The development of students' understanding of science

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Overview

- I will present a summary of some of the findings that have emerged from the research my colleagues and I have conducted over the years on the development of children’s understanding of science.
- These studies range over different science concepts and have made use of a variety of methodologies and experimental designs. They include cross-sectional developmental studies using interviews and open questions, forced-choice questionnaires, categorization experiments, reaction time studies, text comprehension experiments and the design of curricula and learning environments.
- My recent research investigates conceptual change in teachers and the design of interventions to help teachers learn how to change their practices in order to promote student cognitive engagement and agency in STEM classrooms

Learning science concepts is different from learning everyday concepts

- As Vygotsky was first to point out, the learning of science concepts is not the same as that of everyday concepts.
- For me, the main difference in the learning trajectory between these two kinds of concepts is the following.
- In the case of everyday concepts, children construct new knowledge by building on what they already know. However, learning science requires significant *conceptual changes* in what is already known, such as changes in beliefs and presuppositions about the physical world, changes in categorization and changes in representations.
- When children use the same knowledge acquisition mechanisms (adding on and enriching prior knowledge) in the learning of science concepts, the result is often the creation of distortions or misconceptions

The concept of the Earth

(Vosniadou & Brewer, 1992)

Earth as a physical object

Earth is flat

supported by ground, water, etc

stationary

sky and solar objects located above its top

geocentric universe

Earth as an astronomical object

Earth is spherical

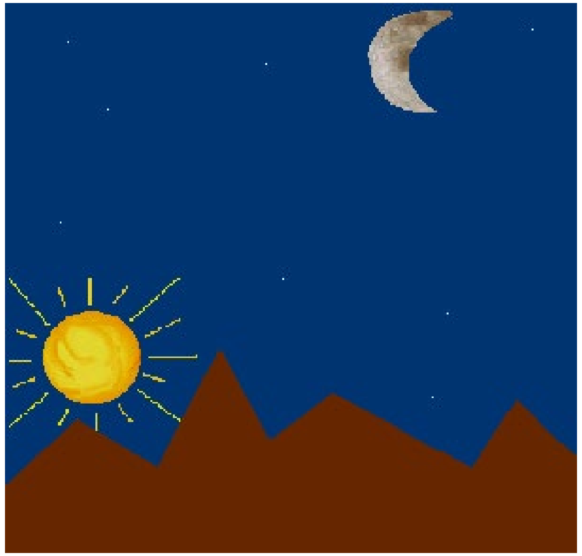
surrounded by space

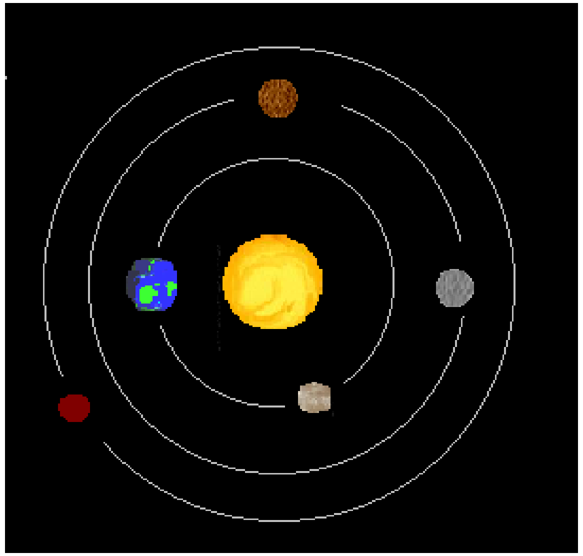
rotating and revolving

space and solar objects surround the earth

heliocentric solar system

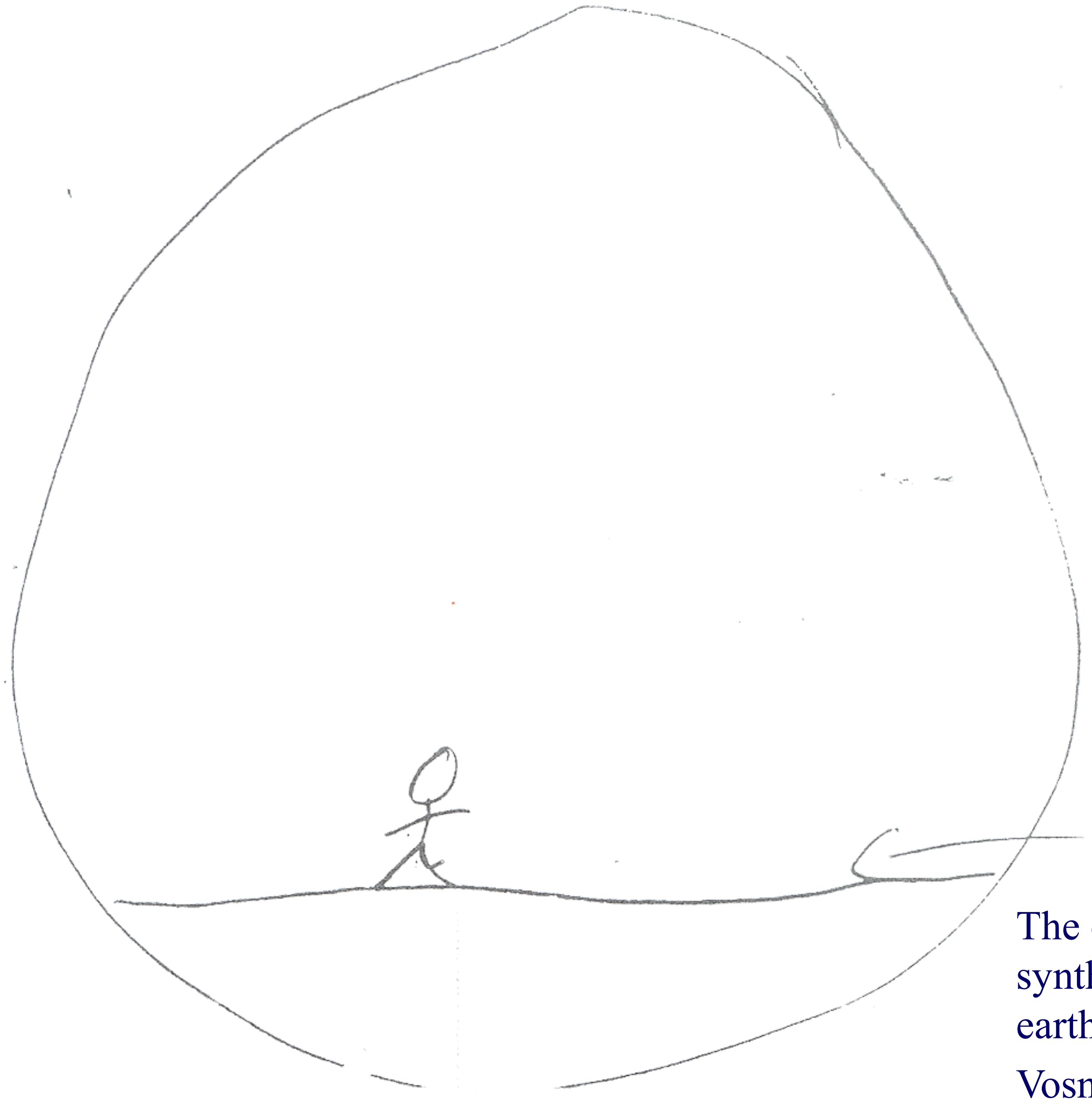
Changes in the representation of the earth with the learning of science





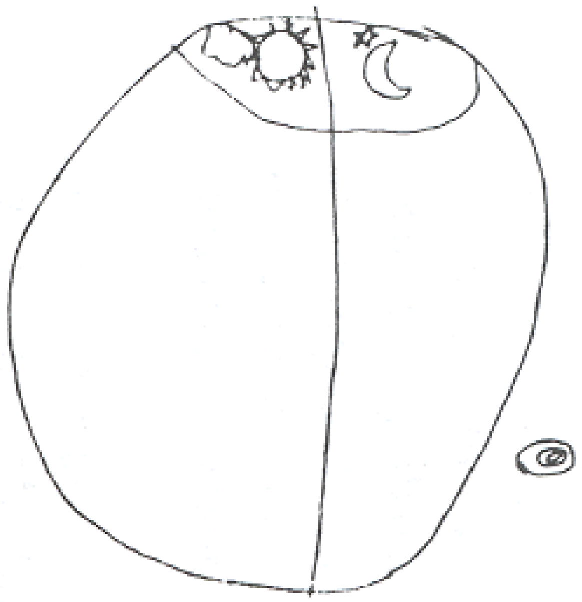
Misconceptions or Synthetic Conceptions

- When students use the enrichment types of mechanisms used to learn everyday concepts in order to learn science concepts, the result is often the creation of misconceptions or of inconsistent – mixed responses
- An overwhelming body of educational research has documented students' misconceptions in science.
- Detailed examination of students' misconceptions in our interview studies have shown that they can be derived from a synthesis of scientific information with inconsistent prior knowledge – prior knowledge constructed from children's everyday observations in the context of lay culture.



The creation of synthetic models of the earth

Vosniadou & Brewer (1992)



C

Venica (3rd grade) (Subject number 33, hollow sphere model)

(Venica drew the picture of the Earth shown in Fig. 2c.)

E: How come here the earth is flat but before you made it round?

C: Because you are on the ground and you make that picture like a shape and you made it a square shape and if you'll look up it'll look like a rectangle or something like that and if you go out of earth and go into space you'll see a circle or round.

E: So what is the real shape of the earth?

C: Round.

E: Why does it look flat?

C: Because you are inside the earth.

E: If you walked and walked for many days in a straight line, where would you end up?

C: Somewhere in the desert.

E: What if you kept walking?

C: You can go to states and cities.

E: What if you kept on walking?

C: (No response.)

E: Would you ever reach the edge of the earth?

C: No. You would have to be in a spaceship if you're going to go to the end of the earth.

E: Is there an edge to the earth?

C: No. Only if you go up.

Later:

E: Can people fall off the end/edge of the earth?

C: No.

E: Why wouldn't they fall off?

C: Because they are inside the earth.

E: What do you mean inside?

C: They don't fall, they have sidewalks, things down like on the bottom.

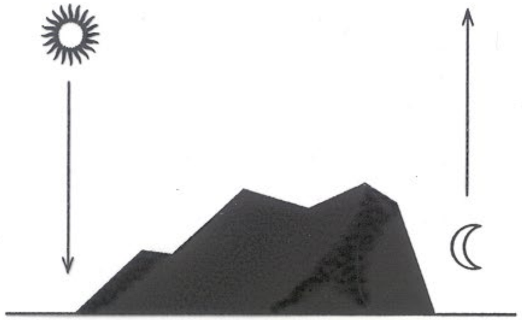
E: Is the earth round like a ball or round like a thick pancake?

C: Round like a ball.

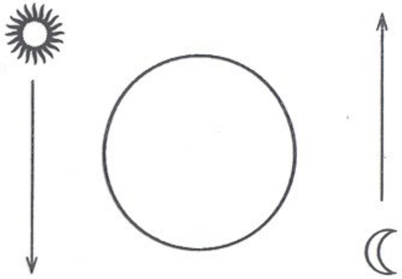
E: When you say that they live inside the earth, do you mean they live inside the ball?

C: Inside the ball. In the middle of it.

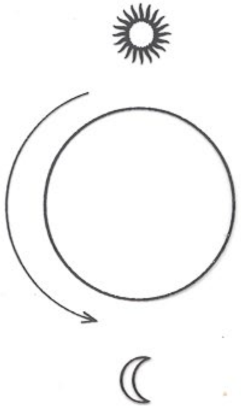
The development of children's explanations of the Day/Night Cycle (Vosniadou & Brewer, 1994)



1. The sun goes down, on the ground, behind mountains, and the moon comes up.

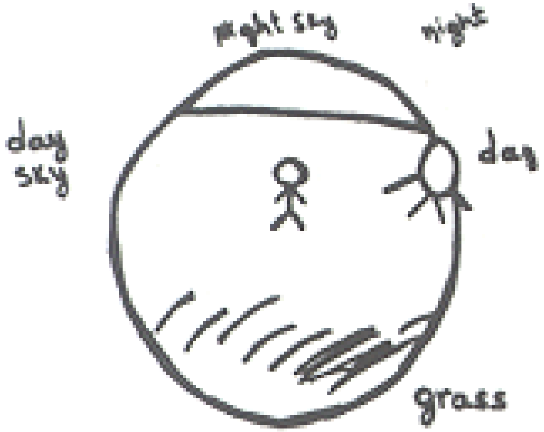


2. The sun goes down, to the other side of the earth, and the moon comes up.



3. The earth rotates in an up/down direction. The moon and sun are located at opposite sides.

4. The earth rotates in an east/west rotation. The sun and moon are located at opposite sides.

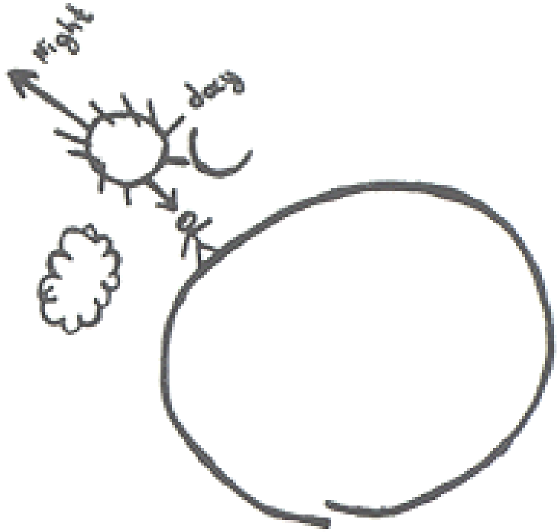


Drawing No. 4

4. The sun goes down on/in the ground (and the moon comes up).

Harmony (No. 41, Grade 1)

E: Can you make it day for this person?
C: (see drawing 4 in Figure 4)
E: Now make it night for that person.
C: To make it night, erase the sun and replace it with the moon.
E: Can you tell me once more how it happens?
C: The sun goes down and the moon comes up, and then the moon goes down and the sun comes up.
E: Where is the moon when the sun is up?
C: The moon is where the sun rests.



Drawing No. 3

3. The sun moves out into space.

Allison (No. 52, Grade 1)

E: Now make it so it is day for that person.

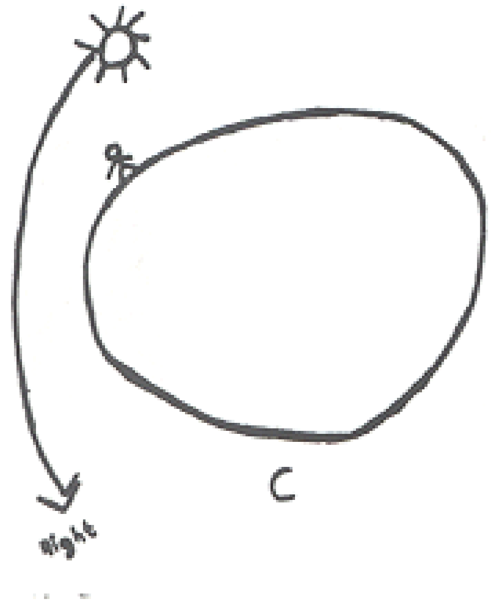
C: (child makes drawing 3 shown in Figure 4) Right here?

E: Whatever you think. Now make it night.

C: It goes in space.

E: Show me. Tell me how it happens.

C: The sun comes back down. It goes into space and when it gets dark the moon comes back out.



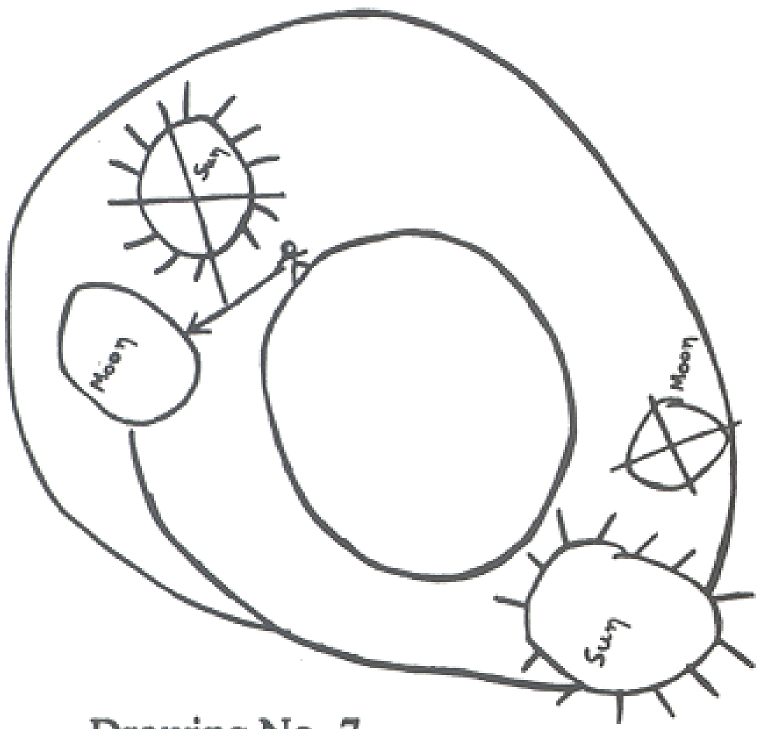
Drawing No. 5

5. The sun goes down to the other side of the earth (and the moon goes up).

Timothy (No. 47, Grade 1)

The child makes the drawings shown in Figure 4.

E: Tell me once more how it happens.
C: When the moon comes up and the sun goes down.
E: Where was the moon before?
C: Under the earth.
E: What time was it when it goes under the earth?
C: Day.



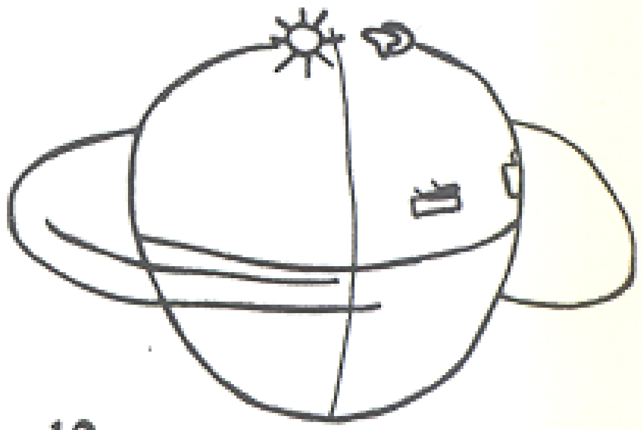
Drawing No. 7

7. The sun and the moon revolve around the earth.

Karen (No. 37, Grade 3)

The child makes drawing 7 shown Figure 4.

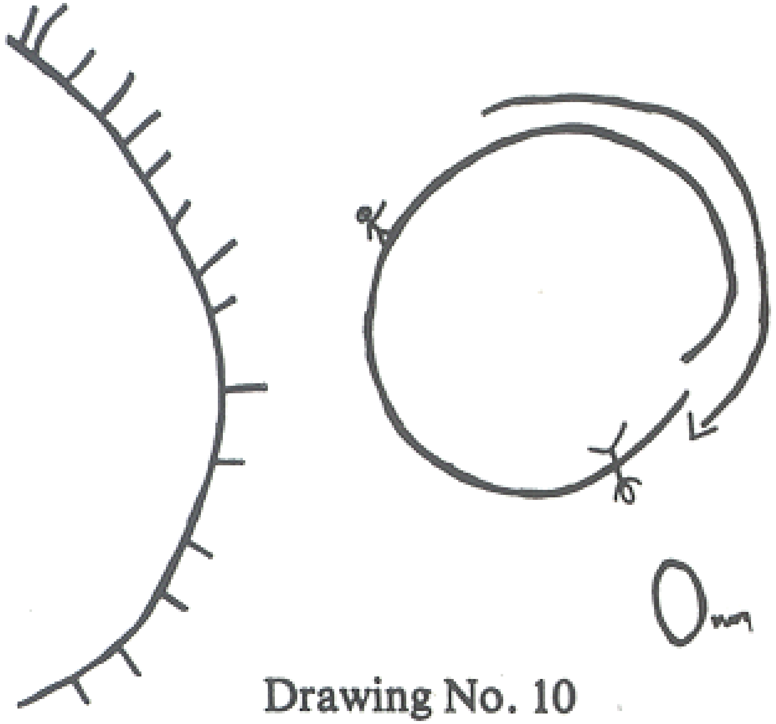
E: Now make it so it is night.
C: We have to cross out the sun and put it over here.
E: Tell me once more how it happens.
C: Well, the sun vibrates around the earth every 12 hours. And then the moon goes the other direction and vibrates around the earth every 12 hours. So both us and China have the moon and the sun.



Drawing No. 12

12. The earth rotates left/right and the sun and moon are fixed at opposite sides.

Venika (No. 33, Grade 3)
C: (Child makes drawing 12, Figure 4)
E: Can you tell me how this happens?
C: When the earth turns around its orbit, this side comes day and the other side comes night.



Drawing No. 10

10. The earth rotates up/down and the sun and moon are fixed at opposite sides.

Robert (No. 5, Grade 5)

E: Now make it so it is day for that person.

C: (child makes drawing 10 shown in Figure 4)

E: Now can you make it nighttime?

C: Can I draw him somewhere else? (draws figure at the bottom of the earth)

E: Sure.

C: (Child draws arrows to show how earth spins)

E: Tell me how it happens.

C: When it was daytime, the earth spinned around to the sun. When it was nighttime, the earth turned around to where the moon is.

Internalisation of the scientific representation is a constructive process

- Our results suggest is that the process of internalisation of the scientific representation is not an act of direct transmission but a constructive process which takes time to be accomplished and which can result in the creation of distortions and internal contradictions.
- What happens when children have access to cultural artifacts that can support their reasoning in science?
- Science instruction often happens in the presence of concrete, physical artifacts, such as for example the globe. Such artifacts can be used as prosthetic devices to facilitate the transition from a representation based on everyday experience to the scientific representation.

The role of cultural artifacts

- Vosniadou, Skopeliti, & Ikospentaki (2005) compared children's reasoning in elementary astronomy with the presence of a globe and without the presence of a globe.
- The results showed that the presence of a globe resulted in
- An increase in the number of children who provided scientific responses, particularly in the case of the older children (5th graders)
- A drastic decrease in the number of children who were categorised as having synthetic models, and
- A drastic increase in the number of children categorized as being internally inconsistent, especially in the case of the younger children (3rd graders)

Reasoning with a globe

- The younger children were able to use the globe to reason with, but only when the answer to the questions could be derived immediately from the cultural artifact. For example, in response to the question ‘do people live at the bottom of the earth’ the children looked at the bottom of the globe. Knowing that people can indeed live in Australia or in the South Pole they responded yes.
- When asked questions the answers to which could not be derived directly from the cultural model however, the children reverted to reasoning based on their prior knowledge (representations inconsistent with a spherical earth model). This resulted in an increase in the number of inconsistent responses provided during the interview.
- Clearly a concrete, physical cultural artifact such as a globe can help children’s reasoning in elementary astronomy. However, even in this case there is room for errors to occur as inconsistent prior knowledge can interfere in the reasoning process

What happens to initial, everyday concepts when scientific concepts are learned?

- Replacement view
- Conceptual change as some kind of restructuring – scientific concepts replace naïve ones
- The Co-existence view
- Recently a body of evidence started to be accumulated demonstrating the co-existence of initial understandings and scientific explanations in various knowledge domains and cultures, using different methodologies.
- This research has shown that both children and adults frequently use, for example, both creationist and evolutionary accounts of the origin of species (Evans & Lane, 2011), biological and supernatural explanations of the transmission and cure of illnesses (Legare & Gelman, 2008, 2009), supernatural and scientific accounts of death (Legare et al., 2012), and both dualistic and materialistic explanations for the mind (Preston, Ritter, & Hepler, 2013).
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Reaction time studies with adults

- Further evidence comes from reaction time studies which show that not only children but even adults and sometimes experts in science are slower (and sometimes even less accurate) when reasoning with experimental stimuli which are consistent with scientific explanations or concepts but inconsistent with initial/naive conceptions or theories.
- DeWolf and Vosniadou (2011) examined this hypothesis in a reaction time experiment which tested 28 undergraduates from CMU in mathematics - in a fraction magnitude comparison task.

The whole number bias in fraction magnitude comparison tasks

- In a fraction comparison task the participants are presented with 2 fractions and must press a button to indicate which of the two fractions is larger.
- In this task half of the presented fraction comparisons consisted of stimuli consistent with natural number ordering, while the remaining half were inconsistent with natural number ordering
- The magnitude of the two fractions can be similar to the magnitude of their constituent parts which are whole numbers – in this case the fraction magnitudes are consistent with whole number ordering
- for example, 2/5 and 5/7 where 5/7 is larger
- Or inconsistent with natural number ordering
- for example, 3/7 and 2/3 where 2/3 is larger

College students less accurate and slower when comparing fraction magnitudes inconsistent vs. consistent with their natural number components

Condition	Accuracy **	Reaction Time (ms) all trials *	Reaction Time (ms) only accurate trials **
Consistent	86%	3378	3240
Inconsistent	77%	3665	3619
Overall	82%	3521	3430

Interference of whole number ordering

The participants were more accurate and faster to respond when the fraction comparisons were consistent with whole number ordering compared to the comparisons that violated whole number ordering.

The results indicate an interference of whole number ordering even in adults who have developed an integrated model of fraction magnitude.

Similar results have been obtained in a host of other experiments with mathematical as well as scientific stimuli.

It has been suggested that the reason for the slower responses in the case of the inconsistent stimuli is that the initial everyday concepts are activated first and **need to be inhibited** to provide access to the scientific representation

The role of inhibition

- Inhibitory control is an important executive function skill
- Executive function (EF) skills such as working memory, task switching or shifting, and inhibitory control are fundamental for engaging in the goal-directed control of thought and behaviour, for managing existing knowledge networks, EF skills have been found to be significantly related to academic achievement even when intelligence and prior knowledge are controlled
- Inhibition is recruited to deal with the interference of learned responses in order to acquire new and counter-intuitive concepts in science and mathematics.

Inhibition is science reasoning tasks

Some of our recent research (Vosniadou et al., 2018) examined the hypothesis that inhibition might recruited in the employment of science and mathematics concepts which require conceptual changes for their construction

512 students ranging in age from 5th graders to College students were administered a Sentence-Picture Verification task (Sp-Ver). The Sp-Ver investigated individuals' abilities judge the truth or falsity of initial (common-sense) vs. scientific statements.

The statements were either consistent with both initial and scientific views or inconsistent with one of them.

The Sentence-Picture Verification Task (SP-Ver)

23 sentence/picture combination types in 4 conditions

Two Consistent with initial explanations (one true-one false)

True: Consistent with both the initial and the scientific explanation (+/+)

False: Inconsistent with both the initial and the scientific explanation (-/-)

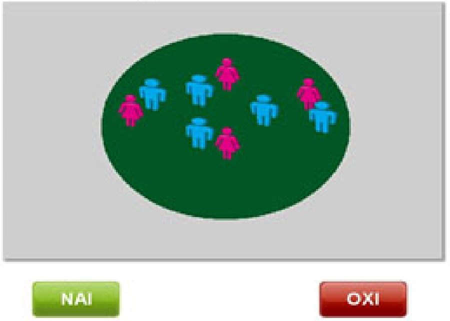
Two Inconsistent with initial explanations (one true-one false)

True: Inconsistent with the initial but consistent with the scientific explanation (-/+)

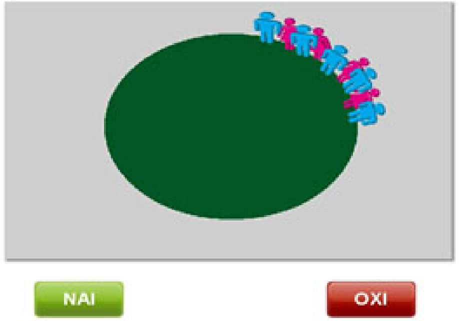
False: Inconsistent with the scientific but consistent with the initial explanation (+/-)

The four conditions of the Sentence/Picture Verification Task

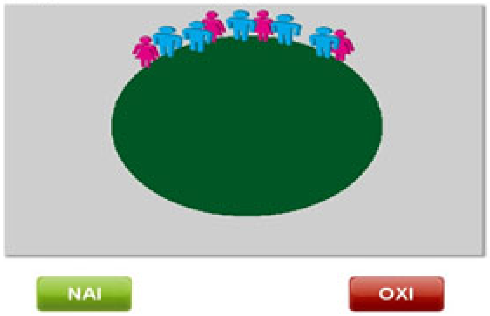
People live
on different parts all over the earth



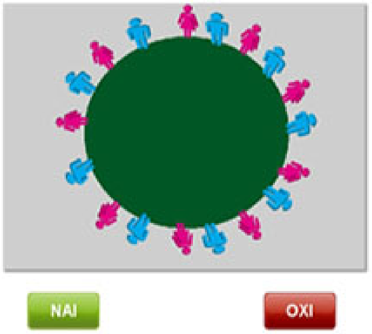
People live
only on the right side of the earth



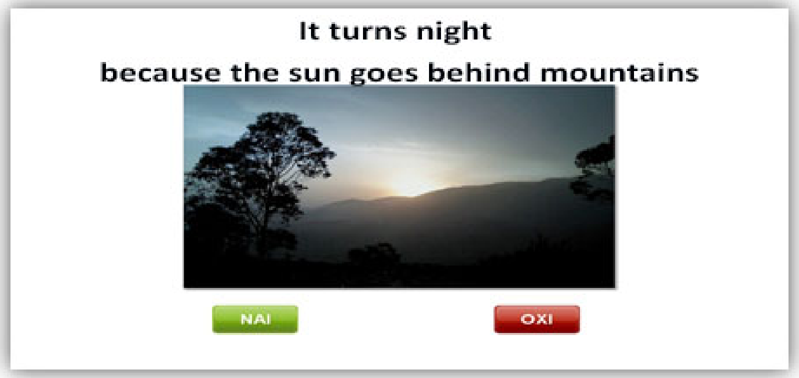
People live
only on the top part of the earth



People live
and on the bottom part of the earth



The inconsistent conditions of the Sentence/Picture Verification Task



Consistent with the initial explanation but inconsistent with the scientific

Inconsistent - False

Inconsistent with the initial but consistent with the scientific explanation

Inconsistent - True

Inhibition is recruited when the task requires the rejection of an initial explanation in favour of a counter-intuitive scientific concept

- The results showed that the participants were more accurate and took more time to verify the sentence/picture combinations in the consistent compared to the inconsistent conditions of the Sp-Ver task.
- In a second study we investigated whether performance in the Sp-Ver tasks could be predicted by the participants’ performance in two EF tasks that investigated inhibition and shifting. The participants were 133 4^{th} and 6^{th} grade children (and were further replicated in an experiment with 7^{th} and 9^{th} grade students).
- A regression analysis showed that shifting was recruited in all the tasks. However, inhibition accuracy predicted accuracy in the Sp-Ver task only in the experimental condition which required the rejection of the initial, common-sense statement.
- This result suggests that inhibition might be a more specialized EF skill that is recruited in certain kinds of conceptual change processes in which the rejection of initial, common-sense concepts or explanations is required.

Summary

- Learning of science concepts is different from the learning of everyday concepts
- Requires conceptual changes in prior knowledge
- The mechanisms used for knowledge acquisition in the case of everyday concepts can result in the creation of distortions and inconsistencies in the case of science learning
- Cultural artifacts and models can certainly help but even then, the internalisation of the scientific representation is not an act of immediate transmission but a constructive process
- Initial concepts built on everyday experience may co-exist with scientific concepts even in scientifically literate adults
- Inhibitory control may be needed to supress the interference of initial concepts in favour of a counter-intuitive scientific concept

Implications for science instruction – The social origins of conceptual knowledge

- Although a large part of my research focuses on understanding individuals' representations of science concepts, I completely agree with Vygotsky that conceptual categories and language are acquired through participation in social contexts and is mediated by the complex interactions between children and adults.
- Instruction for conceptual change requires extensive socio-cultural support. Such socio-cultural support must go beyond practices that support the mere internalization of cultural practices, tools and artifacts. It needs to facilitate conscious, deliberate intentional learning. Students must
  - become aware of the inconsistencies between the scientific concepts and their initial understandings of the physical world based on everyday experience, and
  - Learn to use top-down, conscious and deliberate mechanisms for intentional learning and conceptual change

Creating socio-cultural environments that favour prolonged comprehension activity

- One way to foster deliberate and intentional belief revision needed for conceptual change is through cognitive conflict induced classroom dialogue. This requires the creation
- of classroom socio-cultural environments that favour prolonged comprehension activity and conceptual change.
- of a curriculum that presents students with problems that challenge their misconceptions and with conflicting alternatives

The above are likely to induce the cognitive, epistemic motivation needed to lead students to critically evaluate their prior knowledge

Sequence of Concepts Theoretical Framework	Basic Questions -Entrenched Beliefs	
EARTH SHAPE	**Explain how it is possible for the earth to be spherical when we perceive it to be flat**	
EARTH SHAPE and GRAVITY	**Explain how it is possible for people to live on a spherical earth without falling ‘down’.**	
Relative size and distance of EARTH, MOON and SUN	**Explain the relation between size and distance and differences between perceived size and relative size of sun, moon and earth.** **Explain that the earth is an astronomical object, not a ‘physical object’**	
SOLAR SYSTEM	**Explain the differences between a Geocentric Solar System and a heliocentric solar system**	
EARTH MOVEMENTS	**Explain the Movements of Earth, Sun, Moon**	
DAY/Night cycle	**Explain the day/night cycle in terms of the rotation of the earth during its revolution around the sun**	**V** **i**