Take a clue from the given drawing. (2) *

61. Where else in the body do you see peristaltic motion? (1) *

Task 7. The drawing below illustrates the process of digestion in the human body. Look through the diagram carefully and answer the questions below.



7a. What components of food are shown being taken in through the mouth? (3) *

7b. What changes are shown happening in the mouth? Why do these changes happen? (2) *

7c. What changes are shown happening in the stomach? Why do these changes happen? (2) *

7d. What changes are shown happening in the duodenum? Why do these changes happen? (2) *

7e. What changes are shown happening in the small intestine? Why do these changes happen? (2) *

7f. What components are shown being absorbed in the small intestine? (2) *

7g. What changes are shown happening in the large intestine? Why do these changes happen? (2) *

7h. What components are shown being absorbed in the large intestine? (1) *

7i. What are the components that are shown being excreted? (1) *

7j. Do you think that this diagram shows well what happens to food during digestion? Can you think of a better way of showing this? (2)

C.2.r. Analysis criteria for the Respiratory system (Phase II)

C.2.r.1. Respiratory system Part 1 (Phase II)

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Respiratory system Phase II Part 1: Coding Scheme for Basic Knowledge and Visualisation

Basic Knowledge was derived from performance on Questions 1, 2, 4, 5, 8, 9, 11, 13, 14, 16 and 17 of the Questionnaire B.2.r.1. The responses were coded based on the criteria of Segmentation, Order and Hierarchy. The scheme is summarized in the first four columns of the Table below, followed by the criteria for coding, which show the break-up of the scores.

Table 1: Coding scheme for Phase II Part 1

Basic knowledge				**Visualisation**
Text responses (T)		**Drawn responses (D)**		
Structure (TS)	**Function (TF)**	**Structure (DS)**	**Function (DF)**	**Generation and transformation of images (Text and Diagrams)**
Names of Organs	-	Segmentation (depiction of organs)	-	
Order (location of organs)	Order of action	Order (location of organs)	Order of action	
-	Hierarchy	-	Hierarchy	

Numbers in brackets refer to the total score for that criterion

Comprehension of structure

I. Organs of the system (8)

1. Nostrils (Nose)
2. pharynx

3. trachea
4. bronchi
5. bronchioles
6. alveoli
7. lungs
8. diaphragm

II. Order of functioning (similar criterion for both structure and function) (7)

1. nostrils-pharynx
2. pharynx-trachea
3. trachea-bronchi
4. bronchi-bronchioles
5. bronchioles-alveoli (in lungs)
6. alveoli-bloodstream
7. bloodstream- (cells) organs of the body

Comprehension of function

I. Order of action (similar criterion as for structure) (7)

II. Hierarchy (2)

1. movement of air from the nose to the alveoli and gas exchange; mechanics of respiration (external respiration)
2. internal / cellular respiration

Criteria for visualisation (holistically from both text and drawings)
Coded separately for both structure and function questions

1. Generation of an image (1)
2. Correctness / feasibility of the generated image (1)
3. Manipulation of generated image (1)
4. Correct manipulation of generated image (1)

These criteria will be employed for the following questions alone. This is in addition to analysis using the criteria mentioned earlier.

3. 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 (4)
b) you breathe out (4)

6. The trachea is quite strong and rigid compared to the oesophagus or food pipe. Why is it that way? (4)

7. What would happen if the trachea was a smooth, flexible structure? (4)

10. Describe the alveoli. Think of another shape for the alveoli. What is the difference between the two shapes? (4)

12. Describe the diaphragm. What is the function of the diaphragm? Can you think of another shape for the diaphragm? (4)

15. Draw and explain the changes that take place to the lungs and diaphragm while:
a) you breathe in (4)
b) you breathe out (4)

18. How do you think Oxygen is always taken in, and carbon dioxide sent out of the body? Do you think carbon-dioxide could be taken in and Oxygen sent out? (4)

19. Do you think the air taken into the body could serve any other function besides its role in respiration? (4)

20. What do you think is the difference between a sneeze and a cough? (4+4)

In addition, comparison with standard propositions from the Std. 6 Science textbook was used as a separate criterion to compare propositions in students' responses with standard propositions in the textbook.

Structure propositions (PS)

1. Hair and mucus is present inside the nose.
2. Lungs lie in the chest cavity bound by the ribs and the diaphragm.
3. The chest and diaphragm is made up of muscles.
4. The diaphragm is a powerful muscle situated inside the chest cavity below the lungs.

Function propositions (PF)

1. Respiration involves exchange of gases: intake of Oxygen and release of carbon dioxide. This process is called breathing.
2. Energy released by the breakdown of digested foodstuff is called respiration.
3. Air enters the respiratory system through the nostrils during breathing.
4. The hair and mucus present inside the nose prevent dirt, dust and germs from entering the respiratory system.
5. Air that is rich in Oxygen is inhaled during breathing.
6. Oxygen containing air reaches the lungs, and then Oxygen enters the blood.
7. Blood transports Oxygen to different parts of the body.
8. Blood collects carbon dioxide from the different parts of the body with the help of the pigment haemoglobin present in it.
9. Carbon dioxide is formed as a waste product during respiration.

10. Water vapour and carbon dioxide are released from the blood into the lungs.
11. When we breathe out, water vapour and carbon dioxide are removed from the lungs.
12. Muscles of the chest and diaphragm help in breathing in and breathing out.
13. During inhalation, the diaphragm is pulled down (it appears flattened).
14. The lungs and chest cavity expand during inhalation of air.
15. During exhalation, the diaphragm moves up to its normal, curved position.
16. During exhalation, the lungs deflate or relax by pushing air out.

Summary of the parameters and scores assigned to Part 1 variables

Part I: Part 1 was scored overall for students' responses and not for each question individually except for the questions on visualisation

1. Text-Structure

Organs: 8
Order of location of organs: 7
Standard propositions: 4
Total: 19

2. Text-Function

Hierarchy: 2
Standard propositions: 16
Total: 18

3. Diagrams-Structure

Segmentation: 8
Order of location: 7
Total: 15

4. Diagrams-Function

Order of function: 7
Hierarchy: 2
Total: 9

5. Visualisation

Question nos: 3a (4), 3b (4), 6 (4), 7 (4), 10 (4), 12 (4), 15a (4), 15b (4), 18 (4), 19 (4), 20 (8) Total: 48

C.2.r.2. Respiratory system Part 2 (Phase II)

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Questionnaires with scores assignation
Respiratory system: Phase II Part 2

Numbers given in brackets refer to the total number of points for each question. Only questions which checked for comprehension of Structure-function relationships were taken into account in calculation of average scores. These questions are marked with *. A summary of the questions used is given at the end of the questionnaire.

Read the passages and answer the questions given below each of them. To answer the questions you may use words or drawings as you wish.

The Respiratory system - Passage 1 *(Description of structure)*

The nasal cavities are passages for air to go into the lungs, and to be sent out from the lungs. These cavities also have special receptors for smell. The pharynx is a short, common passageway for both air and food. It also carries air from the mouth. The pharynx leads to the larynx. This organ is involved in voice production. The larynx is followed by the trachea. The trachea is a cylindrical tube. Its wall is composed of soft tissue as well as rings of tough tissue called cartilage. It is lined with mucous membrane. The mucous membrane has hair-like structures called cilia. The trachea divides into two bronchi. The two bronchi lead to two lungs on each side. The lungs are divided into the right and the left lung. The left lung is smaller to accommodate the heart. The bronchi further divide into tubes which are smaller in diameter and are called bronchioles. The bronchioles end in tiny air-sacs called alveoli. Each alveolus has a thin wall lined with a fine network of capillaries.

Questions

a. Draw the respiratory organs mentioned in the passage and the location of each of them with respect to each other (9).

b. What would happen if there was no pharynx, or a common passage, before it divides into the trachea and oesophagus? (1) *

c. Why do you think the larynx or "voice-box" is located at the opening of the trachea? Do you think it could be located elsewhere? (1) *

d. Why does the trachea have both soft as well as tough tissue? (1) *

e. Why does the trachea divide further and further into smaller and smaller passages till it ends in the air-sacs or alveoli? (1) *

f. What is a capillary? Why are the alveoli lined with a network of capillaries? (1) *

Removal of foreign material - Passage 2 ***(Description of function)***

Three mechanisms help in the removal of foreign materials from the respiratory passage:

i) ciliary action
ii) peristaltic motion of the bronchioles
iii) cough reflex

The respiratory passage from the nasal cavities to the bronchi is lined by a layer of sticky mucus. Particles which come in with the inhaled air get trapped in this mucus. They get stuck mainly because of two reasons:

i) To trap the larger particles in the mucus, the direction of movement of air in the throat changes.
ii) To trap the smaller particles, there is a random or unplanned movement of particles in the same direction as the air.

Once the particles get stuck, they have to be removed along with the mucus in which they have been trapped. This is carried out by the cilia lining the inner wall of the trachea, which move the mucus towards the nose and mouth. The cilia in the nose beat downwards, while those in the trachea and the passages below it beat upwards.

A cough is a result of the irritation of the larynx, trachea and bronchi. A sneeze happens because of the irritation of the nasal passages. The outward movement of air sweeps the foreign particles out of the respiratory passages.

Irritation of the respiratory passages and the organs beyond the nose, results in a cough. Excessive irritation of the external respiratory organs results in a sneeze.

Questions

a. Draw diagrams and explain how small and large particles get trapped or stuck in the mucus lining the respiratory passage. (1) *

b. Draw diagrams and explain what is meant by “ciliary action”. (1) *

c. Taking a clue from what we have seen in the case of the digestive system, what do you understand by the “peristaltic motion of the bronchioles”? (1)

d. How do you think peristaltic motion could help in removing the foreign particles from the respiratory passage? (1)

e. Explain the difference between a cough and a sneeze in your own words or using diagrams (1).

Breathing - Passage 3 ***(Description of function)***

Breathing happens in two parts or phases: inspiration or taking in air and expiration or giving out air. When we take in air, the size of the thorax is increased by the contraction of the diaphragm. This causes the elastic tissue of the lungs to expand and fill up the entire region enclosed by the ribs. When we breathe out, the ribs and diaphragm return to their normal positions and the lungs return to their normal size.

Questions

a. How do you think a cross-section of the lung would look like? (1) *

b. Can you think of another object or process in your daily life which you think is similar to the appearance or functioning of the lungs. (1) *

c. What would happen if there was no diaphragm in the respiratory system? (1) *

d. Draw diagrams to show the differences between inspiration and expiration. (2) *

Comprehension of structure-function relationship from text passage

Question nos:
S-F: 1b (1), 1c (1), 1d (1), 1e (1), 1f (2), 2a (2), 2b (1), 3a (1), 3b (1), 3c (1), 3d (4)
Total: 16

C.2.r.3. Respiratory system: Part 3

Homi Bhabha Centre for Science Education
Tata Institute of Fundamental Research
V.N. Purav Marg, Mankhurd, Mumbai- 400088

Respiratory system: Phase II Part 3 questionnaire with scores assignation

Mean scores were calculated by aggregating individual scores for every question. Diagrams have been adapted (simplified and colour converted into black and white line drawings): Broderick, M. (Ed.) (1994). The Human Body. Time Life's Illustrated World of Science. Hong Kong: Time Life Inc.

Task 1

Go through the diagrams (Fig. 1, 2 and 3) carefully and answer the questions given below them.

Fig 1 The trachea, bronchi, bronchioles, alveoli and the lungs

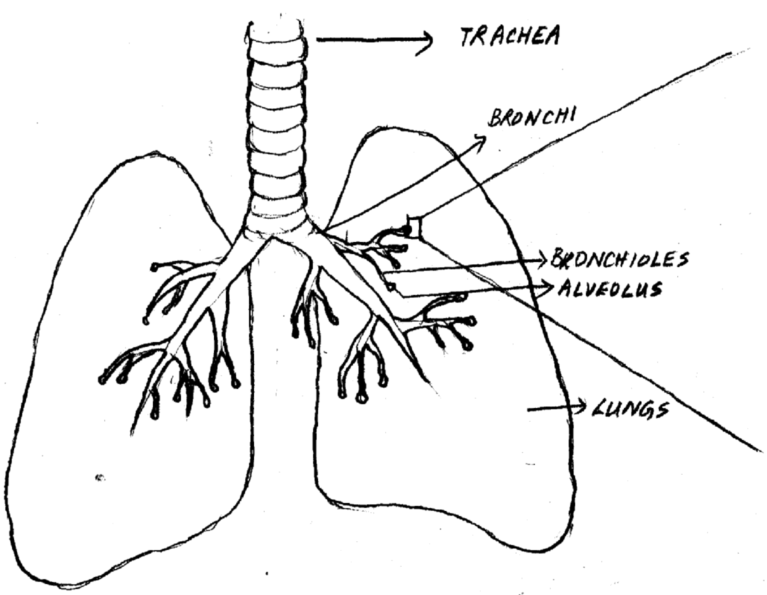
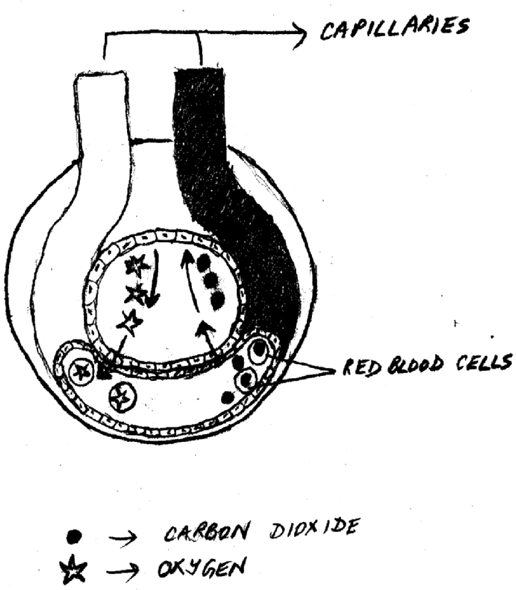
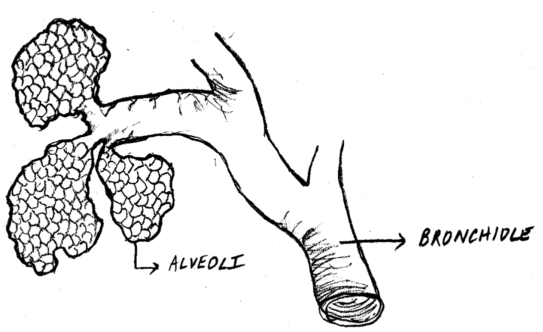


Fig 2 Exchange of gases between an alveolus and a blood capillary





Enlarged bronchiole showing the alveoli

Questions

1a. Fill up the table given below using the information given in Fig. 1, 2 and 3. Use more paper if you wish (15)

Organ	**Its location in the respiratory system**	**Its structure (its appearance, similarity to a familiar everyday object or geometric shape, etc.)**	**Its role or function in the respiratory system**
Trachea			
Bronchi			
Bronchioles			
Alveoli			
Lungs			

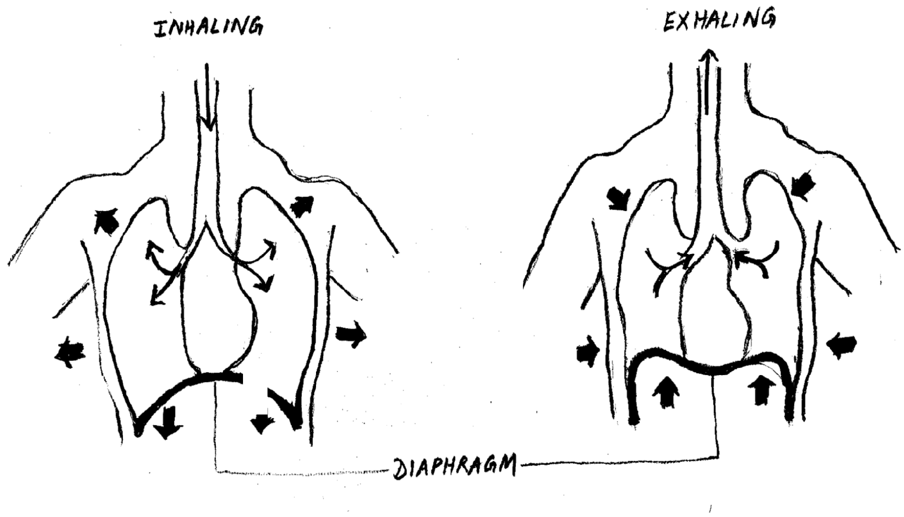
Fig.2 shows an enlarged alveolus, with its cross-section showing the exchange of gases between a capillary and an alveolus. From the figure:

1b. What do you understand by the term "exchange of gases"? (1)
1c. What is a capillary? Why is it present in the alveolus? (1)
1d. Where is the Oxygen shown in the figure coming from? Where is it going to? (2)
1e. Where is the Carbon-dioxide coming from? Where is it going to? (2)

Task 2

Fig. 4 and Fig. 5 show the processes of inhalation and exhalation.

Fig 4 **Fig 5**



2a. What are the changes that take place during both the processes. Use the table below for your answers. Use more paper if you wish (4).

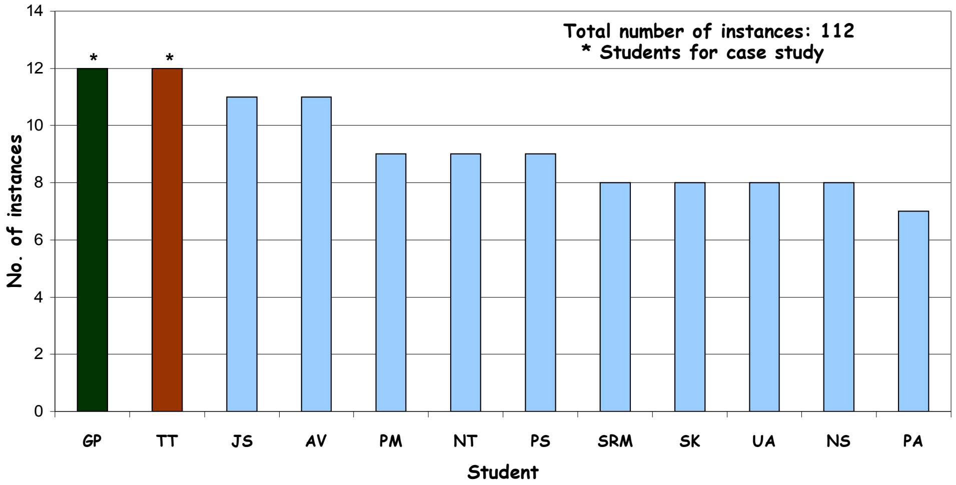
Organ	Changes that happen while breathing in (inhalation)	Changes that happen while breathing out (exhalation)
Lungs		
Diaphragm		

2b. Why do you think there is a curved region in the lower part of the left lung in both Fig. 4 and Fig. 5 (the region marked 'X')? (1)

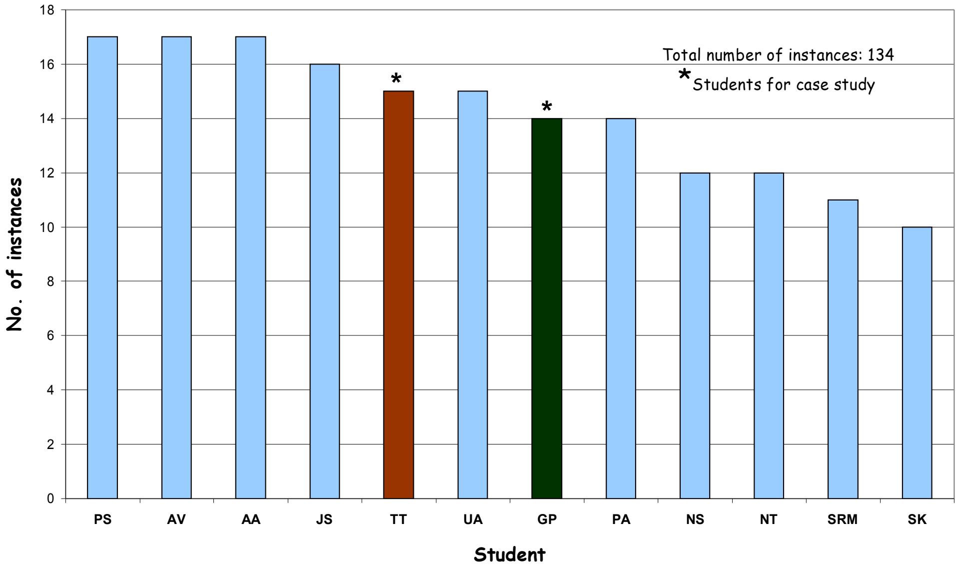
D. Some observations and results

D.1. Observations and results for Phase 1

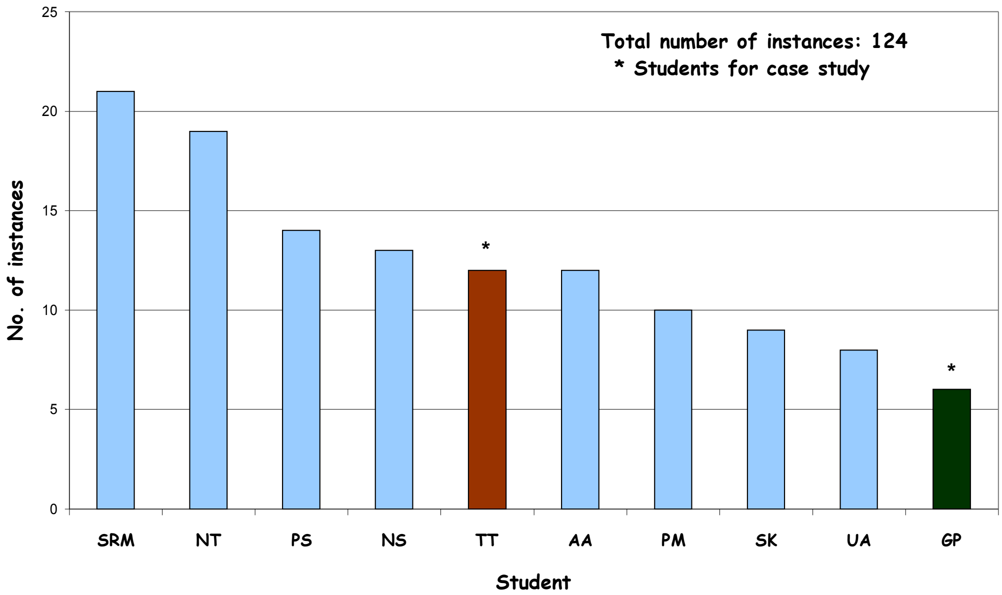
D.1.1. Instances of visual imagery for the digestive system



D.1.2. Instances of visual imagery for the respiratory system



D.1. 3. Instances of visual imagery for the circulatory system



D.1.4. Scores obtained by comparing students' propositions with a standard set of propositions

	PS-dig	PF-dig	PS-res	PF-res	PS-cir	PF-cir	PS-all	PF-all
AV	0.5	0.5	0.4	0.94	--	--	0.45	0.72
GP	0.67	0.5	0.6	1	0.14	0.01	0.47	0.5
JS	0.33	0.5	0.6	1	--	--	0.47	0.75
NT	0.5	0.33	0.6	0.56	0.08	0.01	0.4	0.3
NS	0.67	0.33	0.6	0.81	0.11	0.01	0.46	0.38
PA	0.67	0.11	0.6	0.56	--	--	0.64	0.34
PM	0.33	0.44	--	--	0	0	0.17	0.22
PS	0.17	0.5	0.6	1	0.14	0.01	0.3	0.5
SK	0.33	0.33	0.6	0.81	0.12	0.01	0.35	0.38
SRM	0.33	0.5	0.6	0.81	0.1	0.01	0.34	0.44
TT	0.5	0.56	0.6	0.94	0.13	0.01	0.41	0.5
UA	0.67	0.61	0.6	1	0.14	0.01	0.47	0.54

D.2. Observations and results for Phase 2 Part 1

D.2.1. Table: Average scores for the digestive and respiratory systems for Part 1 variables

	Variable	Criteria	Mean score	
			Digestive	Respiratory
Parameters within text analysis	TS	Names of organs	0.73	0.54
		Order of location	0.62	0.22
	TF	Order of function	0.61	0.22
		Hierarchy	0.66	0.53
Parameters within diagram analysis	DS	Segmentation	0.34	0.3
		Order of location	0.31	0.15
	DF	Order of action	0.38	0.14
		Hierarchy	0.44	0.31
Comparison with textbook propositions	PS	Propositions Structure	0.74	0.37
	PF	Propositions Function	0.52	0.63

E. Consent Letters

E.1. Consent letter for Phase I

HOMI BHABHA CENTRE FOR SCIENCE EDUCATION

(TATA INSTITUTE OF FUNDAMENTAL RESEARCH)

V.N. Purav Marg, Mankhurd, Mumbai 400 088

Subject: Short research study at the Homi Bhabha Centre for Science Education.

Dear parent,

I am a PhD student at the Homi Bhabha Centre for Science Education (HBCSE) pursuing a research study on the 'Role of visual imagery and drawings in understanding human physiology'. As part of my research work, I would like to have a few students at HBCSE for some testing and interviews starting from 5th April to 30th April 2004. The students will have to be present between 10.00 a.m. and 12.00 noon. Any change of timings or days will be intimated to the students. If your son or daughter is available during this period and would like to participate in the programme, I request you to kindly fill up the accompanying form and send it to the school.

Thanking you,

Sincerely,

Sindhu Mathai

HOMI BHABHA CENTRE FOR SCIENCE EDUCATION

(TATA INSTITUTE OF FUNDAMENTAL RESEARCH)

V.N. Purav Marg, Mankhurd, Mumbai 400 088

I want my son/ daughter ------------------------------ (name of student) studying in Std.____ , Section__ , to participate in the research study in May.

My residential address is:

--.

My telephone number is: -------------------------

I shall make up my own arrangements to drop and pick up my child.

Signature of the parent and date:

Name of the parent:

E.2. Consent letter for Phase II

HOMI BHABHA CENTRE FOR SCIENCE EDUCATION
(TATA INSTITUTE OF FUNDAMENTAL RESEARCH)
V.N. Purav Marg, Mankhurd, Mumbai 400 088
Ph: 25580036, 25567711

9 March 2006

Subject: Short research study at the Homi Bhabha Centre for Science Education

Dear parent,

I am a PhD student at the Homi Bhabha Centre for Science Education (HBCSE). My area of research is to understand students' comprehension and expression of understanding of the *human body* through two modes: *writing and drawing*. I am conducting a short research study this summer on students who are going to Std. 7 from five different AECS schools.

Period of the study:

Venue: *Homi Bhabha Centre for Science Education*

Time: *8.00 a.m. to 10.00 a.m.*

I have designed some questions which incorporate both text and diagrams and would help students visualise the structure and functioning of the human body. We also have some *teaching interventions* which would help them better understand the systems of the body. Any change of timings or days will be intimated to the students. If your son or daughter is available during this period and would like to participate in the programme, I request you to kindly fill up the accompanying form and send it to the school. Thank you.

Sincerely,
Sindhu Mathai

HOMI BHABHA CENTRE FOR SCIENCE EDUCATION
(TATA INSTITUTE OF FUNDAMENTAL RESEARCH)
V.N. Purav Marg, Mankhurd, Mumbai 400 088

I want my son/ daughter ------------------------------ (name of student) studying in AECS___, Std.____, Section__ , to participate in the research study.

My residential address is:

My telephone number is: ------------------------
I shall make up my own arrangements to drop and pick up my child.
Signature of the parent and date:
Name of the parent:

F. Content on the digestive, respiratory and circulatory systems in Class 6 NCERT textbook, 2002

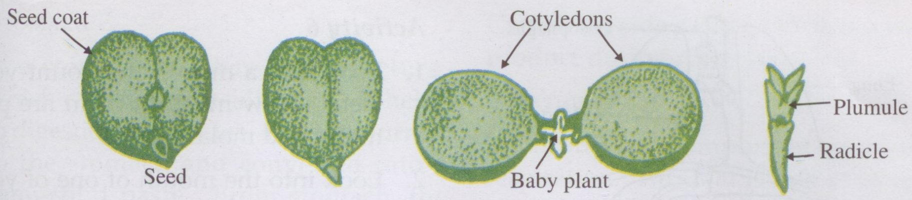


Fig. 8.12 A seed contains a baby plant

THE SEED

The maize, peas and beans are seeds. A seed contains a baby plant and food for the new plant (Fig. 8.12). Generally, a seed consists of a seed coat. It has many other parts like cotyledons, radicle and plumule about which you will study in higher classes.

Activity 5

Take a few seeds of chick-pea (chana), peas and beans. Soak them in water for a few hours. Remove their coats and try to locate the position of the baby plant in each one of them.

8.2 Organ Systems in Humans

All human beings have different organs to perform various functions. Some of these, such as, eyes, ears and limbs are visible. Other organs, like kidneys, lungs, stomach and liver cannot be seen. They are situated inside the body. Each organ of the body has a special function to perform. The ears help us in hearing. They also help us in balancing our body. The eyes help us in seeing things. It would be interesting to know about these organs and the way they function.

You know that many cells join to form a tissue. Many tissues make an organ. When several organs work in co-ordination to perform a distinct function, they make an **organ system**. It is the simultaneous and regulated activity of these organ systems that makes a human body, as shown in the following flow chart:

Cells → Tissues → Organ system→Human body

Let us now learn some more about the various organ systems in human body.

DIGESTIVE SYSTEM

All animals including human beings need nutrients to grow and function properly. They obtain them from food. This purpose is served by the **digestive system.** It includes feeding, digestion, absorption and defecation. When we eat food (**feeding**), it gets broken down into smaller particles. These particles then get changed into absorbable forms in the body **(digestion)**. The digested food is then absorbed and used in the body (**absorption**). The unabsorbed food is thrown out of the body in the form of faeces (**defecation**). There are several organs in the digestive system of human beings that are involved in performing these functions. You already know that one of these organs is mouth. The other organs in the digestive system are oesophagus, stomach, small intestine, large intestine, liver, gall bladder, pancreas and anus (Fig. 8.13).

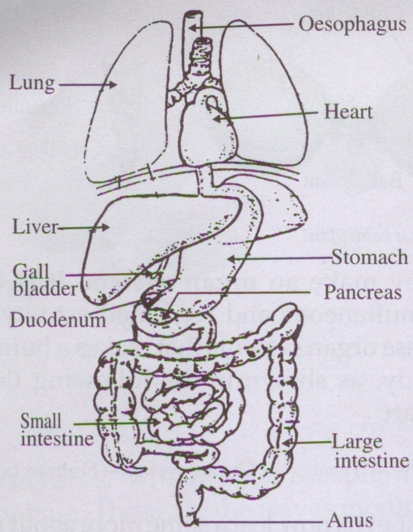


Fig.8.13 The digestive system

The mouth contains teeth, salivary glands and tongue. When we eat food, our teeth grind the food material to smaller particles. These particles mix with saliva secreted by the salivary glands.

There are four types of teeth in our mouth. They are called incisors, canines, pre-molars and molars (Fig.8.14). The incisors help in biting the food; the canines are used for cutting and tearing the food; the pre-molars and molars grind the food. Teeth are used to chew the food. This process is called **mastication** during which saliva mixes with food.

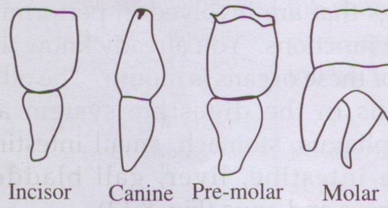


Fig.8.14 Different types of teeth

Activity 6

1. Look into a mirror and count your teeth. How many of them are pre-molar and molar?
2. Look into the mouth of one of your friends. How many incisors and canines are present in your friend's mouth?

Three pairs of **salivary glands** are present in our mouth. These glands secrete a watery material called saliva. You are familiar with the secretion of saliva in your mouth at the sight of good food. Saliva helps in digestion of food.

The **tongue** is a muscular organ (Fig.8.15). It has many functions. It helps us to speak. It also helps in mixing saliva with food, swallowing and taste sensation. You will be surprised to see from Fig.8.15 that different regions of tongue carry different taste sensations.

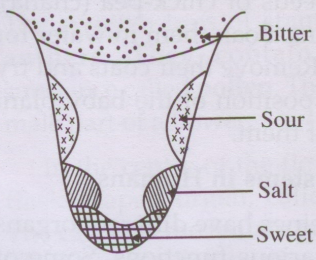


Fig.8.15 Different taste regions of tongue

Activity 7

Taste samples of sugar syrup, lemon juice, common salt solution and the extract of neem leaves or bitter gourd (**karela)** under the supervision of your teacher or parent. Which region of the tongue senses the taste of each one of them?

Oesophagus is commonly called food pipe. It acts as a passage to take the food from mouth to stomach.

Stomach

The stomach is a bag like structure, which contains an acidic juice. It helps in digestion of proteins. Food is churned in the stomach and converted into a semi-solid paste. From stomach, the food goes into the small intestine through the duodenum.

Small Intestine

Small intestine is a long tubular structure. It is arranged in the form of a coil. Digestion of food that starts in stomach is completed in duodenum and small intestine. Absorption of digested food into blood takes place in the small intestine. The waste material left after absorption of food in the small intestine moves to the large intestine.

Large Intestine

The large intestine performs the task of absorbing water. It also helps in removing the undigested solid waste materials from our body through the anus.

It may be interesting to know that the small intestine is larger in length (about 6 metres) than the large intestine (about 1.5 metres).

You will learn about some other organs of the digestive system, for example, liver, gall bladder and pancreas in higher classes.

RESPIRATORY SYSTEM

We know that living organisms need oxygen. It helps in breaking down the food absorbed in the body to release energy. We require energy to do work. This process is known as **respiration.** Carbon dioxide gas is formed as a waste product during respiration.

Breathing

Breathing is an important process of respiration. Air, that is rich in oxygen, is inhaled during breathing. The oxygen-containing air reaches the **lungs**. Here, oxygen enters the blood. Water vapour and carbon dioxide are released from the blood into the lungs. When we breathe out, these are removed from the lungs. We respire about 12-14 times in a minute.

Nostrils (passages in the nose), trachea, bronchi and lungs are the main organs of the respiratory system (Fig.8.16). The muscles of the chest and diaphragm help in breathing in and breathing out.

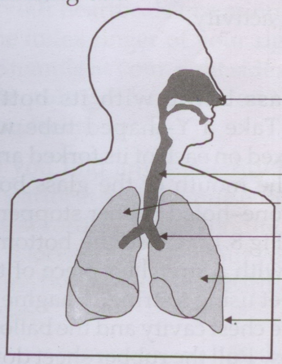


Fig.8.16 The respiratory system

Air enters the respiratory system during breathing through the nostrils. The hair and mucus (a sticky liquid) present inside the nose prevent dirt, dust and germs from entering the respiratory system. Breathing from mouth is not desirable because it may not be dust-free and may contain germs. It may be interesting for you to observe that you breathe in and breathe out mostly with only one nostril at a time.

Activity 8

Keep your finger under your nose, close to the nostrils. Try to feel the air you breathe out. Does the air come out from both the nostrils with the same force?

Also, breathe out air from your nose on a mirror. Does the mirror fog? If yes, give the reason for it. What happens to the fog after some time? Explain your observation.

You have already learnt that diaphragm helps us in breathing out. **Diaphragm** is a powerful muscle situated inside the chest cavity below the lungs. The functioning of the diaphragm can be understood by performing a very interesting activity.

Activity 9

Take a glass bottle with its bottom removed. Take a Y-shaped tube with balloons fixed on each of its forked arms. Fix it on the mouth of the glass bottle through a one–holed rubber stopper, as shown in Fig.8.17. Close the bottom of the bottle with a stretched piece of thin rubber sheet using a string. Imagine the bottle as the chest cavity and the balloons as the lungs. Pull the rubber sheet down. The space in the bottle increases. Due to this, pressure decreases in the bottle. As a result, the balloons get inflated by sucking in the air. When you release the rubber sheet, the balloons get back to the normal size. Similarly, when you press the rubber sheet, the pressure in the bottle increases. Due to this, the balloons deflate by pushing the air out. The action of the rubber sheet shows how the diaphragm works in our body. This is the way we breathe in and breathe out air with the help of the movement of the diaphragm.

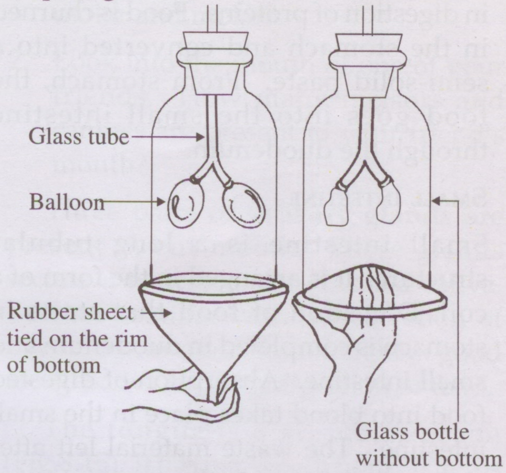


Fig.8.17 Model to show the role of diaphragm in breathing

CIRCULATORY SYSTEM

The system of organs, which circulates the blood through our body, is called

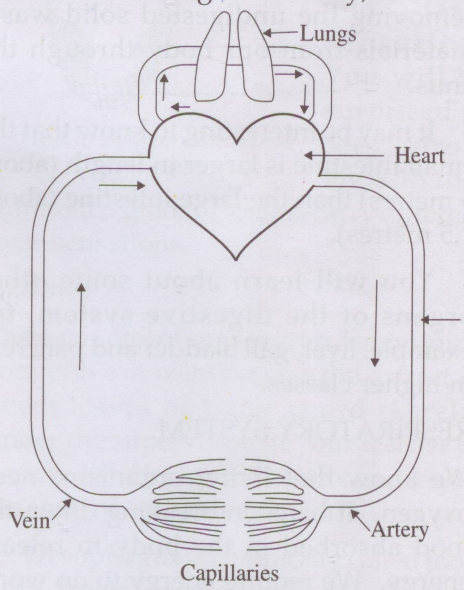


Fig. 8.18 The circulatory system

circulatory system. This comprises heart and blood vessels. You might like to know why such a system exists in our body? It is because food and oxygen are to be supplied to all parts of the body. The circulatory system makes food and oxygen available to every cell of the body through the blood. It also helps in the removal of waste materials from the cells and maintains a uniform body temperature. A network of blood vessels in the circulatory system performs this task. The blood vessels are of three types – **arteries, veins** and **capillaries**.

The **heart** is a part of the circulatory system. It is a very important organ in our body. It is located in the chest cavity, with its lower tip slightly towards the left. It is about the size of the fist of your left palm.

Activity 10

Observe your hands and legs. Also, observe the hands and legs of your father or mother, or any other elderly person. Do you see many greenish blue lines, just below the skin? These are veins and can be easily seen. Arteries lie a little deeper under the skin so they cannot be seen easily. Arteries carry blood from the heart to all parts of the body. The veins carry blood from all the organs of the body back to the heart. However, before re-entering the heart, the blood carrying waste materials is purified by lungs. In this process, the blood is again enriched with oxygen in the lungs. A network of capillaries forms the connection between the arteries and the veins.

Our heart normally beats at the rate of 70-72 per minute. However, during physical exercise or running, the rate of heartbeat generally increases. This can be felt by an increase in the thumping of heart. You can also feel the pressure of movement of blood through the artery at your wrist due to beating of heart. This is called **pulse**. For measuring the pulse, a physician uses a **stethoscope** to hear the sound of thumping of the heart. You can count your heartbeat by a very simple method.

Activity 11

Let us feel our pulse and find out its rate per minute. Place the middle and index fingers of your right hand on the inner side of your left wrist. What do you feel? Do you feel your pulse? Count the number of pulse in a given time, say 15 s. You can find out the number of times your heartbeats in a minute. Next, put the index finger of your right hand on the temple at your right side. Do you feel the pulse? Where else on the body can you feel the pulse?

Do you find any similarity between your heartbeat and the pulse rate? Both change according to the condition of the body. Doctors can tell about your body condition by counting the heartbeats and pulse rate.

You can compare your heartbeats and pulse rate while at rest and after running for 2-3 minutes with a simple device.

Activity 12

Take a 50 cm long rubber tube and fit it tightly at the end of the stem of a funnel (6-7 cm diameter). Put the open end of the tube in one of your ears. Place the funnel on your chest near the heart. Now try to listen carefully. Do you hear a regular thumping sound? These are the heartbeats. Count the number of heartbeats per minute and after running for 2-3 minutes. Compare both.

> **Do you know?**
>
> The average heartbeat of an adult human is 70-72 per minute. Neil Armstrong was the first human being to land on the moon. When he first landed on the surface of the moon, his heartbeats were 156 per minute! More than double the normal heartbeats. It might be interesting for you to know that our heartbeats go up at the slightest excitement, fear, nervousness and stress and strain. However, such a change lasts for a short duration.

STETHOSCOPE

Most of you have seen a stethoscope. A medical practitioner uses it. A stethoscope

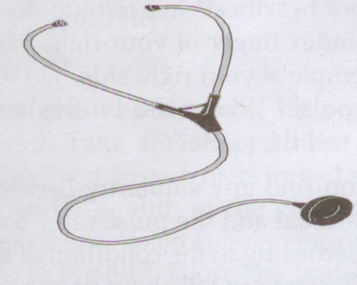


Fig. 8.19 A stethoscope

is a device that amplifies the sound of a heartbeat. It consists of three parts: (a) chest piece that carries a sensitive diaphragm, (b) two earpieces, and (c) a tube joining the parts (a) and (b) (Fig. 8.19). A stethoscope is used to clearly hear the heartbeats and other sounds in the chest and the back by placing the chest piece at the appropriate place.

NERVOUS SYSTEM

You are now familiar with the digestive, respiratory and circulatory systems in our body. You might like to know how such a diverse range of functions goes on so smoothly. The activities of these systems are controlled by the **nervous system**. Organs of the nervous system are nerves, spinal cord and brain. The brain is located in the skull. The spinal cord runs inside the bony structure of the backbone. The nerves are distributed all over the body.

Nervous system receives messages from the brain. They are then passed on to various organs and parts of the body through the nerves. Right portion of the brain controls the left part of the body. The left portion of the brain controls the right part of the body. However, activities like heartbeat take place automatically.

We live in an environment that changes continuously. It can be dark or light, warm or cool. Sometimes it is noisy, sometimes it is quiet. How do we sense these changes? Our sense organs, such as, eyes (light), ears (sound), nose (smell), tongue (taste of solids and liquids) and skin (heat, cold, pain and touch) help us in becoming aware of them.

The sensations caused by the external stimuli, such as, light, heat, smell, sound and touch are carried from the sense organs, through nerves, to the brain or spinal cord. On receiving a message in the form of a sensation, the body reacts to it. This reaction is decided in the brain. The brain then sends out commands to different parts of the body for action, again through nerves. Nerves are distributed all over the body. The