Making Mechanisms: How Academic Language Mediates the Formation of Dynamic Concepts

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Abstract: Science learning requires students to transition from their everyday language to academic language (AL), particularly to understand and internalize new mechanisms, which are constituted (brought into being) through new technical terms. Understanding AL requires turning the inert description of the mechanism in the textbook into a manipulable concept in the student mind. This complex process is mediated through teacher narratives, which scaffold the complex concept integration involved in AL, through metaphors, analogies, gestures and other enactive strategies. We present a preliminary analysis of this complex AL learning process, drawing on the embodied simulation theory of language, and classroom data on biology learning. We then discuss some application possibilities of this theoretical approach.

Keywords: Academic Language; Nominalization; Concept formation; Embodied Simulation Models of Language

1. Introduction

Science learning requires students to understand, and internalise, a new way of characterising reality. This process is mediated by academic language (AL) (Halliday & Martin, 1993), which has features that help promote scientific thinking. The structure of AL makes it very different from the language students use in day-to-day life (everyday language, EL). As AL embeds a new worldview, most students find the shift from EL to AL challenging (Lemke,1990). This transition is particularly difficult for students in non-English speaking countries, as they need to learn both English and AL in parallel. Many students in such countries are first generation learners, who find this transition very difficult. Supporting this finding, neuroimaging results show that parents' language skills correlate with students' reading abilities and related functional connectivity (Su, Li, Zhou & Shu, 2020).

Developing ways to help students gain fluency in AL is a central focus of science education research. We seek a granular account, which could lead to an understanding of the cognitive mechanisms involved in the way AL mediates concept formation. We are interested in using this understanding to design systematic technological interventions that support students' shift to AL. Such technologies could also function as probes to investigate the cognitive mechanisms involved in AL learning.

Our starting premise is that AL has structural features that promote scientific thinking and related concept formation, and the use of *AL is thus required* in science education. The key research questions we are interested in are:
1) How does a naive student develop new conceptual structures, such as the complex mechanism of photosynthesis, which embeds other complex concepts such as oxygen, carbon dioxide, stomata, guard cells etc.?
2) How does AL promote this conceptual integration, and more broadly, scientific thinking?
3) Can learning environments be designed to scaffold such conceptual integration? What role does technological intervention have in the creation of such learning environments?

2. Building mechanisms: A theoretical model

Based on the above premise and research questions, here we develop an analysis of AL learning, and possible ways in which contemporary cognitive theory could help in developing a more granular account of how AL features help promote concept formation. One of the challenges in developing such an account of AL is scaling current models of language understanding -- particularly the embodied simulation model of language -- to support the analysis of whole passages, and technical terms, from their current focus on analysing sentences, and verbs. This scaling is needed because scientific concepts, which are typically descriptions of dynamics and mechanisms, cannot be captured by a single sentence, and require passages made up of sentences that embed technical terms, and these are tightly interconnected structurally and conceptually. The next section outlines the embodied simulation model of language.

2.1 Language Understanding as Embodied Simulation

The embodied simulation model of language (ESML) is a theoretical framework under development (Bergen, 2016), where language is considered to embed sensorimotor elements. Following from this view, understanding the meaning of words and sentences involves activating modality-specific sensorimotor representations and processes. Neuroanatomical evidence grounds this activation in the sensorimotor neural circuits (Pulvermuller, 2010; Glenberg & Gallese, 2012). Supporting this approach, recent studies show that language can both trigger movements and incorporate movements (Glenberg & Kaschak, 2002; Matlock, 2004).

Extending this model to AL-based concept formation, the problem of students understanding passages describing biological mechanisms (see Figure 1 for an example) could be seen as a process of running a dynamic mental model, where perceptual neural networks encoding experience help activate imagery (such as leaves, stems, stomata), and neural networks encoding motor experiences help 'dynamicise' this imagery. Understanding AL passages would thus involve running a simulation of the activity states described by the passage.

2.2 Extending ESML to Biology Mechanisms

Our domain of analysis in this paper is biology learning, where a key focus is helping student understand new mechanisms. Many major discoveries in biology are mechanisms, such as cellular metabolism, DNA replication, protein synthesis, and gene expression in molecular biology. Mechanisms form a significant portion of the school science textbook. For the student to develop an understanding of these mechanisms, she needs to first comprehend the individual concepts that form the mechanism (such as stomata, guard cells), and then the mechanism-specific structural and functional configurations they generate (such as turgidity, transpiration). Thus, comprehending the mechanism requires conceptual integration.

Drawing from ESML, as well as earlier work on simulation of mechanisms and dynamics (Schwartz & Black, 1996, Schwartz & Black, 1999, Hegarty 2004), we consider this conceptual integration as the ability to run a mental simulation of the dynamics made possible by the mechanism components. This simulation would draw on the embodied experiences of the student, when comprehending both the individual parts and the larger configuration. As most of the components and the dynamics are imperceptible, it is very unlikely that the student would have a ready embodied experience to draw on to ground these structures and processes. However, since scientists generate new scientific concepts through integration of other concepts (Nersessian, 1992), it should be possible to scaffold the imperceptible mechanisms using students' sensorimotor experiences.

Since mechanisms have very specific dynamics, they are captured using special technical terms. Understanding these terms requires 'loading' (Redish, 2015) meaning from the world into the terms, based on students' sensorimotor experiences. This is done using teaching narratives, which connect together multiple elements, such as metaphors, analogies, artifacts, drawings and gestures. The teaching narratives thus work as explanatory frameworks. The teacher plays a critical role in this embedding of the world into technical terms, as her enaction starts the process of students learning AL and its associated simulations. Her explanatory framework is carefully built, using such enactive moves as drawings, gestures, metaphors, use of teaching props etc. The teaching narrative often consists of metaphorical or analogical mappings, where the teacher juxtaposes students' experiences (like blowing up a balloon) in relation to the mechanism, to seed the simulation of the mechanism.

Choosing the right analogical or metaphorical structure that would map to the mechanism to be taught is a critical part of the teacher's skill as a practitioner. However, the structures and processes involved in many mechanisms, particularly in biology, are not readily amenable to such embeddings based on embodied experiences. Technological interventions (such as animations, simulations, games, and VR) have the potential to augment the teacher's explanatory frameworks in such cases. Note that such interventions need to also the building of the technical terms and vocabulary (AL), which constitute (bring into being) the mechanisms, similar to the way Lego blocks bring into being a moving Lego robot, or circuit elements (resistors, capacitors etc.) bring into a signal processing circuit. Note also that the loading of embodied experiences into the technical terms allow students to access, and simulate, specific parts of the mechanism when the term is encountered (for instance, 'transpiration' simulates the processes at the surface of the leaf, and not the ATP biochemistry). Such specific and focused re-enaction, based on the loading process, can be thought of as the activation of the neuronal network for the term, formed through the teacher narrative. This activation allows the simulation of the terms to be run separately, or in conjunction with the larger configuration.

3. Building Photosynthesis

To illustrate the above theoretical model, we first present a structural analysis of a passage (see Figure 1) on photosynthesis (edited for clarity) from a grade 10 textbook, and then an analysis of the way a teacher enacted the mechanism, to help students 'load' technical terms with embodied experiences.

Now, let us study how the plant obtains carbon dioxide. In Class IX, we had talked about stomata (Fig. 6.3) which are tiny pores present on the surface of the leaves. Massive amounts of gaseous exchange takes place in the leaves through these pores for the purpose of photosynthesis. But it is important to note here that exchange of gases occurs across the surface of stems, roots and leaves as well. Since large amounts of water can also be lost through these stomata, the plant closes these pores when it does not need carbon dioxide for photosynthesis. The opening and closing of the pore is a function of the guard cells. The guard cells swell when water flows into them, causing the stomatal pore to open. Similarly, the pore closes if the guard cells shrink.

Figure 1. Blue text shows the creation of new concepts, through definitions, and encapsulation of the definitions under a new label. Later use of the label in a different context requires the student to regenerate the definition, to understand the entity it captures. Green text shows embedded dynamics. Pink text shows mechanisms with possible branches.

3.1 The Structural View

Figure 2 presents the elements we use to develop the structural analysis of the simulation process for the passage. Depending on the concreteness of the entities mentioned, we label them as familiar or dense. Familiar entities have a concrete form, and are salient to perception (pore, leaf etc.). The dense entities (stomata, guard cells) are difficult to simulate. The entities set up the physical structure, in/with which the dynamics occurs. A change in physical structures, as a result of interaction between them, is viewed as a transition between forms of the same structure. The opening of stomata for example, is considered a transition from the closed configuration to the open one.

In this analysis, as the defined entities are dense, and appear towards the end of the sentence, the familiar entities are considered to 'fill' these dense entities, making them comprehensible. If these defined entities are encountered again in the passage, they have a status somewhere in between the dense and familiar object. In simulation terms, instead of these dense entities being black boxes, the reader can partially activate the entities that fill them. Lexical items such as "can" act as branching nodes, from which the simulation can proceed along different trajectories. In our case the "can" indicates that if the stomata are open the plant may or may not lose water. A related effect of grammatical structure on the simulation is a zooming in and out of the imagery.

Zooming in and out: The grammatical structure arranges the nouns and verbs (open class elements) in certain relationships with each other. Altering this structure changes the relationships. For example, the relative positions of the various structures in the plant are indicated by prepositions: *tiny pores* *present on the surface of the leaves*. If we rearrange the words around the preposition, preserving their relative positions, we get a zooming in and out effect in the generated imagery.

Zooming In: *Leaves have tiny pores present* ***on*** *their surface, called stomata*
Leaves ***on*** *their surface have tiny pores, called stomata*
Zooming Out: *Tiny pores present* ***on*** *the surface of the leaves, called stomata*

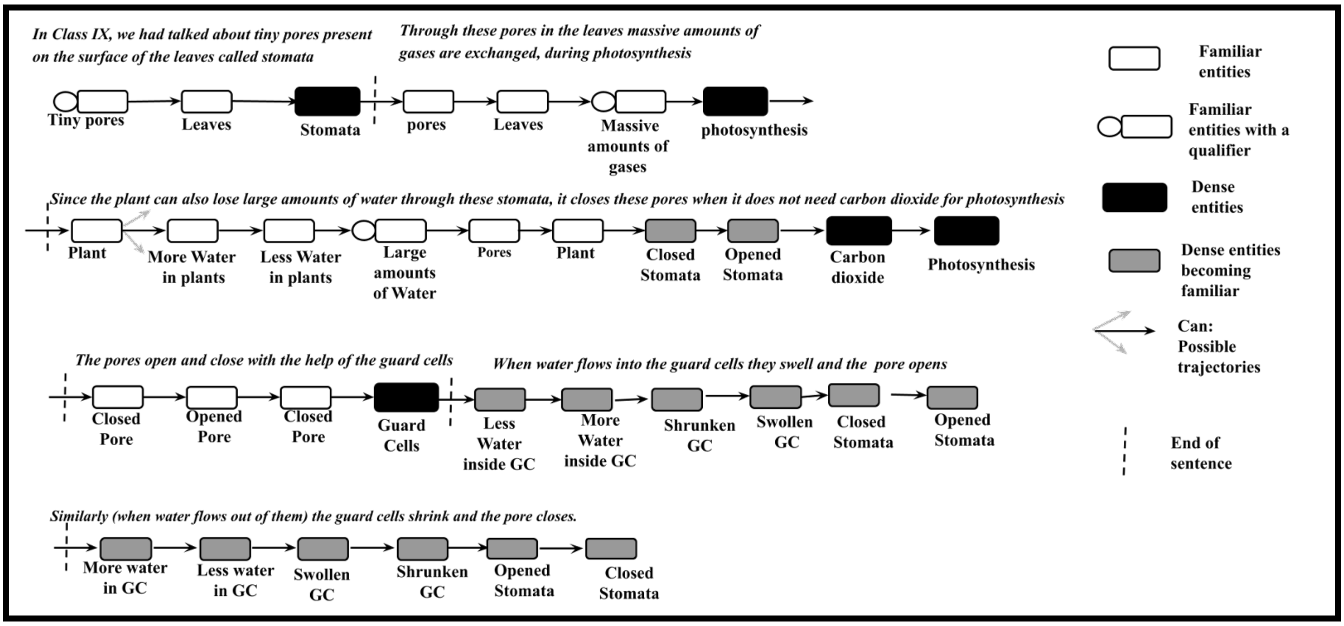


*Figure 2***.** The Structural view

4. Teacher Enaction: Scaffolding Student Simulation

The teacher generates her own simulations when she reads such text describing mechanisms. The student also generates her own simulation of the mechanism from the text, but this often differs from the normative simulation that is expected to be generated from the textbook. The teacher, through her explanatory framework, attempts to converge these two simulations. In doing so, she maps the textbook narrative into an explanatory framework, which often consists of metaphors and analogies, along with gestures and representations that accompany this narrative.

Figure 3 shows an excerpt from a classroom observation of a teacher's explanation of the transpiration process. The teacher narrative is compared to the textbook narrative and the analogical mapping between the two is outlined. In this example, the teacher is trying to explain the mechanism of the opening and closing of the stomata during transpiration. For his, the teacher makes use of the analogy of the balloon, which grounds this imperceptible phenomenon, and its associated technical terms. She introduces words like *turgid* and *flaccid*, which are more precise than terms like tight and loose, in the context of the balloon metaphor. As the balloon is compared to the cell, the conceptual schema for turgidity is exemplified well. The elasticity of both the cell and balloon membrane make it possible for them to expand on filling. The material filled in the cell is water, and that which fills the balloon is air. The experience of the tightness of the balloon connects to the turgidity of the cell. The mapping is not perfect, and it is employed as an overall template to build understanding of the mechanism. The balloon is mapped only to the guard cell, and not the entire assemblage, which includes a pair of guard cells in a specific spatial configuration.

The teacher makes drawings on the board while she is explaining. She draws the guard cell and the stomata, and explains the exchange of gases using arrows. This drawing extends the mapping, by inviting the learner to consider the two guard cells involved as balloons. It also models the shape of the balloon on the guard cells. The teacher's enaction of the mechanism using gestures and drawing further extends the understanding of the mechanism, and its associated flow dynamics.

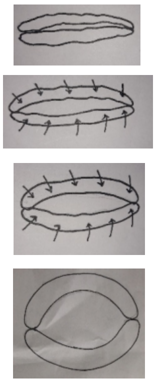
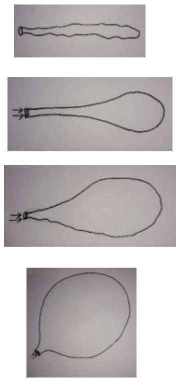
Textbook Narrative	Textbook Representation	Teacher Representation	Teacher Narrative
The guard cells swell when water flows into them, causing the stomatal pore to open	**Loose (Flaccid)**  **Tight (Turgid)**	**Loose (Flaccid)**  **Tight (Turgid)**	"say you have a balloon I am blowing the balloon if I blow the balloon half will it be turgid no…... I really blow into it so that it becomes tight and when it is tight in Biology in a Cell I call it…... it is turgid and remember last year we studied vacuole helps in the turgidity of the cell last year we learnt this word….. so when water enters the guard cells at that time what will happen the guard cells will swell and they will become turgid and when they become turgid they pull and open the stomatal Pore."

Figure 3. Illustration of the analogical mapping in the teacher's explanation for the process of transpiration

4.1 The Gist Simulation

After a first reading of such passages, a student may not be able to access the underlying conceptual structure in all its complexity. Her simulation will be patchy and at a surface level, providing a summary understanding of the text. In our case, the student may not comprehend the opening and closing mechanism of the stomata as given, with all its details. But she may understand that there are pores in the roots, stem, and leaves of the plants, and there is some way in which the pores open and close, which allow some gases to be exchanged when the pores are open. Later, when the opening and closing of the stomata is invoked in another context, only this summary simulation will be activated. We use the term *gist simulation* to refer to such summary simulations. The nature of this simulation would vary between students, depending on their real-world experiences and reading history.

The gist simulation is an important consideration in a classroom context. The teacher, through her own understanding and experience of teaching a topic, as well as her knowledge of how a topic progresses in subsequent grades, settles on a particular level of gist simulation, which she enacts, using the blackboard and gestures. This enaction process helps class participants to converge their own individually varied simulations to a common core, creating a shared understanding. The teacher can then build on this shared structure, to develop more complex discussions and evaluation parameters.

5. Application Possibilities

Embodied learning interventions based on new media technologies have not focused on the problem of academic language and nominalization, and more broadly, on the role of language in education. This could be partly because AL requires analysing the interaction between internal and external representations, particularly the way this interaction drives classroom dynamics. This distributed cognition structure makes the AL problem unappealing to some recent embodied learning approaches which take the position that embodiment and representations are mutually exclusive. Such positions draw on philosophical over-extensions of the Gibsonian framework, even though Gibson himself was more inclusive about the role of representations in cognition (Chandrasekharan & Osbeck, 2010).

Our analysis approach draws on common coding, an embodiment approach that extends the ideomotor theory of William James. This theoretical approach, compatible with the Gibsonian framework (See Hommel et. Al, 2010), is supported by many neuroscience studies. It accepts the role of internal and external representations, and their interactions, in cognition. ESML is part of this neo-Jamesian approach.

Our analysis of AL based on this model opens up AL as a new application space for embodied learning. However, it is unclear how exactly embodied learning could support the formation of mental simulations of mechanisms, in close conjunction with new technical terms.

Further, most embodied learning technologies do not focus on supporting teachers. Technological systems that allow teachers to generate more evocative simulations in students, integrating technical terms smoothly with the mental simulation, would be very helpful in addressing the AL problem, particularly in non-English speaking countries.

Our analysis indicates that these two threads (supporting AL learning, supporting teachers) are best addressed together. However, this requires moving learning environment design into new discussions, related to narratives and their role in generating mental simulation of dynamics. We hope our analysis has created the space to develop such new design conversations.

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