This is an extended web version of '*Srivastava, A. & Ramadas, J. (2013). Analogy and Gesture for Mental Visualization of DNA Structure. In Treagust, D.F. & Tsui, C.-Y. (Eds.), Multiple Representations in Biological Education. Dordrecht, The Netherlands: Springer.*' This version contains data from microgenetic analysis of all five students.

Analogy and Gesture for Mental Visualization of DNA Structure (Extended Version)

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Available at : http://www.hbcse.tifr.res.in/data/pdf/as-jr-dnastudy-extendend-version.pdf

Abstract

We explore five beginning undergraduate students' understanding of the 3-D nature of DNA structure. Through clinical interview-cum-teaching sessions we first recapitulate their background knowledge of basic biology and chemistry prerequisites. We then proceed to a microgenetic study of their understanding of DNA structure, in which we find that initially, all the students interpret their familiar textbook diagrams as 2-D structures rather than 2-D representations of the 3-D structures. We then use multiple models to develop their understanding. Based on previous research we conjecture that gesture, analogy, and mental simulation involving changing the viewpoint of the observer, could be used to link together multiple external representations into an integrated internal representation, and thus bring about mental visualization of the 3-D structure. Through a microgenetic time-sequence analysis we identify episodes during which students show 'positive' i.e. 2-D to 3-D transitions and 'Aha!' moments, and trace these learning episodes to use of gesture, in combination with mental simulation using the 'ladder analogy' with 'character viewpoint' imagery.

Keywords: Analogy, DNA structure, Gesture, Model-based reasoning, Visualization

Introduction

The birth of molecular biology was significantly marked by the discovery of the double helical structure of the DNA molecule by Watson and Crick (1953a). The general correctness of this structure was gradually proven in subsequent years by substantial research on the structural as well as functional aspects of the molecule. The structure of DNA had immediate functional implications: “It follows that in a long molecule many different permutations are possible, and it therefore seems likely that the precise sequence of the bases is the code which carries the genetical information” (Watson & Crick, 1953b, p. 965).

Conceptual understanding in molecular biology involves integration of the macro (genetic traits), micro (cell) and molecular (gene) levels. A student needs to enter into the chemistry of the biomolecule, which in turn calls on understanding of the physics of atoms and molecules. Building up of the molecular structure and its location at the cellular level finally leads to its biological significance, e.g., genetic expression. Marbach-Ad and Stavy (2000) remark that the difficulty in understanding and linking these different organizational levels is “because sometimes one level (e.g., the macro level) 'belongs' to one discipline (e.g., biology), and the other level (e.g., the molecular level) 'belongs' to different discipline (e.g., chemistry)”. In fact, the integration occurs in several ways, one that includes concepts from various disciplines, another that involves the macro, micro and the molecular levels, and finally, the structure-function linkages within and across these levels.

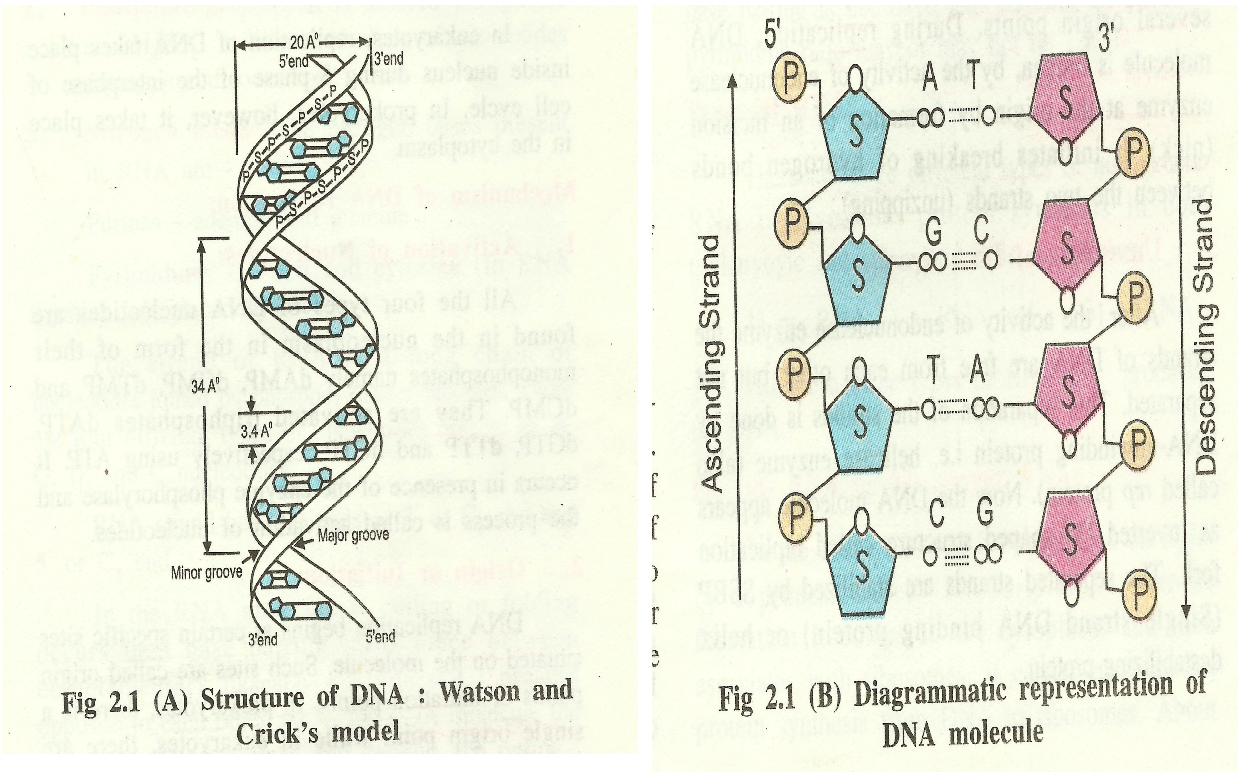
Structural-functional linkages have been identified as a problem area in elementary genetics (Marbach-Ad, 2001; Lewis and Wood-Robinson, 2000; Lewis, 2004). Yet, in a study of major problem areas in biological sciences as identified by students, Bahar et al. (1999) reported that the structure and function of the DNA and RNA molecule was considered as one of the “least difficult” areas. We make a case here that students do have a problem in understanding the basic 3-D structure of the DNA molecule.

Structure of the DNA molecule

The double-helical structure of the DNA molecule can be visualized as two right-handed helices coiled around a central axis. Each helix is composed of a sugar-phosphate backbone and each (deoxyribose) sugar molecule in this backbone is attached with a nitrogen base through a glycosidic bond to form a nucleoside unit. The nitrogen bases - purines (Adenine or Guanine) or pyrimidines (Thymine or Cytosine) are paired in a complementary fashion where Adenine forms two hydrogen bonds with Thymine and, Guanine forms three hydrogen bonds with Cytosine. These hydrogen bonds along with the glycosidic bonds ensure that the nitrogen bases of the DNA molecule are planar ring structures of equal length which are perpendicular to the central DNA axis and also to their attached sugar molecules. Orientation of the nitrogenous base pairs and the specific hydrogen bonding between the complementary base pairs give rise to a basic ladder shape, which is coiled into a right handed helix of specific dimensions. The chemistry of the constituents of DNA, including the details of atomic structure, electronic configuration, chemical bonds, etc., is consequential to the integrity of the overall physical structure of the molecule.

Textbook representations of DNA structure

In Indian schools, the chemical prerequisites for learning the biology of the DNA molecule are built up from middle school till the higher secondary level (age 17), as part of the chemistry curriculum. The higher secondary biology textbook followed by our sample (MSB, 2009), introduces the DNA molecule by describing the components of nucleotides, the pentose sugar, phosphate group and the nitrogenous bases, with their chemical formulae. The analogy of a “twisted ladder” is followed by two kinds of diagrammatic representations. The first (Figure 1 a) is a schematic representation of the “DNA double helix”, depicting two criss-crossing wavy ribbon-like strands, in which are labeled the “S-P-S-P” (sugar phosphate) links in the backbone. Also labeled are the “major groove”, “minor groove” and the 3' and 5' ends. Connecting the backbone are the skeletal structures of the nitrogenous base pairs with the respective number of hydrogen bonds. The dimensional details: diameter of the helix (20 Å), one helical turn (34 Å), and distance between adjacent nitrogenous base pairs (3.4 Å), are indicated. The accompanying text mentions the angle between successive base pairs, or “pitch angle” to be 36˚ and also that each “spiral turn” contains 10 pairs of nucleotides (p. 15).



a b

Figure 1. Textbook diagrams (MSBSHSE, 2009, p. 15): a) Double Helix; b) Ladder Structure

The second diagram (Figure 1 b) is the "detailed molecular structure" which is a ladder structure containing skeletal outlines of the pentagonal sugar molecules connected with the phosphate groups, labeling the 3' and 5' ends. The sugar molecules are shown attached with purines (two joined circles) or pyrimidines (one circle). The hydrogen bonds between the complementary bases are represented through either two (for AT) or three (for GC) dotted lines. Thus, by the end of high school, students are introduced to standard diagrams of the DNA molecule. The "twisted ladder" is an analogy for DNA structure which has considerable potential to help students mentally visualize the structure at both the gross physical and the detailed chemical levels. Our interest was in seeing that whether they are able to sustain the analogy at both of these levels in order to form a mental image of the 3-D molecular structure of DNA.

Role of multiple representations in learning

The role of multiple external representations (MERs) in supporting students' learning has been explored by Ainsworth (1999) and Tsui and Treagust (2003). Multiple representations are believed to support complementary information or processes, by having a familiar representation help to understand the information carried by, or constrain the interpretation of, a new representation. Ainsworth's analysis, and Tsui and Treagust's applications of it to genetics reasoning, are done in the context of computer-aided learning. Both of these papers however refer to MERs in more general terms, and further assume a link between external representations and internal mental representations. Ainsworth suggests that MERs support abstraction, extension and relations among representations while Tsui and Treagust carry out a detailed analysis of students' learning and reasoning in genetics as they use multiple representations (Ainsworth, 1999; Tsui and Treagust, 2003; 2007).

The question of how MERs could connect with internal mental representations is one that is important for science pedagogy to address. Recent research on embodied and spatial cognition provides a possible answer. The embodied view of cognition suggests that our reasoning is enabled significantly by our ability to participate in actions in the world, and that our internal representations are not amodal (propositional), but linked to our sensorimotor perceptions and actions (Clark, 1997; Barsalaou, 1999). One direct implication of the embodied view is that MERs connect to internal representations through the learner's perceptions and actions.

Drawing further from the embodied view of cognition, we suggest that a possible pedagogical route from external to internal (mental) representations might be through the use of gesture. Goldin-Meadow and Beilock (2010) argue that gestures affect thinking by grounding it in action, and that gestures may even be a more powerful influence on thought than action itself. They see gesture as a form of simulated action, in which there is no direct manipulation of the world, but the result of it is a rich internal representation that incorporates the sensorimotor properties required to act on the world (Goldin-Meadow and Beilock, 2010).

This insight from cognitive science was used by Padalkar and Ramadas (2010) to propose a pedagogical purpose for deliberately designed gestures in science. Gestures might be used to “internalize” a natural phenomenon, a model, or properties of space. Models are three dimensional and visually realistic but are limited by the fact that they are not transformationally flexible and hence are less amenable to analytical thought. Diagrams on the other hand are visually economical and precise in capturing analytical relationships, but their two-dimensional, static and abstract nature poses difficulty. Gestures are shown to share complementary properties with both models and diagrams, and thus used to link models with diagrams. Importantly, the gestures in this study serve not only to link external representations with internal mental ones, they are also designed to link two types of external representations (concrete models and diagrams) (Padalkar & Ramadas, 2010).

Mental models are transformationally flexible, and hence can be used to simulate phenomena. The intuitive notion of “transformational reasoning” was developed in Ramadas (2009) and applied in the context of structure and function of human body systems by Mathai and Ramadas (2009). They proposed that tasks calling for imagined manipulation of structure, or changing the viewpoint of an observer, would encourage mental visualization of body systems (Mathai and Ramadas, 2009). The idea of changing observer viewpoint ties in well with Goldin-Meadow and Beilock's (2010) discussion of hierarchies of gestures and actions. In their analysis of McNeill's (1992) classification, 'character viewpoint' gestures reflect actual movements, 'observer viewpoint' gestures capture the goal object or its trajectory, and 'metaphoric' gestures represent abstractions. Goldin-Meadow and Beilock (2010) suggest that character and observer viewpoint gestures, if used in sequence, could provide a bridge between concrete actions and more abstract representations.

Taking all the above proposals together, we suggest that: a. gestures could be used to link external and internal representations, b. gestures could be used to link together different MERs into an integrated internal representation, c. real or imagined manipulations or transformations of structure, and changing the view-point of the observer, could bring about mental visualization of the structure, and d. character viewpoint gestures or actions could help in making a molecular, here, DNA structure, more comprehensible to students.

A complementary approach to building internal mental representations, particularly visual ones, is that of analogy. Gentner (1989) defined analogy as a mapping from a base (familiar) domain to a target (unfamiliar) one. Duit (1991) showed that the analogy relation is intrinsic to model-based reasoning and learning in science. Justi and Gilbert (2006) brought out the close relationship between visualization, mental models and analogy in the history and pedagogy of chemistry. Harrison and Treagust (2006) argued that "analogy is a powerful way to think, construct ideas and test new knowledge". Analogy (like gesture) has a potential to help construct mental visual models from multiple external representations. We used the analogy of the 'twisted ladder' for encouraging visualization of DNA structure at the physical and the chemical levels. A combination of gesture and the ladder analogy, with the device of changing observer viewpoint and specifically, using a 'character viewpoint' simulation of DNA structure, was also possible, and fruitful.

This study

We examined students' reasoning processes in understanding the 3-D nature of the DNA molecule, through the integration of pre-requisite facts from physics and chemistry, supported by appropriate simple and low-cost external representations (MERs) of DNA structure. We explored through a microgenetic study the following research questions:

1. Are students able to link the 'ladder' analogy with common 2-D diagrams of DNA structure to form a mental model of the 3-D structure of the molecule?
2. Can we use gesture to link the 2-D representations and the 'ladder' analogy with the 3-D concrete models of DNA structure?
3. Can we use mental simulation of changing observer viewpoint to link the 2-D representations and the 'ladder' analogy with the 3-D concrete models of DNA structure?

Through a screening test we selected five students of ages 17-19 years, enrolled in the first year of a three year bachelors degree course in the biological sciences (Table 1).

Table 1
Demographic Information of Participants in this Study

Name of the student[1]	Age (in years)	Gender	Mother Tongue	Degree pursuing (Bachelors)	Courses taken in the current semester[2]
Anuja	18	F	Marathi	Microbiology	MPC
Sharada	18	F	Oriya	Biotechnology	BMC
Nitin	19	M	Marathi	Microbiology	MPC
Sandhya	17	F	Telugu	Biotechnology	BMC
Aakriti	18	F	Hindi	Microbiology	MPC

[1]Names are changed to preserve anonymity
[2]MPC: Microbiology, Physics, Chemistry; BMC: Biotechnology, Microbiology, Chemistry

We used a microgenetic research design (Siegler and Crowley, 1991; Siegler, 2006; Flynn and Siegler, 2007) which is appropriate for situations that involve rapid transitions in learning by tracing the processes of the students' learning under dynamic, *in vivo* conditions. The three important attributes of a microgenetic study are: a) Observations span the period of rapidly changing competence, b) within this period, the density of observations is high, relative to the rate of change, and c) Observations are analyzed intensively, with the goal of inferring the representations and processes that gave rise to them. (Siegler, 2006, p. 469). Students are observed very closely during the period of learning and then these observations are revisited again and again for a finer understanding of the patterns that depict "change in real-time as how it occurs" (van der Aalsvoort et al., 2009, p.9).

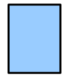
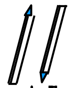
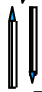
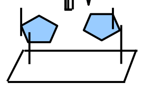
In our study, observations were carried out during six individual sessions held over nine days. Each session involved a clinical interview-cum-teaching sequence for 1 to 1.5 hours for each student per day. The language of the interview was English except for some occasions when Marathi and occasionally Hindi were used for two of the interviewees: Nitin and Aakriti. The prerequisites for the sessions lay within the syllabus for secondary and higher secondary schools recommended by the State Board. Sessions on Days 1 through 4 focused on initial assessment and recall of prerequisite concepts in biology and chemistry. Brief sequences of direct instruction were included in order to bridge some inevitable gaps in understanding. The issue of 3-Dimensionality of DNA structure was addressed on Days 4 through 6 and these data were analyzed microgenetically.

Multiple representations of the DNA backbone and the nitrogenous base pairs

Students were asked to draw the textbook diagrams (the ladder and helical structures of Figures 1 (a) and (b)), and recall the well-known ladder analogy for DNA structure. The DNA backbone was represented by five simple models (M1 to M5 in Table 2). M1 comprised of a sheet of paper laid on the table and the students were asked to consider its long edges to represent the two DNA backbones. M2 was two (anti) parallel pencils laid on the table and considered as the two DNA backbones. M3 was a variant of M2 where the two anti parallel pencils (the backbones) were made to stand erect on the table. M4 was a cutout model depicting the two backbones, each consisting of two phosphate groups attached with one sugar molecule at its 3' and 5' positions, fixed on a cardboard base. M4 thus showed the molecular details of the two sugar-phosphate backbones.

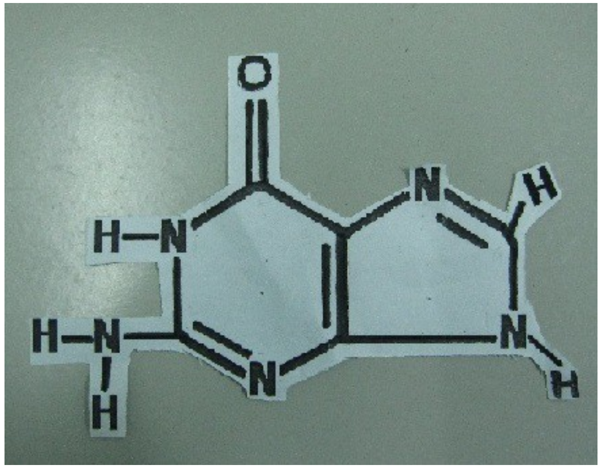
Table 2

Multiple Representations of the DNA Backbone

Model No.	**Backbone representation**	
M1	Long edges of a sheet of paper (laid on the table)	
M2	Two (anti) parallel pencils (laid on table)	
M3	Two (anti) parallel pencils (held to stand erect on table)	
M4	Cardboard cutout of a sugar molecule attached with two phosphate molecules (two sets) standing on a cardboard base	
M5	Clothespin model (ladder representation of DNA which can be assembled on a table and then twisted to form a helix)	

M5, or the 'clothespin model,' was adapted from Venville (2008). Students were provided with two plastic tubes along which could be strung interlocking clothespins of four different colors (green, yellow, blue and pink) to represent the complementary DNA bases. Students were asked to construct the M5 model to depict first the ladder structure and then the helical representation of the DNA molecule.

In combination with models representing the DNA backbone, two types of representations of the nitrogenous base pairs were introduced. The first representation consisted of card cutouts of the different N-bases (Figure 2) which was suggested by Watson's own account of his discovery of base-pairing, as recounted in a beautiful video produced by the Cold Spring Harbor Laboratory. Students were to use these cutouts against the M4 model to depict the orientation of the base pairs in the molecular model, while indicating the position of attachment of the base with the sugar molecule in the backbone.



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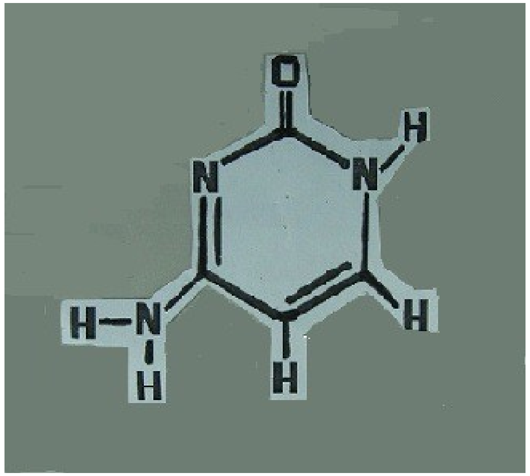


b

Figure 2. Cutouts of molecules of nitrogenous bases – (a) Purine base (b) Pyrimidine base

The other base pair representation comprised of the 'palm gesture' in which the portion from the wrist till the base of fingers was considered as either a purine or a pyrimidine molecule and the straightened fingers as the complementary nitrogen base (pyrimidine or purine) (Figure 3). Students used the gesture to imitate the orientation of the base pairs in the ladder against the models M1-M5, as appropriate.

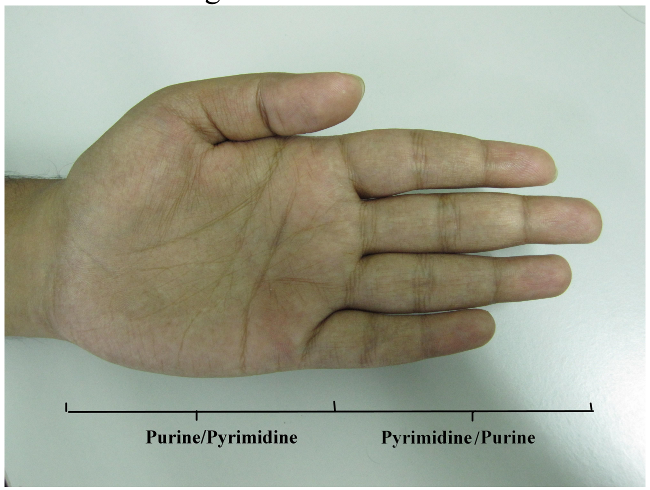


Figure 3. Palm gesture with palm and straightened fingers representing a complementary base pair.

The last type of representation was the ladder analogy, via which the backbone and the base pair representations were combined. Students were asked to visualize, first a straight ladder, and then a twisted ladder. The ladder analogy was used as a reminder to students while they attempted to show the base pair orientation with the help of the palm gesture or the cutouts. If the analogy by itself did not work then the students were instructed to mentally simulate the action of walking up the straight ladder, and in that situation consider how the steps of the ladder would be oriented. The gesture and mental simulation device were also used for the helical ladder structure in model M5. The mental visualization (of the straight or the twisted ladder) and the simulation (of walking up the ladder) correspond respectively to the 'observer viewpoint' and 'character viewpoint' gestures/actions discussed by Goldin-Meadow and Beilock (2010). Here the actions are of course, not actually carried out, but mentally simulated.

Preparing the background (Days 1, 2, and 3)

Day 1 explored students' understanding of the concept of DNA as the genetic material. We probed their familiarity with the terms like 'genetic material', 'gene', 'heredity' etc. Students were asked about cells, the location of genetic material and DNA as genetic material. Almost all the students had problem in understanding the relationship between the gene and DNA, for example, whether gene is inside the DNA or DNA is inside the gene. A discussion on the Hershey and Chase experiment, which proved that DNA is the genetic material, showed that all the students were unclear about the structure and function of a virus, or bacterium, and they were unable to recall anything about radioactivity. Each day from Day 2 till Day 6 began with students' diagrammatic representations of the DNA ladder and the double helix as some approximation of the two familiar textbook diagrams (Figure 1 (a) and (b)). Day 2 focused on recapitulating elementary background related to the chemistry of the DNA molecule where, despite many confusions revealed along the way, students were re-introduced to the idea of nitrogenous bases (purines and pyrimidines) and the electronegative nitrogen atom in them which can interact with a positively charged hydrogen atom of another nitrogenous base to form a hydrogen bond. On Day 3 students explored different pairing possibilities between the bases using cutout models of the N-bases. They eventually used the cutouts to form the A-T double bond and G-C triple bonds, to demonstrate that the base pairs were planar and of identical lengths.

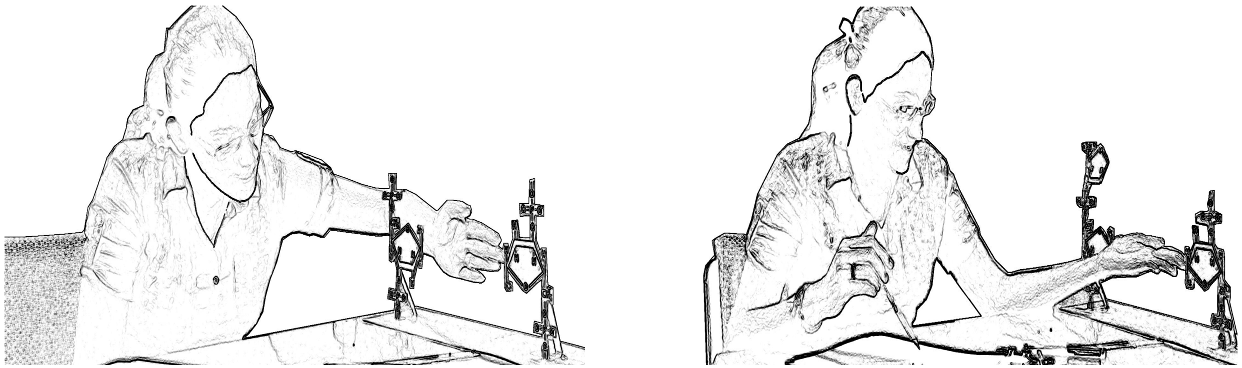
Introduction to the nucleoside (Day 4)

At the start of Day 4, students were introduced to the 'palm gesture' (Figure 3), asked to imagine its correspondence with the planar base pairs, and to use the gesture against the M1 and/or M2 model. All students began with an incorrect gesture, i.e., they showed the base pairs in the plane of the straightened parallel backbones. This was the first episode of the microgenetic study to which we will turn in the coming sections. Day 4 then continued with questions and tasks which required re-visiting of the concepts like chemical bonds and the valencies of atoms depicted in the cutouts of the nitrogenous bases and the sugar molecule. Students were shown the M4 model of the sugar phosphate backbone and were asked to depict base pair orientation against it through the 'palm gesture' as well as through the cutouts of the bases. The day also involved instructions regarding heterocyclic atoms, functional groups and IUPAC numbering conventions for bases and sugar. This line of discussion was significant to help students understand the structure of the nucleotide unit and the antiparallel nature of the two strands.

Sharada and Aakriti needed to build their background on atomic structure and bonds (hence they were introduced to M4 only on Day 5). The purpose of Days 2, 3 and 4 was to familiarize the students with the planar structures formed through the bonding of the purines and pyrimidines and the chemistry involved in the formation of individual DNA units along with introducing gesture and analogy as tools to visualize the orientation of the nitrogenous base pairs. Student interactions on Days 5 and 6 then dealt largely with the 3-Dimensionality of the DNA structure, which was analyzed microgenetically.

Data analysis (Microgenetic study)

The video data from Day 4 to Day 6 was subjected to a time-sequence analysis. This time period, from between 189 and 235 minutes for the five students, was scanned for 'episodes' consisting of continuous stretches of time during which students engaged themselves with the 3-Dimensionality of the DNA molecule. An episode had either one or more 'events' where the learner made a guided or a spontaneous attempt to depict base pair orientation or twisting of the M5 backbone. The base pair orientation was indicated by their 'palm gesture', i.e. placing of the palm against the DNA backbones (M1-M5), or through similar placing of the cutouts of the base pairs (against M4 only) (Figure 4). The backbone models (M1-M5) in use during that episode were noted, along with the correctness ('+' event) or the incorrectness ('-' event) of placing of the base pairs. The time period was counted from the start of Day 4 as t=0.



a b

Figure 4. Palm gesture used with M4 model – (a) Incorrect (-) gesture; (b) Correct (+) gesture

Tables 3 (a-e) describe the sequence of correct (+) and incorrect (-) events for each student and the specific backbone models (M1-M5) referred to in each event of the episode.

Table 3

a) Microgenetic analysis of episodes related to 3-dimensionality of the DNA structure for Anuja

Day	Day 4										Day 5							Day 6						
Start time[1]	7.5 min		37.1 min								55.5 min	74.09 min		122.3 min	125.6 min		134.4 min		164.2 min					
Episode No. (Duration)	**I** (0.3 min)		**II** (5.6 min)								**III**	**IV** (0.4 min)		**V**	**VI** (1.1 min)		**VII** (3.0 min)		**VIII** (2.2 min)					
Event +[2]							M3	M2	M4	M4 (c)	M4 (c)	Air z	Air z	M5 x	M5	M5	M5 z	M5 z			M4	M4 (c)		M4 (c)
Event -[3]	M1	M1	M4	M1	M2	M2													M4 (c)	M4			M4 (c)	

M5 ladder construction (Start time - 75.0 min)
M5 helix formation (Start time - 119.3 min)

[1]Start Time : The start time denotes the beginning of the episode with Day 4 starting at t=0
[2]Event + : Palm gesture or cutout orientation (c) perpendicular to DNA axis (correct)
[3]Event - : Palm gesture or cutout orientation (c) parallel to DNA axis (incorrect)
M4 (c) indicates that the cutouts of the N-bases were being used to show orientation. In all other cases, the palm gesture was being used.
The shaded events depict palm gesture in reference to the helical model, in M5 or in Air.
0: none of the base pairs twisting; x: Only two base pairs twisting; y: Partial or non-uniform twisting; z: uniform twisting

b) Microgenetic analysis of episodes related to 3-dimensionality of the DNA structure for Sharada

Day	Day 4		Day 5											Day 6
[1]**Start time**	4.4 min		56.1 min						110.2 min				121.2 min	134.1 min
Episode No. (Duration)	**I** (1.6 min)		**II** (1.1 min)						**III** (1.0 min)				**IV**	**V**
[2]**Event +**								Air		M4	M4 (c)	M4 (c)	M4 (c)	M5 z
[3]**Event -**	M1	M2	Air	Air z	Air z	Air z	Air		M4 (c)					

M5 ladder construction (Start time - 58.1 min) **M5 helix formation (Start time – 130 min)**

[1]Start Time : The start time denotes the beginning of the episode with Day 4 starting at t=0
[2]Event + : Palm gesture or cutout orientation (c) perpendicular to DNA axis (correct)
[3]Event - : Palm gesture or cutout orientation (c) parallel to DNA axis (incorrect)
M4 (c) indicates that the cutouts of the N-bases were being used to show orientation. In all other cases, the palm gesture was being used.
The shaded events depict palm gesture in reference to the helical model, in M5 or in Air.
0: none of the base pairs twisting; x: Only two base pairs twisting; y: Partial or non-uniform twisting; z: uniform twisting

c) Microgenetic analysis of episodes related to 3-dimensionality of the DNA structure for Nitin

Day	Day 4								Day 5														
[1]**Start time**	8.2 min		55.3 min	65.4 min					76.5 min	115.4 min						122.1 min	125.2 min						
Episode No. (Duration)	**I** (0.8 min)		**II**	**III** (3.6 min)					**IV**	**V** (3.5 min)						**VI**	**VII** (1.1 min)						
[2]**Event +**							Air	M4 (c)	Air				M1	M4	M5				M4		M4		M4 (c)
[3]**Event -**	M1	M2	M4	M4	M4	Air				M4 (c)	M4	M1				M4 (c)	M4 (c)	M4		M4 (c)		M4 (c)	

M5 ladder construction (Start time - 77.2 min)

Table for Nitin continued...

Day	Day 5 Contd.				Day 6						
[1]**Start time**	129.1 min			132.2 min	158.3 min				172.5 min		
Episode No. (Duration)	**VIII** (0.5 min)			**IX**	**X** (0.3 min)				**XI** (2.1 min)		
[2]**Event +**			M4 (c)	M4 (c)	M5		Air	Air z	M5 0	M5 z	Air z
[3]**Event -**	M4 (c)	M4 (c)				Air					

M5 helix formation (Start time – 133.1 min)

[1]Start Time : The start time denotes the beginning of the episode with Day 4 starting at t=0
[2]Event + : Palm gesture or cutout orientation (c) perpendicular to DNA axis (correct)
[3]Event - : Palm gesture or cutout orientation (c) parallel to DNA axis (incorrect)
M4 (c) indicates that the cutouts of the N-bases were being used to show orientation. In all other cases, the palm gesture was being used.
The shaded events depict palm gesture in reference to the helical model, in M5 or in Air.
0: none of the base pairs twisting; x: Only two base pairs twisting; y: Partial or non-uniform twisting; z: uniform twisting.

d) Microgenetic analysis of episodes related to 3-dimensionality of the DNA structure for Sandhya

Day	Day 4																Day 5
[1]**Start time**	4.4 min		36.2 min			42.6 min		46.6 min				52.4 min	57.3 min				71.1 min
Episode No. (Duration)	**I** (0.8 min)		**II** (2.3 min)			**III** (0.3 min)		**IV** (2.2 min)				**V**	**VI** (2.0 min)				**VII**
[2]**Event +**					M4		M4 (c)	M4 (c)		M4 (c)	M4 (c)	M4 (c)	M4 (c)	M4 (c)		M4 (c)	Air
[3]**Event -**	M1	M2	M4	M4		M4 (c)			M4 (c)						M4 (c)		

M5 ladder construction (Start time – 71.2 min)
M5 helix formation (Start time – 106.5 min)

Table for Sandhya continued...

Day	Day 5 Contd.														Day 6					
[1]**Start time**	121.3 min														151.4 min					156.4 min
Episode No. (Duration)	**VIII** (4.3 min)														**IX** (3.0 min)					**X**
[2]**Event +**					M1	M5		M5	M1	M2			Air	M5 x		M5 y	Air	Air y	Air z	Air z
[3]**Event -**	M5	Air	M3	M1			M5				Air 0	Air 0			M5 y					

[1]Start Time : The start time denotes the beginning of the episode with Day 4 starting at t=0
[2]Event + : Palm gesture or cutout orientation (c) perpendicular to DNA axis (correct)
[3]Event - : Palm gesture or cutout orientation (c) parallel to DNA axis (incorrect)
M4 (c) indicates that the cutouts of the N-bases were being used to show orientation. In all other cases, the palm gesture was being used.
The shaded events depict palm gesture in reference to the helical model, in M5 or in Air.
0: none of the base pairs twisting; x: Only two base pairs twisting; y: Partial or non-uniform twisting; z: uniform twisting.

e) Microgenetic analysis of episodes related to 3-dimensionality of the DNA structure for Aakriti

Day	Day 4		Day 5															Day 6						
[1]**Start time**	6.2 min		62.2 min					101.2 min								109.3 min		144.1 min		159.5 min	166.1 min		179.1 min	182.4 min
Episode No. (Duration)	**I** (1.2 min)		**II** (2.7 min)					**III** (3.6 min)								**IV** (1.2 min)		**V** (0.1min)		**VI**	**VII** (2.7 min)		**VIII**	**IX**
[2]**Event +**				M1	M1	M1	M1		M1		M4		M4 (c)	M4 (c)	M4 (c)	M4 (c)	M4 (c)	M5	Air	M5	Air z	Air z	Air z	Air z
[3]**Event -**	M1	M2	M1					M4		M4		M4 (c)												

M5 ladder construction (Start time – 71.2 min) **M5 helix formation (Start time – 117.3 min)**

[1]Start Time : The start time denotes the beginning of the episode with Day 4 starting at t=0
[2]Event + : Palm gesture or cutout orientation (c) perpendicular to DNA axis (correct)
[3]Event - : Palm gesture or cutout orientation (c) parallel to DNA axis (incorrect)
M4 (c) indicates that the cutouts of the N-bases were being used to show orientation. In all other cases, the palm gesture was being used.
The shaded events depict palm gesture in reference to the helical model, in M5 or in Air.
0: none of the base pairs twisting; x: Only two base pairs twisting; y: Partial or non-uniform twisting; z: uniform twisting

The un-shaded events in Table 3 indicate that the straight ladder structure is under discussion. Models M1-M4 are always straight ladder structures. If model M5 is being used, or if the gesture is being made in air (i.e., without support of one of the backbone models), then the ladder structure under discussion could be straight (un-shaded event) or helical (shaded event).

Students' understanding of the ladder structure

At the beginning of Day 4 it was clear to us that all the students were visualizing the 'steps' of the DNA ladder to be 'flat'. Notice that the first event on Day 4 for every student is a '-' event, referring to a straight ladder structure where students depicted the base pair orientation in the plane of the backbones. This turned out to be a strongly held misconception, probably reinforced by Figure 1b which is common in textbooks.

The initial incorrect palm gesture in Episode I on Day 4 was followed up by between 30-55 minutes of questions-cum instruction related to the formation of the nucleoside and bonding of the DNA base pairs, after which the students were asked to repeat the palm gesture (Episode II). Although all the students began with the incorrect 'in the plane of the backbone' gesture, Table 3 shows that they quickly changed to the correct gesture (in Episode II or Episode III). We refer to this as a “+ve” transition, indicating a realization of the 3-Dimensionality of the ladder structure. Strikingly, however, the correct response was not stable in any of the students. As the interviews proceeded, all the students showed a series of “-ve” and “+ve” transitions, that is, they kept switching between the correct and incorrect response. This was notwithstanding the fact that the correct response was often accompanied by an 'Aha!' moment (described later) and positive encouraging feedback (a broad shared smile, and 'good!' or 'very good!') from the interviewer. The type of model being used during the episode was one factor which may have determined their response.

With Anuja the first “+ve” transition happened with the use of M3, that is, when she picked up the parallel pencils (representing the backbone) lying on the table and held them to stand vertically (Episode II). Anuja sustained the correct orientation through Day 4 and even Day 5, when she worked with M5, the clothespin model. But on Day 6, when Anuja returned to the M4 (cutout) model, she reverted to a series of incorrect and correct orientations (Episode VIII).

With Sharada and Nitin the first “+ve” transition happened as they were doing the palm gesture in the air. But both of them underwent a “-ve” transition when they had to place the base pair cutouts against the M4 model. With Sharada, use of the palm gesture (Episode III) helped to correct her orientation, and she maintained the correct orientation through till the end of Day 6. Nitin however went through 6 “-ve” and 6 “+ve” transitions between Day 5 and Day 6.

In Sandhya, the first “+ve” transition happened on Day 4, using the palm gesture with M4. However, when in the next episode, four minutes later, Sandhya had to place the base pair cutouts against the M4 model, she reverted to the incorrect orientation. Over a total period of 16.7 minutes on the same Day (Episodes III – VI) as she was using the M4 (c) base cutouts, Sandhya showed a series of 3 “-ve” and 3 “+ve” transitions. In Episodes VIII and IX too, as she worked with the straight and then helical M5 model, Sandhya showed 4 “-ve” and 4 “+ve” transitions.
Aakriti's '-' events of Day 4 continued on Day 5 with the M1 model. Her first “+ve” transition occurred in Episode II when she was using the palm gesture with M1. But, she too was stumped when, in Episode III, she was asked to depict the base pair orientation using the 'palm gesture' against M4, the cutout model. In a remarkable sequence of flip-flops, when she was asked to go back to M1 she recalled the correct orientation and then also corrected her gesture in M4, but, just as quickly, when she picked up the cutouts of the N-bases, she first oriented them in the wrong way (Table 3(e), Episode III). At this point it was the ladder analogy which helped her correct herself (see 'Context of the “+ve” transitions').

Aakriti, who was otherwise very shaky on her chemistry and biology concepts, was the only one who achieved a stable correct response on Day 5, which continued into Day 6. Sharada, Nitin and Sandhya achieved a stable response on Day 6. Anuja however was fluctuating in her response till the end of Day 6.

Students' understanding of the helical structure

The palm gesture was used with models M1-M4 to represent the fact that the base pairs were planar (of equal lengths), parallel to each other, and perpendicular to the two backbones, just like the steps of a ladder. The DNA ladder being a helical one, the next task for the students was to depict the base pairs orientation in a helical ladder. For this they had to maintain the base pairs locally perpendicular to the two backbones and to the axis of the helix, but show that each base pair was twisted (by 36º) with respect to its adjacent base pair. This could be indicated by the student positioning their two palms in parallel planes, but angularly displaced with respect to each other, either in the air, or against the M5 (clothespin) model.

In Tables 3 (a-e) the shaded events indicate that students were showing the base pair orientation in the helical structure. A '+' or '-' event indicates that the base pair is shown perpendicular (correct) or parallel (incorrect) to the axis of the helix. The twisting of the base pairs is shown by a 0, x, y or z in the shaded boxes, with 0 for no twisting of the bases, x for relative twisting of two base pairs only, y for non-uniform or partial twisting of some base pairs and z for uniform or continuous twisting of all base pairs such that the first pair is aligned with the eleventh one (correct response).

Before the M5 model was constructed, students were asked whether the base pair orientation would change if the straight ladder was twisted to form a helical one. Interestingly, only Anuja and Sharada said that the base pair orientation would change in the helix while the other three students said that the bases would remain parallel, exactly as in the straight ladder structure. Anuja and Sharada indicated a continuous twisting in air with the base pairs perpendicular to the DNA axis (Anuja, Episode IV) or parallel to the axis (Sharada, Episode II).

The construction of the M5 model is indicated by two arrows below the Tables, a hollow arrow for the straight ladder and a shaded one for the twisted ladder. The straight ladder construction involved attaching the clothespins (bases) to the plastic tubing (backbone) and pairing the A-T and G-C bases. With some help 3 of the students (except Nitin and Aakriti) placed the bases equidistant along the backbone. However when it came to twisting the ladder something unexpected happened. Anuja and Sandhya crossed the two backbones and, instead of making a helix, pressed the backbones and the bases flat on to the table. Nitin did the same, even before he was asked to form the helix. The shape that these three students formed looked uncannily like the diagram (Figure 1 a) in their textbook. In this configuration the distance between the two backbones decreased and went to zero at the crossing, hence it was no longer possible for the students to fit any base pairs in the narrowed space. They dealt with this problem by moving the base pairs away from the point of crossing, leaving a gap there. All these three students had earlier asserted that the distance between any two base pairs was 3.4 Å, but after forming their "helix" they said there would a gap at the "point" of the helix. Anuja even suggested that when the DNA replicates an incision is made at this "point"!

Sharada and Aakriti made a reasonable M5 helix, but Sharada spoke (in Episode V) about the "turning" in the molecule, "the place where it rotates" and the "two units" of the helix. Aakriti too spoke in Episode V about a "point" of the helix. Even after the construction of the M5 helix (shaded arrow in Tables 3 (a-e)) it was not immediately obvious to the students that each base pair was turned by the same angle with respect to its adjacent base pair. This was a classic case of observation being shaped by preconceptions!

All the students remembered that there were 10 (Nitin thought 8) base pairs in one helical turn, and there was a 36º angle involved somewhere, but none guessed that 36º was the constant angle between the base pairs. Even as she handled the M5 helical model, Anuja still thought that only the two base pairs at the “center” were turning (Episode V). This was in contradiction to to the correct gestures in air that she had shown in Episode IV. Notwithstanding their problems with the M5 model, all except Nitin had some idea of a helical shape as in a telephone cord, spiral-bound note-book or a spiral staircase. Nitin however was misled by the Marathi term “*sarpil*” for helix, meaning 'snake-like', which he illustrated with a wavy 2-D shape made from stiff wire. When shown a wire wound around a pencil he said in Marathi, “It is like a snake wound around a tree.”

Next there was a pedagogical intervention to remind the students about “10 base pairs in a helical turn”, “one turn is 360º” and “10*36º = 360º”. In all the students this led to an 'Aha!' moment, i.e., sudden realization or acceptance of the fact of uniform turning of the base pairs, indicated verbally or through a convincing facial expression. The intervention took place in or after the final gesture episode for all the students, except with Anuja, for whom the intervention happened in Episode VII. We cannot tell about the stability of this learning, since it happened at the very end of the sessions. The 'Aha!' moments were more prominent in the contexts of the “+ve” transitions (parallel to perpendicular orientation of the base pairs) which are analyzed next.

Context of the “+ve” transitions

Throughout the Days 4-6 when students were questioned about the orientation of the base pairs, they frequently switched between a '-' (incorrect) response (base pairs locally in the plane of the backbone) and a '+' (correct) one (base pairs locally perpendicular to the plane of the backbone). The “-ve” ('+' to '-') transitions were all unconscious ones, whereas the “+ve” ('-' to '+') transitions were usually the result of an interjection or a hint by the interviewer. Of the 19 “-ve” transitions for all the students, 12 took place when the students used the cutouts with the M4 model. Here they had to simultaneously grapple with the chemical bonding between the bases and sugar, and the orientation of the base pairs with respect to the backbones. They had to recall that the bases were to be bonded with the Carbon atom at the 'first (prime)' position of the sugar molecule, and that it was the Nitrogen atom at the first and the ninth position of a purine and a pyrimidine respectively which bonded with the sugar. With Sandhya several negative transitions happened while using the M5 model where she had the twin task to consider the perpendicular orientation of the bases to the backbone or axis, as well as the angular turn of N-base pairs.

The “+ve” transitions were more interesting, since they represented a learning episode. Hence we asked, what were the types of intervention that led to “+ve” transitions? Table 4 summarizes the number of “+ve” transitions for each student and the context of each transition. The first “+ve” transition for each student occurred after they were given the ladder analogy: “Have you seen a ladder?” Initially, for Anuja, Nitin and Sandhya, the ladder analogy by itself did not help. So the interviewer followed it up with an instruction to the student to (mentally): “Try to climb the ladder.

Where will you step? How will you place your foot?” This instruction to mentally simulate walking up the ladder immediately led to an 'Aha!' moment and a quick correction of the gesture or the cutout orientation. Anuja, Sharada, Sandhya and Aakriti spontaneously laughed out aloud. Sharada asked incredulously, “The real ladder?!” She then proceeded to correct her orientation without further instructions for mental simulation. Nitin was generally more reserved in his expression but he too gave a hint of a smile with vigorous shaking of head, showing he had realized something.

Table 4
Summary of Number of “+ve” Transitions and their Contexts

Name of the student	No. of '+ve' transitions	Context of the transitions
Anuja	3	1. [1]**Ladder analogy with mental simulation**; 2. reminder about gesture against M1; 3. reminder about orientation.
Sharada	2	1. **Ladder analogy**; 2. palm gesture.
Nitin	7	1. **Ladder analogy with mental simulation**; 2. palm gesture; 3. palm gesture; 4. reminder of earlier orientation; 5. reminder of earlier orientation; 6. ladder analogy with mental simulation; 7. ladder analogy with mental simulation.
Sandhya	8	1. **Ladder analogy with mental simulation**; 2. **ladder analogy**; 3. reminder about base positioning; 4. reminder about earlier gesture; 5. palm gesture; 6. ladder analogy with mental simulation; 7. ladder analogy; 8. reminder about the base placement.
Aakriti	4	1. Ladder analogy; 2. ladder analogy; 3. **ladder analogy with mental simulation**; 4. **ladder analogy**.
Total	**24**	Ladder analogy (6), ladder analogy with mental simulation (7), palm gesture (4), reminders (7)

[1]All contexts which had direct bearing on the “Aha!” moment of the student are given in bold font.

With Aakriti the first and the second “+ve” transitions came by suggesting to her the ladder analogy and going from the M4 to the M1 model. Her third and fourth transitions, which came in the space of one minute and twenty one seconds (Episode III), brought the spontaneous 'Aha!' moment accompanied by wholehearted laughter. All through the rest of Day 5 and Day 6 she maintained the correct orientation.

Out of the total of 24 “+ve” transitions for the five students, 13 transitions came about when the interviewer gave the ladder analogy, by itself or accompanied by instruction to mentally simulate walking up the ladder. Sandhya and Aakriti had a second 'Aha!' moment with just the ladder analogy, after the instruction to simulate had been given in a previous episode or event. Possibly mental simulation recurred in those events, spontaneously, without being cued explicitly by the interviewer.

After the initial 'Aha!' moment seven of the subsequent “+ve” transitions occurred simply with a reminder to the students about their previous gesture or orientation. Four of them occurred when the students spontaneously corrected their gesture. Of these self-corrections two occurred while gesturing with the M1 model. The other two occurred with the M4 model, when the students were asked to use the palm gesture. Thus, after the 'Aha!' moment a simple reminder or use of the palm gesture was sufficient to bring about a “+ve” transition.

Visualizing the 3-D structure of DNA

The results of this study were striking and surprising to us. We anticipated that biology students might have some problem in visualizing the precise 3-D structure of the DNA molecule. We were not too surprised when all the students in our sample initially thought that the DNA base pairs (the 'steps' of the ladder) were in the plane of the backbone. This was a natural misconception to follow from the common diagrams (for example, Figure 1 b), and we found it in senior biologists too. Most available visuals, physical models and videos on DNA structure do not emphasize this particular feature, though it is significant enough that Watson and Crick's (1953 a) original paper mentions it.

What surprised us then was the difficulty that students had in correcting their apparently simple misconception. All of them had one or more 'Aha!' moments when they realized that the base pairs were 'really' like the steps of a ladder, i.e., planar and perpendicular to the backbone. But, especially while dealing with the molecular (M4 and M4 (c)) or the helical (M5) models, they rapidly and repeatedly forgot this simple fact. The difficulty here probably lay in a limitation of working memory. In the case of M4 students were not able to simultaneously hold in their mind the molecular structure, the bondings, and the base pair orientation. In the case of M5, they had to keep in mind the twisting of the base pairs along with their perpendicularity to the backbone.

The second surprise came when three of the students constructed the DNA 'helix' as two criss-crossing backbones with base pairs between them, forcibly flattening them to lie flat on the table! The DNA helix is an icon of modern scientific culture. Undergraduate science students in urban India are exposed to this image not only in their classrooms but also in the media. All the students in our sample had attended tutorial classes in which they had been exposed to clear and more detailed diagrams than available in their regular textbooks. In informal conversation they told us that in the (1-3 day) interval between two sessions they had looked up their study materials and also videos and illustrations of DNA structure on the internet. Despite this considerable exposure they had not realized the essential 3-Dimensionality of DNA structure.

It seems to us that the idea of a helical ladder structure is not a difficult one to convey, if it is done early enough, before the students' minds get cluttered with details of the molecular model. The dimensional details including the equidistant placing of the base pairs (3.4 Å), 10 base pairs per helical turn, and 36º angle between the base pairs, could also be taught, before the molecular model is built up on this basic structure.

Palm gesture as an instructional tool and a diagnostic tool

The palm gesture could be a basic, simple tool to convey the orientation of the base pairs in the ladder structure. We used the gesture as a means to connect the multiple models (M1-M5) of the DNA backbone. The gesture is powerful and flexible enough that it is not tied to any specific orientation of the backbone. Models M1 and M2 were laid flat on the table, M3 and M4 standing up, and M5 could be rotated in any direction. Gestures in air could be done in any direction, which students sometimes did. The palm gesture served to abstract out the idea of base pair orientation, independent of the particular model that was being used. It was for us as a diagnostic tool to begin with, but as the interaction proceeded, it also became an instructional tool.

Use of analogy for visualization

The ladder analogy was crucial in correcting the students' base pair orientation. The planarity of the base pairs arises due to the hydrogen bonds between them, while their perpendicularity to the DNA backbone comes from N-glycosidic bond between the base and the sugar molecule. The helical ladder structure of DNA is formed due to the tendency of the bases to avoid contact with water and stack one above the other, an arrangement that is further stabilized by Van der Waals forces and polar interactions between the adjacent bases.

The ladder structure thus has functional implications, though students may learn about these only at a later stage. Structure-function linkages in biology help students make sense of what they learn, and are thought to play a role in mental visualization (Mathai and Ramadas, 2009). Yet in the absence of knowledge about functional features, the ladder analogy helped students find a beautiful and pleasing consistency between what they knew and what they had to learn.

In the framework of Goldin-Meadow and Beilock (2010), the ladder analogy by itself is observer-centric, and the palm gesture is an 'observer viewpoint' gesture. We found that these were not sufficient in most cases to bring about learning. We then had to ask students to imagine themselves actually stepping on the ladder, i.e., getting 'inside' the model. This could be seen as the equivalent of 'character viewpoint' gestures or actions, which may have provided for the students a bridge between an imagined concrete action and the abstract representation of base pair orientation. Our results show that, though students did not spontaneously link the ladder analogy with their textbook diagrams, gesture could be used to link 2-D representations with multiple 3-D models of DNA structure, and mental simulation involving changing observer viewpoint, to one from 'inside' the molecule, could effectively link the ladder analogy with the molecular structure of DNA.

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