Performative Bundles: How teacher narratives reconfigure academic language, to help students build mental models

Synopsis of PhD Thesis

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By

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Publications

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Conference Paper:

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Conference Abstracts:

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Salve, J., Narwal, A., Upadhyay, P. Mashood, K. K., & Chandrasekharan, S. (2021). Learning to enact photosynthesis: Towards a characterization of the way academic language mediates concept formation. Proceedings of the Annual Meeting of the Cognitive Science Society, 43. Retrieved from https://escholarship.org/uc/item/9vf9k03h

Performative Bundles: How teacher narratives reconfigure academic language to help students build mental models

Abstract

Science learning requires students to build new mental models of imperceptible mechanisms (photosynthesis, circadian rhythms, atmospheric pressure, etc.). Since mechanisms are structurally complex and dynamic, building such mental models requires mentally simulating novel structures, their state changes, and higher-order transformations (transpiration, oscillation, liquid levels, etc.). These mental simulations also need to be intertwined with a series of external representations (ERs), including formal terms (stomata, guard cells, mass points, damping, etc.), schematic structures (figures, graphs, etc.), and mathematical notations (equations, vectors, etc.). Students' later encounters with these ERs need to activate the dynamic mental model of the mechanism. Further, these mental models and ERs are embedded in specialised and discipline-specific linguistic forms, called Academic Language (AL), which the students need to learn in parallel. To help learners build these many-layered and dynamic mental models of mechanisms – especially in contexts where access to technology is limited – teachers narrate, and act out, the structures, state changes, transformations, related ERs, and thessociated AL structures. These cohere together to constitute (bring into being) the mechanism models.

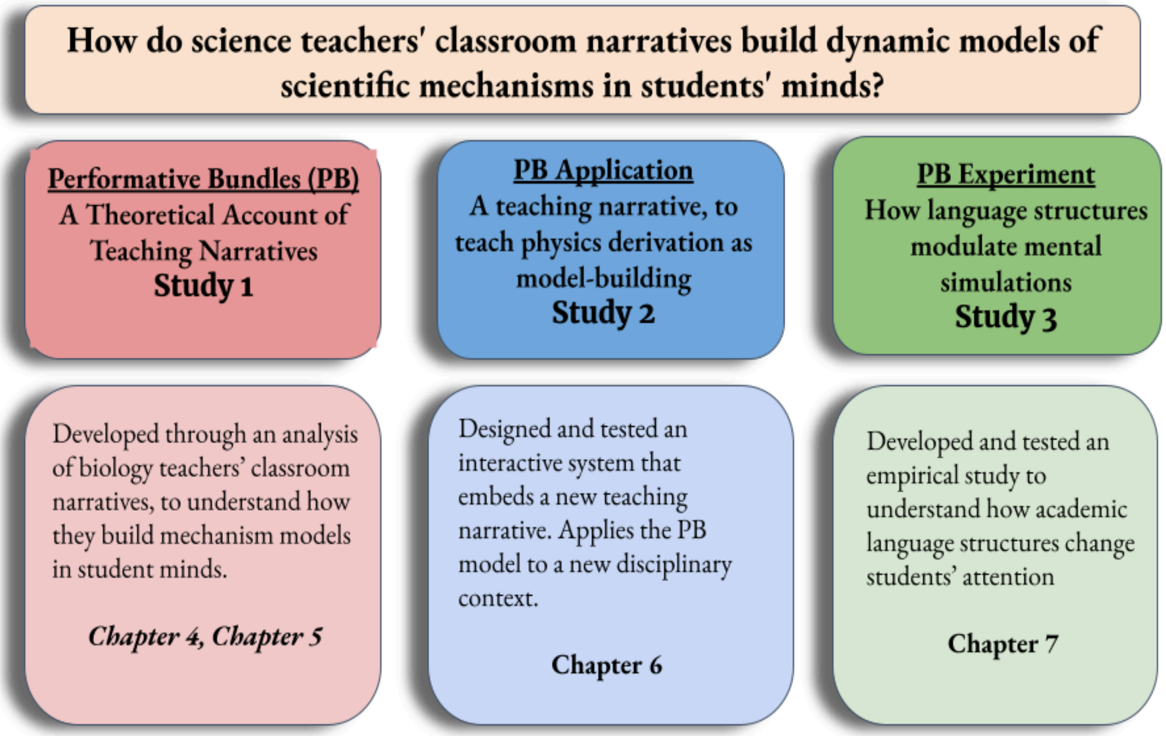
In the first study, we present a theoretical account of this complex teaching to build process, using three case study analyses of classroom teaching data (on the teaching of a biology mechanism model). We propose that teaching narratives and AL structures act as 'performative bundles' (PBs), which embed sensorimotor processes, and thus allow students to mentally simulate the target mechanisms. Further, PBs also allow students to associate these dynamic simulations to mechanism terms and AL structures, allowing these mechanism models to be retrieved and manipulated later, in new contexts and situations. This data-driven theoretical account extends and integrates two cognitive science frameworks – the Embodied simulation theory of language (ESTL) and the distributed cognition theory (DC) – and thus presents one of the few cases of education studies contributing back to basic science.

The second study developed an application of the PB theoretical account, to restructure the dominant teaching narrative on the building of a mechanism model in physics (derivation), using an interactive simulation. An experienced physics teacher presented the interactive system to first year master's students. This study extends the PB model to technologically-augmented teacher narratives, and also to the new disciplinary context of physics. Results showed that the new design helped students understand derivations better, and also solve open-ended problems. This results provides support to the PB account.

The third study developed a psychology experiment, to delve deeper into the connection between AL and the mental simulation process, and elucidate the nature and dynamics of this connection. Results from this empirical study indicate that academic language structures modulate attention. This process could be one of the possible cognitive mechanisms involved in the way teacher narratives and academic language structure alters student comprehension.

We close with some theoretical and pedagogical implications of the PB model and the three studies.

Graphical Overview of the Thesis



How do science teachers' classroom narratives build dynamic models of scientific mechanisms in students' minds?

Performative Bundles (PB)
A Theoretical Account of Teaching Narratives
Study 1

Developed through an analysis of biology teachers' classroom narratives, to understand how they build mechanism models in student minds.

Chapter 4, Chapter 5

PB Application
A teaching narrative, to teach physics derivation as model-building
Study 2

Designed and tested an interactive system that embeds a new teaching narrative. Applies the PB model to a new disciplinary context.

Chapter 6

PB Experiment
How language structures modulate mental simulations
Study 3

Developed and tested an empirical study to understand how academic language structures change students' attention

Chapter 7

1. Introduction

Science learning requires learners to understand and internalise a new way of characterising reality. This new characterisation places several demands on the learner. While the difficulties involved in learning science concepts have been studied extensively, aspects pertaining to the role of language in science learning have gained attention only in the last few decades. This recent focus (Anstrom, 2010) is driven by classrooms becoming increasingly multilingual, and English language learners (ELLs) finding it particularly difficult to cope with the specialised disciplinary forms of language required for science. Several curricular policy documents – such as the NGSS (Next Generation Science Standards), the NCF (National Curriculum Framework), CCSS (Common Core State Standards) – have stressed the importance of Academic Language (AL) in learning, especially in the context of ELLs.

AL has been characterised in different ways, and for different purposes (Lemke,1990 ; Halliday, 2003, Anstrom, 2010). There is however no consensus on a clear definition of AL. It is broadly considered as a form of language that helps students acquire and use science and other formal knowledge. AL has been approached from highly diverse perspectives, leading to multiple characterisations. One prominent perspective characterises AL as a set of registers (Halliday, 2003; Schleppegrell, 2001), and portrays its acquisition as socialisation into that register. This view also foregrounds the variability in the learners' familiarity with academic registers before they enter school. This variability correlates with the social location of the learner (Scheppegrell, 2012; Snow, 1983). This can be an important factor that reinforces social inequalities in the classroom. For instance, it is well-documented that learners from middle class families have more familiarity with the language of the school than those from working class families (Bernstein, 2003; Bordieu, 1984; Heath, 1983; Snow, 1983). Different approaches have been adopted to address this inequality. At one end of the spectrum, language simplification was adopted as a means to bridge the gap. At the other end, it is argued that AL is an important skill to participate in academic practice (Lemke, 1990) and it must thus be explicitly taught as part of the school curriculum. In this view, simplification of AL may not serve any long-term purpose in the academic development of a learner.

Simplification however, appears in other guises in the classroom context. Teachers construct explanations to help learners understand the complex models embedded in the textbook discourse. Explanations become especially important in contexts where learners do not have access to educational resources apart from the teacher and the textbook. This simplification does not involve mere breakdown of complex words into their meanings, but subscribes to the idea that AL is an important part of school academics. Teacher explanations thus seek to channel what students already know, to make sense of the unknown. Here, teachers often make use of the learners' experiential resources, to familiarise them with the unfamiliar and abstract ideas presented in the textbook. Explanations are thus carefully constructed narratives that serve as a connecting bridge between students' experiences and these abstract concepts in the textbook.

1.1 Bringing Action Back to the Discourse on Teacher Narratives

Extensive research in science education has examined the role student experiences play in sense making (Clark, 2006; diSessa, Gillespie, & Esterly, 2004; Carey, 2000; Chi, 2005; Ioannides & Vosniadou, 2002). However, a significant component of these studies are focused only on the cognition aspects of learning, and are mostly based on classical information processing models of cognition. The action dimension in student experiences has thus been ignored consistently. Actions form a fundamental aspect of our existence. We both act on the world as well as perceive actions. They are also an integral part of our language systems. The description of any event structure would not be complete without action elements. Actions crystallised in language, and their deployment in specific linguistic forms such as AL, forms a crucial aspect of academic discourse.

The enactive cognition framework prioritises actions, and it can thus provide an integrated account of the role of actions in learning. In learning science, empirical studies show how moving in new ways – based on designed technological contexts – can lead to new learning (Abrahamson, 2016). However the interface between language and actions has not been studied very extensively within the larger 4E cognition model. Embodied simulation theory of language (ESTL), a theoretical framework under development, provides a way to address this gap (for a detailed review refer to section 4.3). According to ESTL, understanding any text involves running a mental simulation of the events described in the text using language. The content of this simulation would draw from readers' embodied action experiences in the world. This account is based on studies of everyday language, which has evolved to describe the experiences of day to day life. This throws up an interesting question: what happens to these action experiences and everyday language as we shift to AL and formal academic contexts? The following section explores a possible answer to this question.

1.2 How AL Freezes Dynamicity

Many analyses of AL consider nominalization as one of its key features (Halliday & Martin, 2003; Schleppegrell, 2001; Snow, 2010). Given the centrality of AL in science learning, this view suggests nominalization could be playing a crucial role in supporting the shift to mechanism models and a scientific worldview. The following examples illustrate the way nominalization turns EL expressions to AL (in italics):

1. The ball moves towards the fence
The movement of the ball towards the fence

2. Chlorophyll absorbs light energy
Absorption of light energy by chlorophyll

3. Water molecules split into hydrogen and oxygen
The splitting of water molecules into hydrogen and oxygen

In general, nominalization does not add more information to the sentence, but generates a reframed version of existing content. Specifically, nominalization generates entity categories from active process categories. For instance, in (1), the process nature of “moving” in the verb phrase “The ball moves” is objectified in the nominal phrase as “movement.” This form of redescription has the effect of turning processes into reified concepts, which can then be treated as manipulable entities. According to Sfard (1991), nominalization plays such a reification role in the learning of mathematics concepts as well, as this process helps turn (mathematical) process categories, which are action-like, into manipulable (mathematical) objects. In her view, learners transition to such a systematic object-based understanding of processes across a long period, and this gradual development is constantly modified by experience. Sfard argues that such reification of processes into structural concepts makes the processes available for manipulation as objects. In the reification view, nominalization works as a form of “freezing” of active processes, which turns them into entities.

1.3 Broad Research Questions and Thesis Structure

This interconnection between language and its understanding through this mental simulation presents important questions that can have major implications for textbook writers as well as teacher education.

Some broad questions related to science education emerge from this preliminary analysis. I outline three of them below:

a. How do teacher explanations in science education make AL accessible to students, allowing them to transition from everyday language to AL?
b. How can new teacher narratives be designed, to help students understand the construction of formal knowledge structures used in science, such as equations?
c. How can we study the cognitive mechanisms involved in the processing of academic language, particularly in science education?

This thesis explores the above three broad questions. To operationalize these questions, we examine the teaching of scientific mechanisms. The studies we report are at the interface of language, teacher narratives and student understanding. More specific research questions, and details of related studies, appear in section (2.3 and 3).

We adopt an enactive cognition perspective to explore the above questions. To answer the first question, we build on the Embodied Simulation Theory of Language (ESTL) and Distributed Cognition theory, to analyse episodes of classroom teaching of biology mechanisms. We propose ‘Performative Bundles’ (PBs) as a theoretical construct to analyse teacher narratives related to science. Specifically, PBs are a way to understand AL structures, such as formal terms used in science. Such terms are characterised as linguistic entities that embed teacher actions, which build multiple connections between students’ known experiences and the unfamiliar science mechanisms that they need to learn. These connections can be based on analogical mappings, where the analogy used by the teacher during her explanation allows students to extend their own action experiences to mentally simulate the dynamics of unfamiliar and abstract science concepts, such as transpiration. The analogical structure can then be further extended, or combined with other representations, to generate more complex formal representational forms, such as cycles, equations, figures etc. Enactive elements used by the teacher during her explanation – such as gestures – also coalesce into the bundle. The formal terms used in AL are thus multilayered linguistic entities, supporting the running of mental simulations related to scientific mechanisms, which drive student understanding of the mechanism. A brief evaluatory study with practising teachers provided support for this new way to characterise teacher explanation of scientific mechanisms and related AL.

To answer the second question, we extended the performative bundle idea, to develop an interactive simulation that embedded a novel way to teach physics derivations – as the ‘loading’ of real world mechanisms into equations. This system was then presented to students. They were then asked to solve an unfamiliar physics problem. Their responses were tracked during problem-solving. Results showed that the new design, based on the characterisation of teacher narratives of AL as performative bundling, were helpful in advancing students’ ability to solve novel problems.

To address the third question, we developed an exploratory psychological study, using attention modulation as a probe, to understand the cognitive mechanisms involved in processing AL. Results provided indicative evidence for the proposal that the structure of AL significantly reoriented readers' attention.

The thesis is organised into eight chapters. The first chapter spells out the complex interconnections between language, knowledge and understanding. It also sets out the background in which the problem of students’ struggle with Academic Language (AL) is situated.

The second chapter reviews the literature related to teacher explanations, academic language, concept formation, and conceptual blending. This analysis helped characterise the differences in theoretical orientations, and identify gaps in existing research.

The third chapter provides a summary of the research questions identified through the literature survey. It provides a rationale for choosing a particular methodology over others, to address the research questions.

The fourth chapter provides an overview of the theoretical frameworks adopted for the analysis of AL. As the analysis we provide, draws on multiple ideas within the embodied and distributed cognition framework, we provide a summary of these approaches, and describe the various these ideas intersect, and also present them as a whole.

Chapter five provides an analysis of teacher explanations of different biology mechanism models related to photosynthesis. We analyse multiple teaching episodes, identified from transcripts of audio recordings of classroom observations.

The sixth chapter discusses the extension of the PB approach, to develop an interactive simulation that seeks to help teachers teach the building of physics derivations, and allow students to build a systematic mental model of this process.

Chapter seven presents a psychological study exploring the complex inter-relations between academic language, student understanding and attention. This study of student cognition was conducted using the context of biology mechanism models. In the eighth chapter we draw conclusions from the above three studies, and explore some of their implications.

The next section introduces some of the key research paradigms that were extended, to address the problem of AL and its teaching.

2. Literature Review

2.1 Dynamic View of Conceptions

A range of studies in learning sciences have focused on developing theoretical accounts of student learning of concepts. Among these, the view of conceptions as dynamically emergent structures (DES) within a conceptual ecology, proposed by Brown (2014) and others (Posner & Strike, 1992), is closely related to the work we present here. This is a dynamic view of conceptions, in contrast to the view of concepts as rigid structures (Driver, 1989). The DES framework considers students' conceptual resources—such as their conscious models, implicit models, and associated core intuitions, along with verbal-symbolic knowledge (Brown, 2014; Cheng & Brown, 2010)—as important factors in students' generation of an explanatory model. In this view, domain-general core intuitions can get refocused through the explanatory model, which in turn affects the overall intuitive sense a student has of a situation. The conscious model and imagistic construal (Brown, 2017) share some correspondence with dynamic imagery and mental simulations, which are the theoretical resources we draw on to develop our account. Stephens and Clement (2010) also consider "animated mental imagery" as associated with scientific reasoning. Along the same lines, Nersessian (2010) considers simulated model-based reasoning, a central component of scientific reasoning. Another related approach is representational gesturing (Mathayas et al., 2019) and cued gesturing (Mathayas et al., 2021), which consider students' mechanistic explanatory models as grounded in action, thus aligning with the larger narrative of embodied cognition.

2.2 Teacher Explanations

Teacher explanations have been analysed from multiple perspectives and their features have been characterised. Analogies have been identified as an important feature of teacher explanations. Glynn (2012) proposes the teaching-with-analogies model. According to this model, the teacher identifies similarities between the analog concept and the target concept. The differences are also identified, and parts where the analogy breaks are discussed. Glynn (2007) extends the analysis on the use of analogies by exemplary teachers and textbook writers to web-based instruction. Here they propose guidelines for designing elaborate analogies used in web based instruction. Wong (1993) points to the generative capacity of analogies in generating new insights and inferences, in addition to fuelling conceptual understanding. Thiele and Treagust (1994) report that analogies are used by teachers for individual students as well as groups. The triggers for their use can also be different in different contexts. Treagust et.al, (2003) identify both submicroscopic and symbolic representations in chemical explanations, which play a role in the development of relational understanding in undergraduate students. They also point out the assumptions made by teachers, about students' understanding of the role of representations.

The use of animism and anthropomorphism in early science teaching is attributed by teachers to cause cognitive problems in young children. The prevalence of this use has been also correlated to lack of content and pedagogic knowledge on the part of the teachers (Kallery, 2004). Apart from this, teleological explanations have also been found to lead to alternative conceptions, which provide explanatory reasons for the occurrence of chemical transformations (Talanquer, 2007). Their use is generally correlated with the use of chemical transformations and over-generalisations.

Most of the above studies focus on students' concepts, and do not focus on the teacher's perspective during classroom teaching. Even studies that focus on teacher explanations mostly stay at the level of categorising them, into different lots. Our interest is in the role of AL in science learning, and the teachers role in making it accessible to students. This aspect is unexplored in the literature. Based on this gap in the literature, we identify the following specific research questions.

2.3 Thesis Research Questions

1) How do teachers restructure AL, to build new internal models of scientific mechanisms in student minds?

2) What are the cognitive mechanisms involved in this process?

3) How does AL bring into being (constitute) scientific mechanisms?

4) How can we build educational technology applications that allow teachers to systematically build mental models of scientific mechanisms in student minds?

3. Methodology

The research reported here broadly aims to explore the complex inter-connections between language, actions, and related semiotic resources, which together allow teacher narratives to advance student learning of mechanism models. Teacher narratives are highly dynamic, as they are contingent upon the classroom context and student feedback. The diverse experiences that students bring to the classroom, the teacher's own understanding of the nature of science, and her beliefs about teaching, along with the school's larger philosophy of education, contribute to the kind of approach a teacher employs in constructing explanations, and the teaching narratives that are generated. As the research questions above explore different dimensions of this problem, this thesis makes use of different methodological stances, across three studies. The studies and methods are briefly outlined below.

3.1 Study1: Characterisation and Generalisation

In order to characterise teacher narratives in all their richness, the researcher needs to observe and document the unfolding of narratives in a classroom context. Also, to account for the diverse instances of teaching narratives, diverse classroom contexts need to be observed.

The first study was our initial foray into the task of characterising teacher narratives (TNs). For this, we adopted a **case study** approach, which is a naturalistic form of research that allows exploring a bounded system embedded in a wider context. It also allows drawing on data collected using a variety of methods. The different methods are combined with the purpose of illuminating a case from different angles, and triangulate the results (Johansson, 2007). Taking photosynthesis as an illustrative mechanism case, we observed teaching narratives related to this topic across grades, teachers, and school systems.

3.1.1 The Choice of Photosynthesis

Photosynthesis was chosen particularly because several studies have pointed out that students find the learning of photosynthesis challenging (Cañal, 1999; Barker & Carr, 1989; Métioui et al., 2016), with many conceptual difficulties related to photosynthesis, at different stages in school education, documented by research studies (Marmaroti & Galanopoulou, 2006; Södervik et al., 2015). Teachers too find the teaching of photosynthesis conceptually challenging (Krall et al., 2009). Our choice of the photosynthesis topic is based on these challenges faced by students and teachers. Apart from this reason, we also consider photosynthesis illustrative of the nature of biology, as it is structured as a network, containing, and also interconnecting, many mechanism models. It also connects to other concept networks, with mechanism models of their own, such as respiration in plants. Even models at the ecological scale—such as energy flow, biomass, plant-animal interaction, and sudden transitions in ecosystems— are related to the photosynthesis network.

3.1.2 Data Collection

The following table captures the total classroom sessions observed. Out of these sessions, we focus only on the photosynthesis sessions (marked in red) for the analysis.

Teacher	Grade	Topic	Board	Classes observed
T1	10	Photosynthesis	CBSE	1
	7			1
T2	7	Photosynthesis	State	1
	7	Cell		3
T3	10	Reproduction in Plants	CBSE	2
T4	7	Cell	State	2

Table1: *The distribution of sessions observed. The ones highlighted in red were used for analysis.*

We observed the classroom teaching learning sessions and recorded them using two recorders, one kept at the front and the other at the back. Audio data from the observed teaching sessions was transcribed, and some main teaching episodes and common themes were identified. These episodes and themes, as well as the textbook descriptions of the mechanism that the teacher was teaching, were then analysed from two perspectives:

1) A "teacher cognition" perspective, where we examined the episodes and themes from the standpoint of the teacher and the cognitive problems she was facing and solving

2) A cognitive mechanism perspective, where we examined the episodes and themes from the standpoint of the cognitive processes involved in (a) student understanding of the biological machinery under discussion and (b) the building of the teacher narratives of the biological mechanisms

3.2 Study 2: Extending the Model of TNs

In the second study we extend the model developed in study 1, to understand how a specially designed teacher narrative, made possible using an interactive simulation system, changed the development of student mechanism models in physics. An interactive system to teach physics derivations was designed, based on the idea of derivations as the process of 'loading' the real world into equations. This narrative was presented to students, as the students interacted with the system that embedded this view of derivations. The data collected included the interactions patterns of students, and their performance in a set of tasks that were given at the end of their interaction with the system. This qualitative study (see section 5 for details) was conducted online.

3.3 Study 3

To answer research question 2, we undertook an empirical investigation, exploring the possible cognitive mechanism involved in students' understanding of AL related to the photosynthesis mechanism. This psychological study specifically focused on how changes in the structure of language caused shifts in the attention of the learner. The design of this study extended existing psychology studies on attention, and also language. The design followed a pretest, treatment, and post test design. For details on the study please refer to section 6

4. Study 1 Analysis

Distinct classroom episodes of TNs related to a biology mechanism model (photosynthesis) were analysed. The analysis progressed in three distinct steps, and each step is presented as a figure. In the first step, we compared the textbook narrative (AL) with the teacher narrative. This comparison is important, as it provides a theoretical lens to view the translation of the AL narrative into the teacher narrative. It helped us see how the model in the text is transformed pedagogically. In the next step, we characterised the teaching episode using categories at a higher level. These categories describe the different strategies used by the teacher, along with the way they are used. Finally, in the third step, we abstracted away from the specific details of different episodes and developed a generalised picture of TNs. This three-step structure, derived from empirical data, was then used to articulate a theoretical model of how TNs generate mechanism models in student minds.

4.1 Mechanisms and their Understanding

As discussed, our analysis is focused on the way TNs promote student understanding of scientific mechanisms. Formally, mechanisms are a specific class of scientific explanations, studied mostly in the philosophy of biology and philosophy of science (Glennan, 2017; Machamer et al., 2000). Apart from biology, mechanism-based explanations are also developed in physics and engineering. To capture the role of mechanism-building in science and engineering, philosophical concepts related to mechanisms—such as *nomological machines* (Cartwright, 1997), the *machinic grip* (Pickering, 2010), and *representational machines* (Chandrasekharan & Nersessian, 2021)—have been developed in the philosophy of physics and philosophy of engineering. The philosophical literature on mechanisms is quite complex and spread across multiple domains. A deep dive into these detailed discussions would take us far from our teacher education objective, of developing an account of how TNs promote student learning of mechanisms. Since such an exhaustive review is also not necessary for our purposes, we will be working with the following two consensus definitions of mechanism (Craver, & Tabery, 2019):

A mechanism for a phenomenon consists of entities and activities organized in such a way that they are responsible for the phenomenon. (Illari & Williamson, 2012)
A mechanism for a phenomenon consists of entities (or parts) whose activities and interactions are organized in such a way that they produce the phenomenon. (Glennan, 2017)

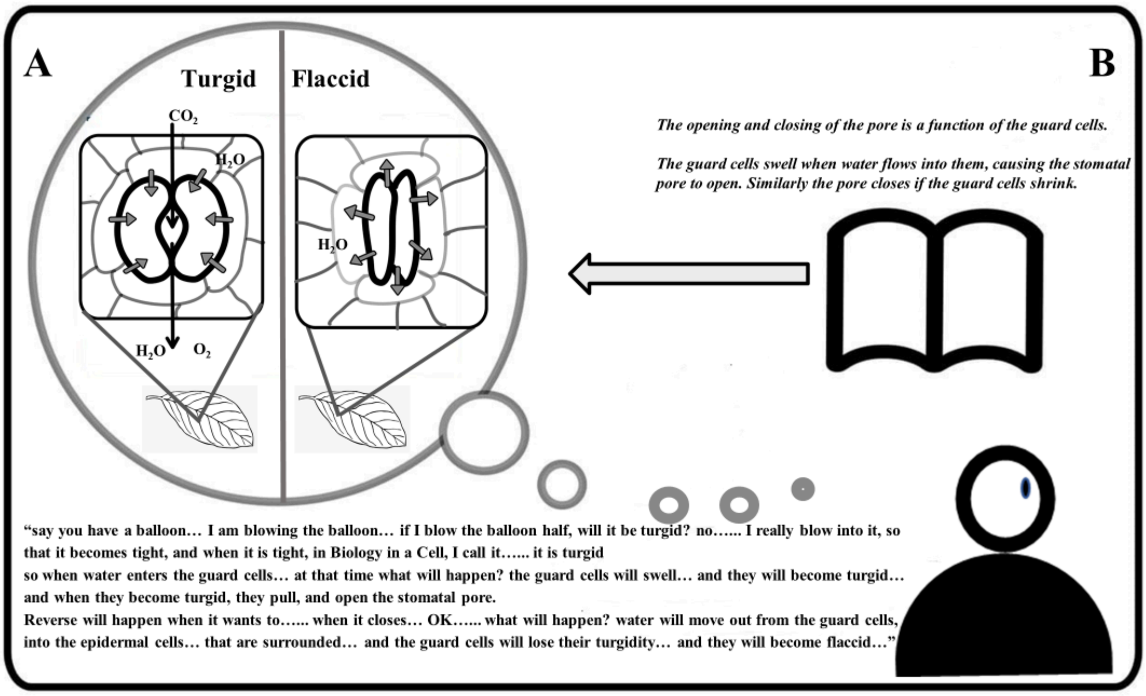
Note that these definitions consider the mechanism as a specific way of characterizing a phenomenon in the world. In this view, idealizations (pendula, orbits, etc.) would also be considered mechanisms, as they are made up of entities whose activities are considered to produce the phenomenon in the world.

Drawing on these definitions, and the wider philosophical discussion on mechanisms, the main aspects of mechanisms we focus on here are as follows:

- Their part-whole (componential) structure
- Their activity (dynamic) nature
- Their “bundling” into mechanism terms and other external representations (ERs; Kirsh, 2010)

In our view, for learners to understand a mechanism, they need to interlink these three aspects (components, dynamics, ERs) into a cohesive network. We consider the term "mechanism concept" as referring to this integrated network. Here, we use the term "mechanism model," instead of "mechanism concept," as we analyze the nature and learning of the first two properties of the network (componential nature, dynamics) as a model, and examine separately how these are encapsulated within formal symbolic systems ("bundling" of mechanisms into formal terms and ERs).

To illustrate our case-study bases analysis, we provide below the analysis of a teaching episode related to the mechanism of the opening and closing of the stomata during transpiration.



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.

"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
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.
Reverse will happen when it wants to…... when it closes… OK…... what will happen? water will move out from the guard cells, into the epidermal cells… that are surrounded… and the guard cells will lose their turgidity… and they will become flaccid…"

Figure1*: A schematic representation of the teacher's explanation of the transpiration process. The teacher narrative (part A) is presented alongside the textbook narrative (part B). The dynamic process of the opening and closing of the stomata in the teacher narrative maps the structure and dynamics of the mechanism, as given in the textbook narrative. This mapping is done by expanding and enacting the textbook narrative, making the mechanism dynamics action-based, and "loading" technical terms like "turgid" and "flaccid" with mental simulations—all using the action-based narrative*

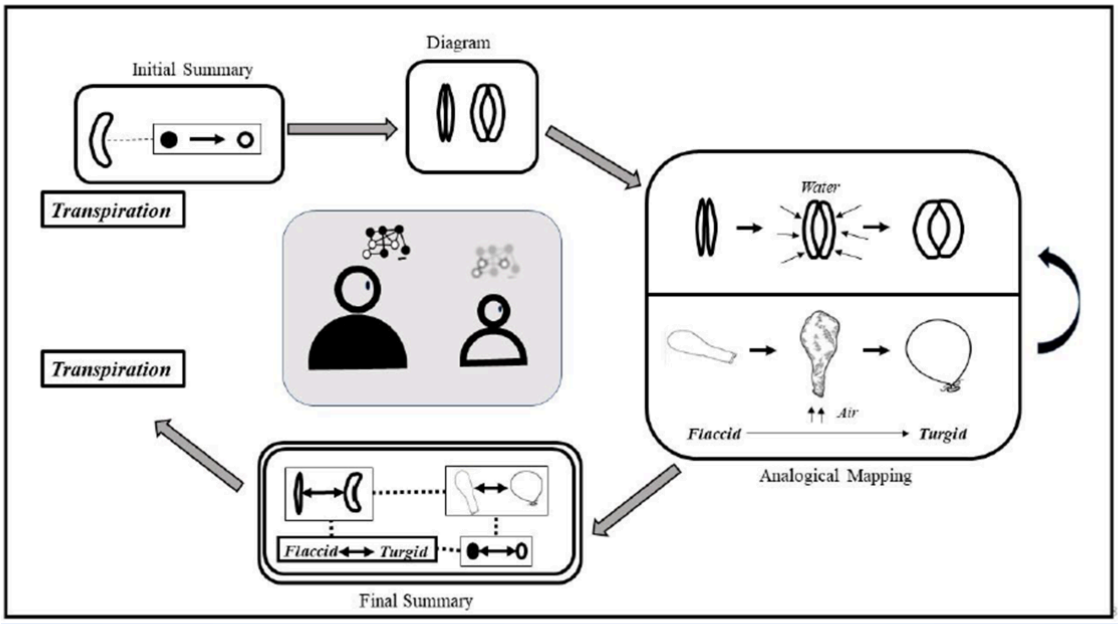


Figure2: *A structural analysis of the teaching episode. It depicts the teacher's use of several enactive moves,to build a mental simulation of the imperceptible transpiration process in students' minds. This includes the initial use of summaries and diagrams (top left panels), gestures, analogical mappings (right panel), andfinal summary (bottom left panel). These components together build internal models of the imperceptible mechanisms, by drawing on learners' existing sensorimotor experiences. This process refines the student's initial gist simulation of the mechanism model (hazy network in the middle panel), moving it closer to the canonical mechanism model (the teacher's sharper network in the middle panel)*

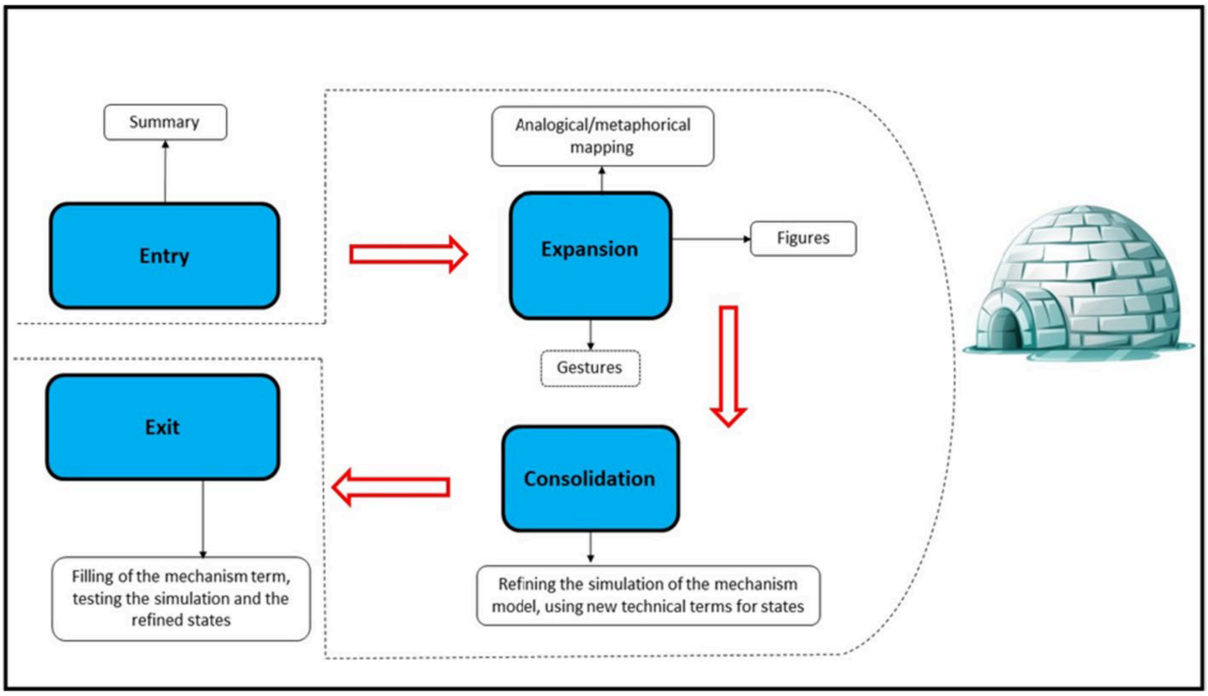


Figure3: *The igloo model: how teachers build mental simulations of scientific mechanisms in students' minds, and "load" these simulations into technical terms, for later activation. This figure presents a schematic general model of the way a mechanism model is built. This schema idealizes the earlier figure, capturing the teacher's explanation of the transpiration process as a general pattern,*

abstracting out the different phases in a teacher's model-building. The teaching narrative starts with the entry into the model-building episode, using an initial summary. The teacher then expands on this summary, using several enactive strategies to extend and remap learners' existing sensorimotor experiences, thus generating the new mechanism model. This is followed by a consolidation phase, where the initial summary is modified, to include the refined understanding generated in the expansion, and also some new technical terms. During this process, the teacher also links the refined mental simulation of the mechanism to the top-level technical term. Later encounters with the term can now activate the mechanism model, as well as its specific states. The teaching episode then exits, with an evaluation, particularly by testing the stability of the new states and associated terms that have been added to student simulations of the mechanism. In terms of overall structure, this process—of generating the internal mechanism model, and encapsulating the model and its parts into technical terms—resembles an igloo

4.2 The Biology Mechanism Model

The above case presents an example of our three-step analysis of the TN involved in a teaching episode, where the teacher is trying to explain the mechanism of the opening and closing of the stomata during transpiration. For this, the teacher makes use of the analogy of a balloon, which grounds this imperceptible phenomenon, and its associated technical terms, using a sensorimotor experience familiar to students. Note that the structure of this sensorimotor experience is only similar to the structure and dynamics of the opening and closing of stomata. It does not provide a fully accurate mapping of the mechanism. It is used to start a "seed" mental simulation, which reorganises students' existing sensorimotor experiences in a specific way. This reorganised structure generates a stable simulation in student minds, which can then be revised systematically, to generate a closer mapping to the textbook description of the mechanism. The teacher also introduces novel words like turgid and flaccid, which are more precise than terms like "tight" and "loose," in the context of the balloon example. 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 makes it possible for them to expand on filling. The material filled in the cell is water, while the balloon is usually filled with air. The experience of the growing tightness of the balloon connects to the turgidity of the cell. The mapping is not perfect, and it is deployed as an overall template to build an initial understanding of the dynamics of the imperceptible mechanism. The balloon is mapped only to the guard cell, and not to 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 mapping the two structures. She draws the guard cell and the stomata, and indicates the exchange of gases using arrows. This drawing extends the mapping, by inviting the learner to consider the two guard cells as balloons. It also maps the changing shape of the balloon to the changes in the guard cells. The teacher's enaction of the mechanism using gestures and drawing further consolidates the understanding of the changes in the mechanism components and its associated flow dynamics. Note that the teacher has reconfigured the balloon experience, to develop the detailed structure of the guard cell. This process requires the student to revise her internal mental simulation of the balloon significantly, to track the mapping the teacher is setting up.

4.3 Embodied Simulation Theory of Language

Which cognitive mechanisms allow the teacher's narrative to change students' understanding (which we define as mental simulation) of the transpiration mechanism? This question could be answered by the enactive simulation theory of language (ESTL), a theoretical framework under development (Bergen, 2015; Pulvermuller & Fadiga, 2010; Glenberg & Gallese, 2012), where language is considered to embed sensorimotor elements. In this view, understanding the meaning of words and sentences, particularly related to actions and dynamics, involves activating modality-specific sensorimotor representations and processes in the brain. This activity is equivalent to running mental simulations.

Supporting this language-as-condensed-enaction view, studies show that language can both trigger movements and embed movements (Bergen & Wheeler, 2010 the hypothesis that actions are mentally simulated in response to language stimuli. For instance, a study by Glenberg and Kaschak (2002) showed that participants were quicker in judging the direction of motion for sentences like "open the bottle" (anticlockwise rotation) if the actions they performed in parallel were compatible with those suggested in the sentence. This result is found to hold even in cases where abstract transfer is involved. For example, in sentences like "Liz told you the story," participants' responses in judging the direction embedded in the sentence were quicker if the action they did in parallel was away from the body. Similarly, Zwaan et al. (2010) showed that reading of sentences implying motion in the clockwise ("He turned the key to start the car") or anticlockwise direction was affected by the action of turning a knob in a clockwise or anticlockwise direction to reveal the next part of the story. Even in cases of fictive motion sentences (such as "the road runs through the valley," where the road is not an entity that can run), studies have shown that participants exposed to story stimuli involving longer distances, rough terrains, slow travel rates, etc. took longer to judge a test sentence (Matlock, 2004; Talmy, 1983, 2000). Apart from such behavioural studies, evidence from eye-tracking studies also indicates the involvement of mental simulation in language comprehension. In a study by Spivey and Geng (2001), participants were asked to look at a blank screen while they listened to a story about a spatial scene. Even though the stories were not about motion, participants were found to shift their visual attention to different regions on the screen, in response to the position of spatial events in the story. For instance, for events happening on the top floor of the building, participants' visual attention shifted to the top of the screen.

Neuroanatomical evidence grounds such mental simulation in the covert activation of sensorimotor neural circuits (Pulvermuller & Fadiga, 2010; Glenberg & Gallese, 2012), i.e., without overt movements. Brain imaging studies show that when participants process verbs (such as walk, lick, and hit), motor areas related to these movements are activated (Pulvermüller & Fadiga, 2010). A reverse correlation supporting this neural process is established by studies of the progression of motor neuron disease, which affects the processing of verbs disproportionately, compared to the processing of nouns (Bak et al., 2012). Supporting the enactive view further, a recent study showed that a patient with a double motor cortex exhibited faster performance for action concepts than object concepts (Miranda et al., 2022).

4.4 Performative Bundles: A Theoretical Account of the Nature of Teacher Narratives

Extending this theoretical view, and related empirical results to the process of generating mechanism models in student minds, the problem of understanding passages describing biological mechanisms could be seen as a process of running a dynamic mental model, where perceptual neuronal networks encoding sensory experience help activate imagery (such as leaves, stems, stomata; components and their structure), and neuronal networks encoding motor experiences help "dynamicise" this imagery (dynamics of the guard cell). Understanding mechanism passages would thus involve running a mental simulation of the structure and activity states embedded in the passage (Mak & Willems, 2019).

In this account, for a teacher to develop an understanding of the canonical mechanism described in the textbook, she needs to first activate neuronal networks that instantiate sensorimotor models that form the mechanism structure (such as stomata, guard cells), and then the mechanism-specific structural and dynamic configurations they generate (such as turgidity, transpiration). As most of the mechanism components and the dynamics are imperceptible, and quite different from everyday experience and their language forms, it is very unlikely that the teacher would have a ready sensorimotor experience to draw on, to ground these novel structures and processes. Thus, the teacher's comprehension of the mechanism requires reconfiguring or recombining her sensorimotor experiences, particularly ones that are most similar in dynamics to the described mechanism (Rahaman et al., 2018; Schubotz, 2007). She then needs to integrate these reconfigured neural activities to generate the mechanism model. Note that this reconfiguration process is driven by the text. Language here functions as a system that helps activate, recombine, and finetune mental simulations.

To transfer this mechanism model to students' minds, the teacher needs to do another reconfiguration, to adapt her simulation model to students' existing models and experiences, and also their language abilities. For this, she juxtaposes common student experiences (such as blowing into a balloon and seeing it expand) in relation to the mechanism, and then maps this sensorimotor experience systematically to her own model of the mechanism, thus acting out in the classroom the imperceptible structure and dynamics, using a narrative the student can follow. Since mechanisms in science have very specific dynamics, which are different from state changes familiar to students from their experience of everyday events, the mechanism state changes are labelled using special technical terms. The teacher invokes these terms in tandem with the teaching narrative, so that they are associated with the narrative of the mechanism. Note that the terms are not playing just a passive role in fine-tuning students' simulations. They allow students to segment (and keep segmented) different components of the mechanisms. They also stabilise the different dynamic states associated with the segments. This means the terms play a causal role in 'constituting' (i.e. bringing into being) the mental model of the mechanism.

At the students' end, ESTL suggests that attending to the narrative of the teacher generates a mental simulation process, where the learners' perceptual and motor systems are activated virtually/covertly, to generate an approximate version of the structural components of the narrated mechanism (such as the balloon and guard cells) and their dynamics (opening and closing). These simulations are then associated with the mechanism terms (MTs). Understanding of MTs thus emerges through the process of students simulating the integrated dynamics (of the balloon narrative and the guard cell drawing).

Importantly, the teacher's invoking of MTs with the dynamic model allows "loading" (Redish & Kuo, 2015) the new integrated structure and dynamics into these MTs. In most cases, this loading is a gradual process, based on many intermediary ERs (such as metaphors, drawings, gestures, etc.), which the students "bind" together, to generate the specific simulation that is loaded into the MT. Once the mental simulation and the formal symbolic terms are thus intertwined, encountering the MTs can reactivate—and also focus attention on—specific parts of the mechanism simulations (such as guard cells, and turgidity), or the mechanism simulation as a whole (such as transpiration). Since such later encounters with

MTs activate mental simulations, these terms acquire a "performative" nature, making them similar to action verbs (such as kick, pick, and suck), which have been shown to generate covert motor activation (Bergen & Wheeler, 2010; Bub & Masson, 2012; Glenberg & Kaschak, 2002; Matlock, 2004; Pulvermüller & Fadiga, 2010; Wilson & Gibbs, 2007; Yee et al., 2013).

However, the mechanism terms (MTs) are more complex than verbs, as they have the following features:

- They are built up through extended teacher narratives and enaction.
- They are generated through reconfigurations of sensorimotor experiences, artifact states, and mental simulations.
- They thus have intricate—circuit-like—internal structure, which can change systematically,
based on new experiences and narratives that are embedded in the MTs.
- They are "stacked" to form mechanism complexes.
- They can be finetuned and used to focus attention on specific parts of the mechanism.
- They activate mental simulations of inanimate movement.

These novel properties, and the detailed simulative nature of MTs, make them different from verbs. Such terms are better thought of as "performative bundles," as (1) they contain intricate internal structures that can activate mental simulations in specific and nuanced ways and (2) they are built up through a series of teaching actions. We term this process— the enactive building of such bundles—performative bundling. A significant problem in building up such bundles is the "correct" activation of the mechanism simulation in student minds, such as the right orientation, mapping, and sequencing of transformations, as the teacher narrative may not cover all these aspects in full detail. This suggests students initially generate only a "gist" simulation of the mechanism, based on the teacher's enaction.

These student simulations will be patchy and at a surface level, providing just a summary understanding based on the teaching narrative. For instance, in the case of transpiration, the student may not comprehend the opening and closing mechanism of the stomata as given in the text, with all its details. But they 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 allows some gases to be exchanged. Later, when the opening and closing of the stomata are invoked in another context, only this summary simulation will be activated.

This account provides a theoretical framework to understand the cognitive processes involved in the way TNs generate mental simulations of scientific mechanisms.

5. Study2: Interactive System for Physics Derivations

Disciplinary differences related to student difficulties – in terms of the language used, the different representational resources employed etc. – are well documented. To explore whether the PB account could be extended to other disciplines, particularly to design new teacher narratives, we examine the applicability of the performative bundle account to the case of physics derivations. This account involved developing a new educational technology – in the form of an interactive system that embedded the loading narrative above – along with the associated narrative of an experienced physics teacher while the students interacted with the system. An important difference in this case is that the previous analysis is based on a minimal classroom, where the teacher's access to technological applications is limited. Here we examine how teacher narratives could be changed, and also augmented, in combination with an interactive system. Note that this system was designed specifically to generate a new teacher narrative, and thus a new kind of student understanding of physics derivations.

We outline the design and testing of this interactive teaching system. The design sought to help teachers develop a new model-building narrative of derivations, and thus help undergraduate physics students develop a model-building understanding of derivations, particularly considering derivations as the process of loading reality into equations (Redish & Kuo, 2015). The system also sought to develop a new teaching narrative, which allowed teachers to 'enact' (rather than describe) the building of a canonical model in physics, and thus advance undergraduate physics students' model-building capabilities. This interactive system would allow us to explore whether, and how, students internalised this new building narrative.

5.1 Key Design Elements

To make the performative character of the equation and the derivation process better available to teachers and learners, enactable visualisation elements were added to the interactive system. Secondly, in the derivation system, learners were provided ways to manipulate the onscreen activity at most points in the 5-step process. This allowed the real-world activity that eventually became the equation to be 'kept alive' at each of the transformation stages. The active manipulation was also designed to engage the students' sensorimotor system, so that later recall of the equation would include this sensorimotor activation (mental simulation). Finally, the manipulations, which augmented the continuing thread of real-world activity embedded in each step, were designed to promote integration of the different derivation elements, by extending the action system's inherent capability to integrate many sensorimotor elements. Since the process of derivation involved starting from a concrete representation and progressing towards an abstract one, the design of these enactive elements also incorporated recommendations driven by the theory of concreteness fading (Fyfe & Nathan, 2019).

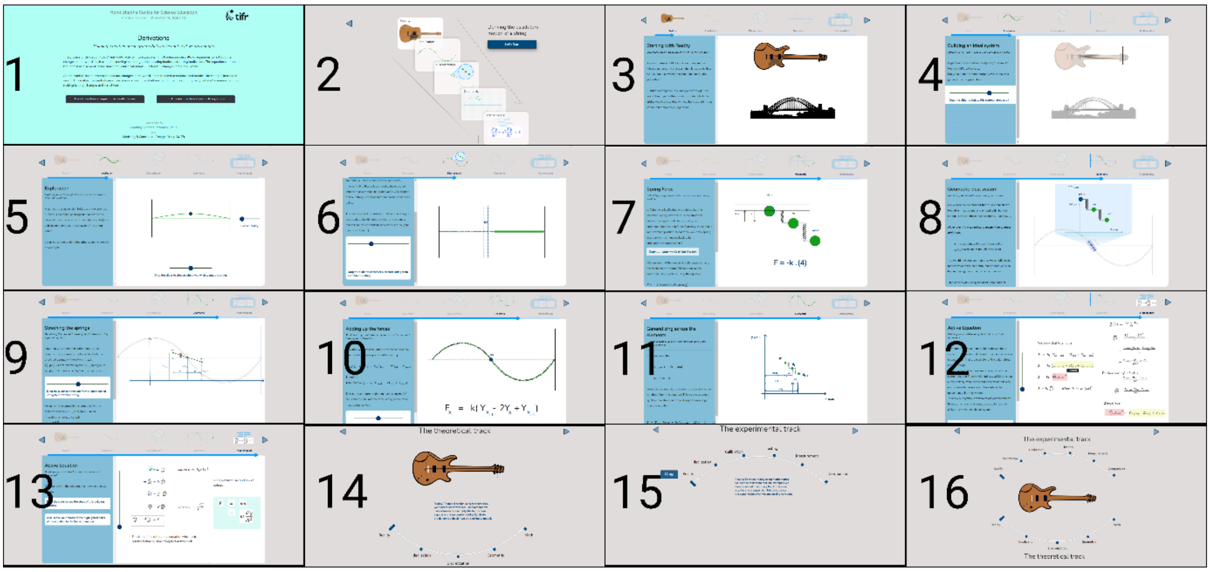


Figure 4: *shows a snapshot of the interactive learning system. Screen 1-2 are introductory, Screen 3-13 explain each step in the sequence through enactive elements, text, and the 5-step sequence at the top. Screen 14-16 provides a summary of this sequence, and situates it in the larger framework of the scientific method. The interactive system can be explored on a laptop/PC (with Google Chrome) using this link: Outline (ambargithub.github.io)*

5.2 Implementation of the Study

Ten physics major students, attending the first semester of a master's degree in physics (after three years of undergraduate study), were recruited. As shown in the figure below, each participant's study was done in three parts (in online mode due to covid), over a period of two days. First, the process of equations 'acting out' the behaviour of phenomena in the real world (Majumdar et al., 2014) was illustrated using a novel simulation system, which showed the equation's variables changing in tandem with changes to the real-world system and a graph. Learners were asked to manipulate different states of this simple pendulum simulation, to develop a qualitative sense of the equation-as-machine notion. After this, students moved to interacting with the derivation system.

On day 1, students were asked open-ended questions in a semi-structured format, before and after they experienced the derivation system. The physics expert ensured that the system was understood by each student. After experiencing the system, students were asked to describe how they thought the system related to their understanding of derivations. Secondly, they were asked how they would explain derivations and equations to a non-physics friend, to track the changes in their understanding about these key concepts. They were also asked to solve an open ended problem related to the derivation in the system they experienced.

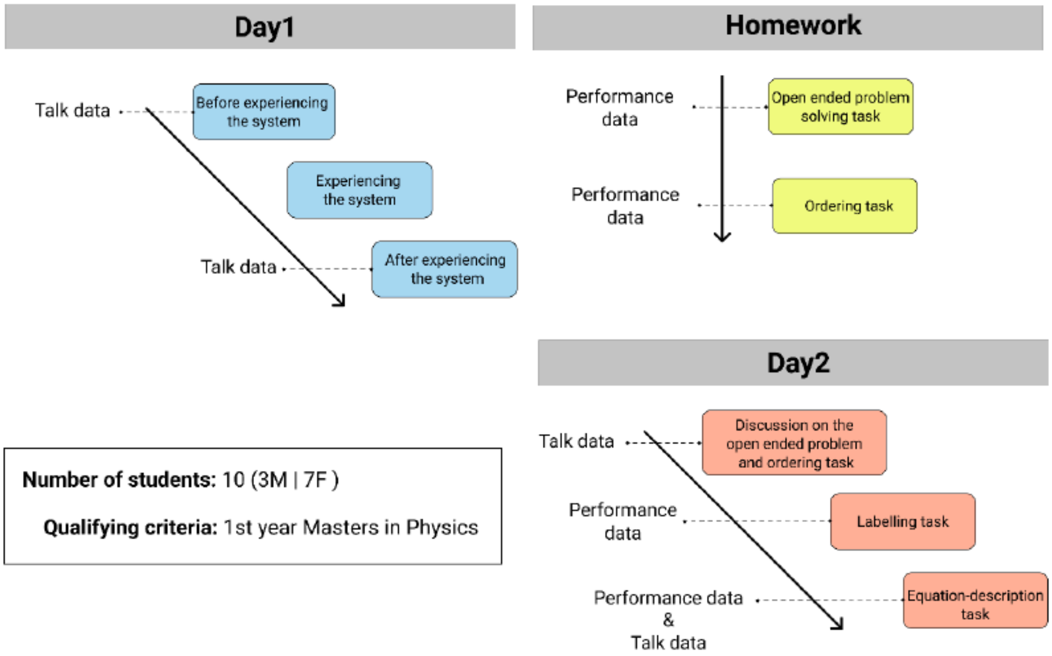


Figure 5: *shows the three parts in which each participant's study was conducted, along with the types of data collected. Day 1 (in blue) shows the three stages of the study. This was followed by homework tasks (in yellow). On Day 3 (in orange), the student was first asked to discuss his reasoning behind the homework tasks. This was followed by two other tasks*

5.3. Data Analysis

We identified *intertwining* as an important theme of analysis. Intertwining is the flexibility to navigate between concrete scenarios and abstract conceptual knowledge of physics. Higher intertwining demonstrates a better understanding of the connection between reality and equations (ability to load reality into equations), as well as an integrated understanding of the way reality gradually turns into equations (understanding of the different components of the conversion of reality into equations during modelling). For comparison, quotes from the interview exemplifying high, medium and low intertwining are given below.

High Intertwining:

"We are interested in quantity, let us say the angle from the vertical, of the, since we are talking about the pendulum, we are interested in the angle from the vertical. So we want to write the angles on the vertical as a function of something, that is we want to find out how the angle varies, and in our case we want to find out how it varies with time. That is we want to be able to predict the angle at any given time, that is our aim. Aim of deriving an equation is to formulate an equation such that we can express a required quantity as a function of some other quantity which we are provided with already."

Medium Intertwining:

"I feel when I start to do something I feel stuck somewhere maybe because, due to the advancement of the topic and alot of assumptions that we take in a certain situations maybe that. Yeah in pendulum and spring like we in plus two and all we didn't consider the damping and all you know we went with the flow that was out of syllabus for us but when it came to college we have to consider all those things damping, energy differently"

Low Intertwining:

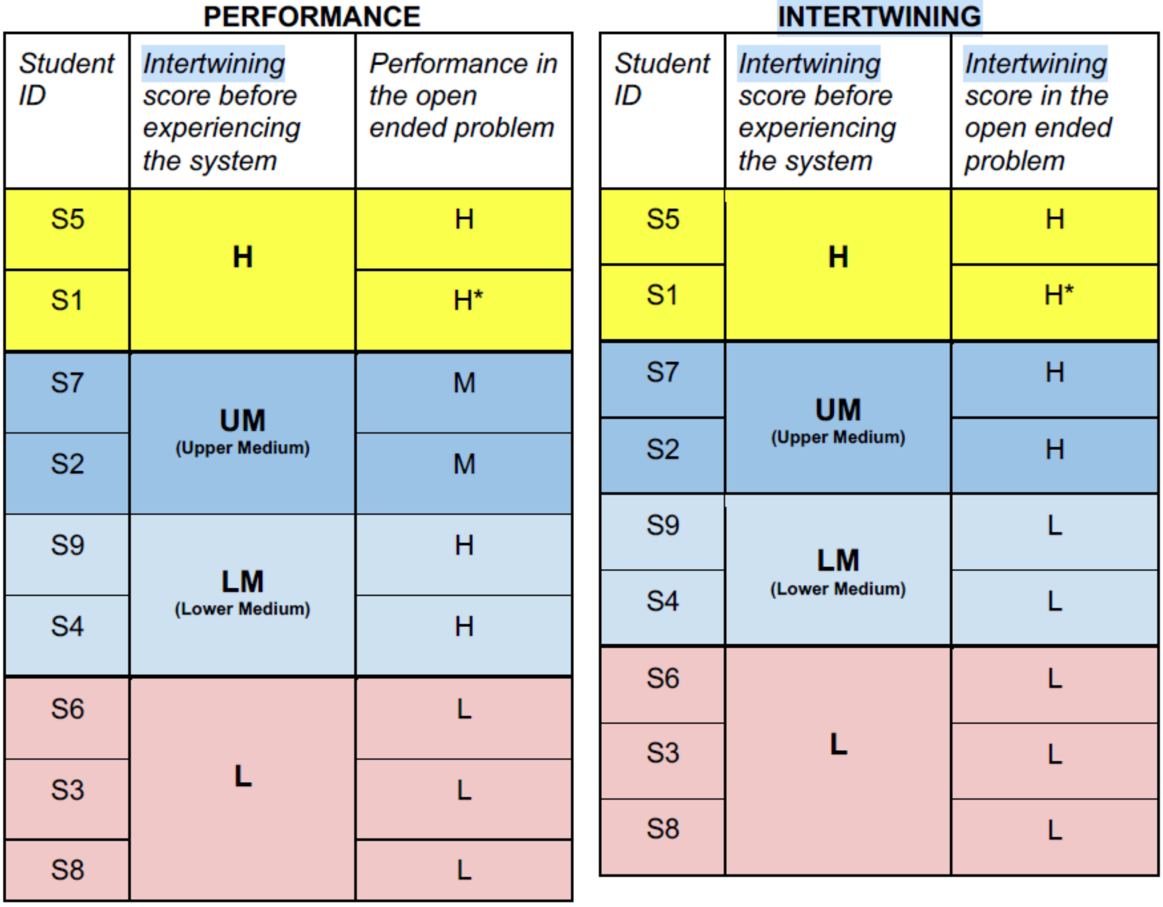
"So if you, if you talk about solid state physics, we just used to consider about the vibration, the vibrational thing the damp.., you know the acoustical motion everything. So I really feel whether I will miss out something like, there are a lot of things we need to consider. while we study solid state physics. "

The interview data was transcribed for all the ten students. One student's (S10) interview responses data was found to be insufficient for analysis. The final data analysis was thus conducted for nine students in total. The transcribed data was then analysed for episodes of intertwining, both pre-intervention and post-intervention. The intertwining theme was taken as the key indicator because, as discussed above, the ability to intertwine ERs is central to the building of equations. This ability also indicates understanding of the component ERs. The transcripts were read by two raters, and the task performance, themes for intertwining, as well as the ratings for each student, were arrived at through discussion. A third rater (the physics education researcher who did the teaching) independently rated the performance data, as well as the level of intertwining for each student, in the pre and post data. The two independent ratings were later compared, and any differences were resolved through discussion, to arrive at the final rating.

5.4. Summary of Results

We found that students who had a low score on intertwining before experiencing the system exhibited low performance in solving the problem, as well as in intertwining different steps in the derivation. Students who had a high /upper medium (UM) score before experiencing the system were able to intertwine different derivation steps while solving the open-ended problem.

In general, a student with a higher pre-score had a high performance and intertwining score, while a student with a lower pre-score had a low performance and intertwining score while solving the open-ended problem. S1 was not given the open-ended problem, as its design had not settled when he was interviewed. His classification is based on performance in the other tasks. The following tables report the performance on the task for each student, and a representative quote for high intertwining score. For students with a low intertwining score, there was very little data that indicated intertwining.



PERFORMANCE

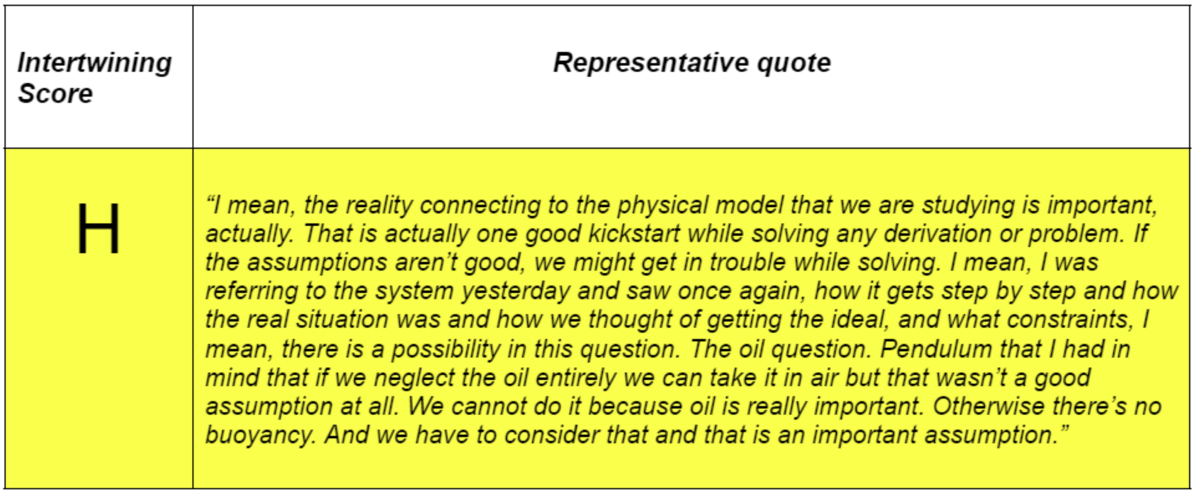
Student ID	*Intertwining score before experiencing the system*	*Performance in the open ended problem*
S5	**H**	H
S1		H*
S7	**UM** (Upper Medium)	M
S2		M
S9	**LM** (Lower Medium)	H
S4		H
S6	**L**	L
S3		L
S8		L

INTERTWINING

Student ID	*Intertwining score before experiencing the system*	*Intertwining score in the open ended problem*
S5	**H**	H
S1		H*
S7	**UM** (Upper Medium)	H
S2		H
S9	**LM** (Lower Medium)	L
S4		L
S6	**L**	L
S3		L
S8		L

Table 2: *details the students' performance on the open-ended problem. Table on the left is each student's performance on the task, against their intertwining score before experiencing the system.*

Table on the right shows how well the students were able to intertwine different steps explained in the derivation system while solving the task.



Intertwining Score	Representative quote
H	*"I mean, the reality connecting to the physical model that we are studying is important, actually. That is actually one good kickstart while solving any derivation or problem. If the assumptions aren't good, we might get in trouble while solving. I mean, I was referring to the system yesterday and saw once again, how it gets step by step and how the real situation was and how we thought of getting the ideal, and what constraints, I mean, there is a possibility in this question. The oil question. Pendulum that I had in mind that if we neglect the oil entirely we can take it in air but that wasn't a good assumption at all. We cannot do it because oil is really important. Otherwise there's no buoyancy. And we have to consider that and that is an important assumption."*

Figure 6: *shows a representative quote for a student exhibiting high intertwining between derivation steps in the open ended problem solving task*

6. Study3: Exploring the Language, Simulation and Attention Interaction

The mental simulation generated by reading any text is affected by the content of the text, and also by the way language is structured in the text. Several studies have characterised the ways in which the structural and dynamic features of the text change the mental simulations. The nature of this simulation would vary significantly between students, depending on their real-world experiences, reading comprehension, and attention. The detailed nature of the mental simulations generated by different text structures – particularly in relation to AI – remains an under-researched topic in ESTL. An understanding of the relation between language structure and the way a mental simulation progresses through reading, and the possible cognitive mechanisms modulating this connection – would contribute significantly to the design of new teacher training models. In the third study we designed an empirical study to better understand this connection.

Both lexical and grammatical aspects of language have been shown to affect mental simulation. For instance subject nouns and main verbs were found to trigger visual imagery, when used in literal sentences about real space (Bergen et.al., 2007). Stanfield and Zwaan (2001) show that the object orientation implied in sentences produces interference effects, when executing actions in orientations incompatible with those implied in the sentence. In cognitive semantics, grammatical elements are considered to constitute a fundamental conceptual structuring system (Talmy, 2000), and changes in the grammatical structure of sentences are shown to generate related changes in meaning. Supporting this view, Bergen & Wheeler (2010) showed that the grammatical aspects of sentences about hand movement affect their mental simulation. In this study, sentences about hand motion with a progressive aspect were shown to be simulated, compared to sentences similar in every other respect except having a perfect aspect. The progressive aspect is thought to foreground the internal structure of an event, whereas the perfect aspect highlights the end states. Also, people are able to simulate spatial location if the grammatical aspect of sentences is progressive, rather than perfect (Liu & Bergen, 2016). These studies indicate that grammatical structure alters the perspective of the mental simulation. Further, Talmy (2000) argues that changes in perspective (of the mental simulation), brought about by linguistic structuring, can lead to effects on attention.

These studies have significant implications for education – particularly science education – as academic language (AL) seeks to generate very specific and focused simulations, and this objective is achieved partly through the grammatical structuring of AL. For instance, nominalisation, which is considered a marker of AL (Halliday & Martin, 2003) is based on a type of linguistic restructuring where verbs and adjectives are converted into nouns. The studies reviewed above suggest that this linguistic structure could be working as a way to generate a specific perspective, where the action relationship between the interacting entities gains prominence, rather than the entities or the actions themselves.

6.1 Participants, Task, and Materials

Our sample comprised 18 female and 17 male high school students (N = 35), who were enrolled in grade 9. In this sample, 65% of students self-reported that they could read English well, while 35% considered their English reading ability to be medium. 62% of the participants reported that they could understand a sample text written in English well, while 38% evaluated their English comprehension ability as medium. The majority of the participants (86%) reported that they were taught mostly in English, but that their teachers would often resort to explanations in the local language as well.

Reading Task

We selected 3 passages from biology textbooks (grades 9 and 10). One described the structure and function of the Golgi apparatus, another explained photosynthesis, and the third one ecological succession. These passages were 6 sentences long (on average), and were selected because they described a scientific mechanism. In the context of our study, ‘mechanism’ refers to either the mechanics of a biological or anatomical structure (e.g., Golgi apparatus), or to the causal explanations of a biological or physiological phenomenon and/or process (e.g., ecological succession) (Nicholson, 2012).

Following the analysis presented in studies 1 and 2, we assumed that reading any passage outlining a mechanism generates a simulation. This process involves a distribution of attention, because, to generate the simulation, each element that is read needs to be processed in relation to other elements that are encountered. The attention distribution would vary with different language structures, which organise the text elements differently. For textbook passages, the linguistic structuring is based on AL features, such as nominalization. The event structure of the dynamic mechanism, which needs to be generated from the passage structure, would be difficult to build (and thus understand) in the AL case, because AL sequences start with the detached action, rather than the object. This structure prioritises a detached action perspective, and thus an object-like treatment of action (nominalisation). The action/process part of the mechanism is foregrounded in this structure, pushing the interaction between the entities to the background. Consider the following example used earlier:

1) The ball hits the stack of cards and they fall.
2) The hitting of the ball makes the stack of cards fall.

The event structure in 2 is relatively difficult to simulate, compared to 1, because the hitting action is detached and foregrounded, and it then needs to be connected to the falling of the cards, in a lego-like structure, rather than as an interaction between the ball and the cards. In AL, the nouns used are generally dense concepts with nested conceptual structure embedded within them (stomata, oxidation, carbon dioxide etc.). This dense structure would also hinder the mental simulation of dynamics, because these dense concepts themselves need to be simulated, as they are part of the created event structure.

To generate the experiment condition, we modified the textbook AL passages using the following rationale. We edited the text to bring the object to the foreground, so that the interaction of agents is more apparent, and easier to mentally simulate. This process only alters the perspective. The edit did not change the dense conceptual structure of nouns. The following edits were made in the passage:

- Passive voice was turned to active voice, wherever possible

● We shifted the initial focus to the object elements, and the interactions they generate, rather than the process elements (which are often nominalised in AL).

This process yielded 3 unmodified passages. A sample textbook passage and the modified passage are below.

Sample A (Textbook Passage)

An important characteristic of all communities is that their composition and structure constantly change in response to the changing environmental conditions. This change is orderly and sequential, parallel with the changes in the physical environment. These changes lead finally to a community that is in near equilibrium with the environment and that is called a climax community. The gradual and fairly predictable change in the species composition of a given area is called ecological succession. During succession some species colonise an area and their population become more numerous whereas populations of other species decline and even disappear.

Sample B (Modified Passage)

The way all communities are composed and structured constantly changes as environmental conditions change. This is an important characteristic of all communities. This change occurs in an order and a sequence, as the physical environment changes. A community that is in near equilibrium with the environment is finally formed due to these changes. It is called a climax community. The species composition of a given area changes gradually and in a fairly predictable way, this is called ecological succession. Some species colonise an area during succession and their population become more numerous whereas populations of other species decline and even disappear.

In the study, the time spent on reading the passage was recorded for every participant.

6.1.1 Divided Attention Task

We used a letter-identification task comprising a set of 14 Navon figures, where each figure contained a big (global letter, say H) made up of small (local letters, say L) in a 5 X 5 matrix. A global letter measured 4.7 cm in height and 4.1 cm in width, while a local letter measured 0.7 cm in height and 0.6 cm in width. In this task, letters E and H were the target letters that the participants were required to identify. All Navon figures were incongruent, implying that the target letters to be identified – E and H – were only presented at the global level (i.e., H/L, H/T, H/F, E/L, E/T, E/L) or the local level (i.e., F/E, T/E, L/E, F/H, T/H, L/H), but never simultaneously congruent at the global and local levels (i.e., the global/local letters could never be E/E or H/H). Upon presentation of the Navon figure, participants were required to respond via a key-press (key z for letter H, key m for letter E) if the presented image had H or E, either at the global or the local level. All Navon trials were presented in a random order, and participants' reaction times (RTs) and accuracy data were recorded.

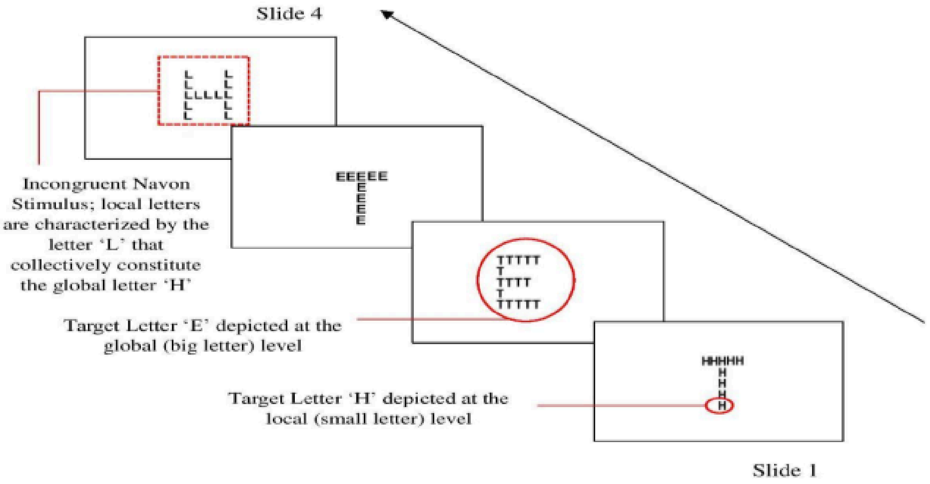


Fig 7: Schematic of the trial sequence of the Global Local Attention task.

6.2 Experimental Design and Procedure

To determine the effects of linguistic restructuring on participants' attentional states, the study employed a mixed repeated measures design, with the following factorial structure: 2 (between subject factor: nature of passage- textbook, modified) X 2 (within subject factor: target letter type-local, global) X 2 (within subject factor: test sessions- pretest, posttest). All participants were administered the Navon task pre and post the reading comprehension task (the intervention). Participants were randomly assigned to either the textbook passage (non-modified, control condition) or the modified passage (experimental condition), respectively. All testing was conducted in-person, in a single session, on a 15.6 inch LED HP laptop screen. Both task stimuli and task sequence were pilot-tested with a sample of ten 9th grade students before they were implemented in the study. Consent was provided by all participating students before the experiment. Each student was exposed to 14 Navon task trials in the pre and post tests. The pre and post tests contained 7 local and 7 global trails, randomly assigned.

6.3 Analysis

We calculated the mean Global-Local RT bias (GLB) for each student. If participants respond faster to the local trials, they have a local bias. If they respond faster to global trials, they have a global bias. GLB is the difference between the mean global reaction times (GT) and the mean local reaction time (LT), across trials.

$$GLB = GT - LT$$

If the GLB is negative, it indicates a global bias i.e., on average the reaction to global stimuli was faster than the local stimuli. Similarly, a positive GLB indicates a local bias i.e., on average the reaction to local stimuli was faster than the global stimuli.

6.3.1 Results and Discussion

The bar plot in figure 2 compares participants' performance on the divided attention task in the pre- and post- test conditions, as well as between control (textbook passage) and experimental (modified passage) conditions. The yellow-coloured bars depict participants' (mean) LT and the blue-coloured ones, their (mean) GT.

In the control condition, the (mean) LT for participants in the pretest session was found to be higher than their (mean) LT in the posttest session, However, their (mean) GT in the pretest session was found to be lower than their (mean) GT in the posttest session. This trend suggests that post intervention (the unmodified, textbook passage), participants in the control condition reacted faster to the local-level (Navon) stimuli than the global-level (Navon) stimuli. This indicates their local bias.

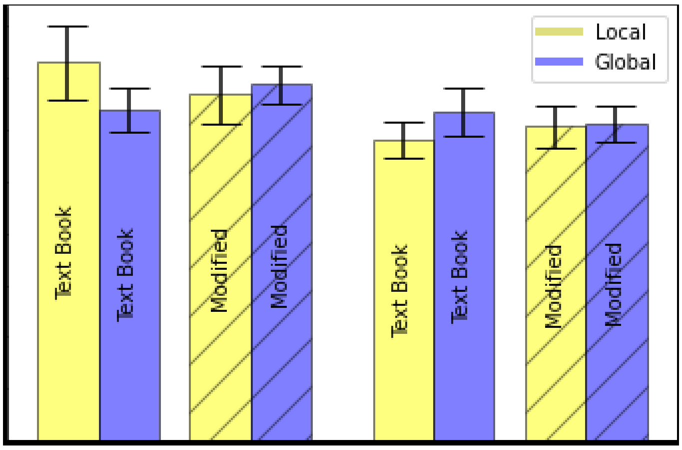


Figure 8: *Bar plot depicting reaction time results from Global Local Task. The error bar indicates standard error of mean (SEM).*

In the experimental condition, on the other hand, the (mean) LT for participants in the pretest session was found to be higher than their (mean) LT in the posttest session. However, their (mean) GT in the pretest session was found to be modestly lower than their GT in the posttest session. This trend suggests that post-intervention (the modified passage), participants in the experimental condition reacted faster to global-level (Navon) stimuli. This indicates their global bias.

Although the results are not conclusive, there is indicative evidence that nominalisation may alter the nature of the simulation by altering the attentional states. It suggests that passages with nominalised phrases distributed attention locally while those without them showed a global bias. A more structured and detailed study, designed taking inputs from this study, could help understand these connections better.

7. Discussion and Implications

The complexity of the teacher's task in classrooms, especially the way she constructs "explanations", is highly underappreciated. The teacher's task becomes more difficult in contexts where students' access to technology is very limited, as they then heavily rely on the teacher's narratives and the textbook, which are the only available resources. The teacher connects students' experiences to abstract models embedded in the textbook using AL, a language that is very different from their everyday language. She also has to help students build this specialised language, along with the mechanism models.

To explore this complex process, we conducted three studies. The first study, focusing on the case of the mechanism model of photosynthesis, analysed classroom teaching data, and proposed an initial theoretical model of teacher narratives as "performative bundles", which allowed students to replicate the teacher enaction embedded in the narrative, and thus generate the mechanism model in their own minds. This initial model provides an account of both the process of teaching-to-build mental models and the building of AL. The performative bundle model provides an integrated account of teacher narratives, based on ESTL and DC theory. Analyses of more classroom data, covering a diverse range of teaching contexts, can provide a much clearer picture of the process of teaching-to-build mechanism models.

In the second study, we extended the findings from the biology mechanism models, to develop a new teaching narrative, which sought to teach a physics mechanism model (derivation) in a new way, using an interactive simulation. Results indicate that this is a promising approach to teach derivations as model-building. This work indicates the kind of changes required to our original model to accommodate the requirements of the physics model.

The third study explored a hypothesis on the possible cognitive mechanism involved as students make sense of AL as presented in the textbook. We explored whether changing the linguistic structure of textbook passages of scientific mechanisms would modulate attention, via changes in the mental simulation associated with the different passage structures. The attentional states that we examined in this study are global attention and local attention. The results we report here indicate a trend, where the systematic change in the structure of the textbook passage has a systematic effect on the attentional state of students. Specifically, attention shifted from a local attentional state for the textbook passage (Al) to a global attentional state for the modified passage. This transition indicates that the change in the structure of AL, particularly nominalisation, has a modulating effect on attention. This study however can be improved with more structured design, based on the inputs of this initial study and also with larger sample size.

Embodied cognition theory, which we used to develop our account of teacher narratives, have been applied in education contexts, to develop technological interventions that build on bodily movements to advance student learning and understanding. The affordances provided by new technological interfaces allow creating a space where movements and actions can attain a completely new meaning. Our model of language triggering accumulated action experiences, in the form of mental simulations, can help advance science teaching in technologically under-resourced classrooms, which rely on teacher narratives for sense making. We explore some application implications of our account teacher narratives below.

7.1 Implications

The theoretical analysis we have presented provides a systematic and unified cognitive approach to understand the roles played by teaching narratives and academic language in science education. We outline below two application implications of this analysis, focusing on how the account could help refine (1) teacher training and (2) educational technology development, for teaching and learning of science.

7.1.1 Teacher Training: The performative bundling account could be used to develop pedagogical constructs and narratives that support the training of science teachers. For instance, teacher training modules in biology could introduce the idea of mental simulation of mechanisms, and the way such simulations could be seeded for complex concepts, using narratives based on everyday sensorimotor experiences. Mental simulation, and its neuroscientific basis, could thus be a central construct in training biology teachers. This approach would provide an empirical grounding for the popular idea of teachers "explaining" complex concepts, using cognitive neuroscience findings. Further, the ideas related to narratives— particularly the way narratives embed and promote simulations, and the way they "tune" initial gist simulations generated by students—could provide novice teachers with a systematic approach to classroom practice.

Similarly, teacher training modules in physics could outline the way formal derivations seek to "load" real-world phenomena into equations (see Mashood et al., 2022, for details), and how this general structure could be used to develop a model-based understanding of physics. Generalizing from this, the construction of all formal external models in science could thus be understood as a "loading" process. The idea of "loading" reality into formal terms and mathematical functions could be thus a systematic construct in developing science teacher training modules. More generally, our account provides a way for teachers to approach all science topics and terms from a systematic mechanism perspective. Apart from supporting the training of teachers in developing narratives that build mechanism models, our account also helps develop novel evaluation methods. For instance, the analysis of student understanding of the later use of defined technical terms—which requires students to regenerate the imagery (leaf, pores) and simulation of a dynamic scenario (opening, closing) based on the imagery—provides teachers with a systematic approach to probe a student's understanding of mechanisms. This structure, when used systematically as part of teacher training, could also open up new evaluation methods. At the policy level, the discussion of science teaching based on performative bundling would reveal the sophistication of the cognitive processes involved in science teaching, and this could possibly lead to institutional structures that value teaching and teachers more highly.

7.1.2 Educational Technology Design: Arthur Glenberg, one of the founders of embodied cognition and ESTL, reports an interactive system that promotes mental simulation, designed specifically to advance reading skills in primary students (Glenberg et al., 2011). The system allows students to read sentences that embed activities, while also manipulating the same activities on screen (for example, on a reading task related to Halloween, a reader reads a sentence like “Ben hooks a cart to the tractor.” After reading the sentence, the reader manipulates the image of Ben with a cart, by moving it and attaching it to the tractor). This basic association framework could be extended to develop educational technologies that support students’ understanding of mechanisms. A prototype system along these lines is illustrated by Salve et al. (2021).

Following our simulation-based account of AL, a key premise underlying this system was that learning and using AL is not optional while learning science, as the specific processes and states that constitute mechanisms are generated and supported by AL structures. The idea of “loading” mechanism structures and activities into specific technical terms, and using these to reactivate the mechanisms later in different contexts, has been extended to the building and use of formal structures, particularly physics equations. Interactive systems3 to learn derivations, based on this loading premise, have also been developed, based on 4–5 standard steps (idealisation, discretization, geometric description, algebraic description, generalisation/solving), which are key components in most physics model building (derivation) processes (Mashood et al, 2022). These systems illustrate how the performative bundling theory could be applied to develop productive educational technological approaches that advance the teaching/learning of science. The current systems do not specifically seek to support the building of teacher narratives, but they could be easily adapted for this purpose, and also to support better teacher training.

References

Abrahamson, D., & Sánchez-García, R. (2016). Learning Is Moving in New Ways: The Ecological Dynamics of Mathematics Education. *Journal of the Learning Sciences*, *25*(2), 203–239.

Anstrom, K., DiCerbo, P., Butler, F., Katz, A., Millet, J., & Rivera, C. (2010). A review of the literature on academic English: Implications for K-12 English language learners. *Arlington, VA: The George Washington University Center for Equity and Excellence in Education*.

Bak, T. H., & Chandran, S. (2012). What wires together dies together: Verbs, actions and neurodegeneration in motor neuron disease. *Cortex*, *48*(7), 936–944.

Barker, M., & Carr, M. (1989). Teaching and learning about photosynthesis. Part 1: An assessment in terms of students’ prior knowledge. *International Journal of Science Education*, *11*(1), 49–56.

Bergen, B. (2015). Embodiment, simulation and meaning. In *The Routledge handbook of semantics* (pp. 142–157). Routledge.

Bergen, B. K., Lindsay, S., Matlock, T., & Narayanan, S. (2007). Spatial and Linguistic Aspects of Visual Imagery in Sentence Comprehension. *Cognitive Science*, *31*(5), 733–764.

Bergen, B., & Wheeler, K. (2010). Grammatical aspect and mental simulation. *Brain and Language*, *112*(3), 150–158.

Bernstein, B. (2003). *Class, codes and control: Applied studies towards a sociology of language* (Vol. 2). Psychology Press.

Bourdieu, P. (1984). A social critique of the judgement of taste. *Traducido Del Francés Por R. Nice. Londres, Routledge*.

Brown, D. E. (2014). Students' Conceptions as Dynamically Emergent Structures. *Science & Education*, *23*(7), 1463–1483.

Brown, D. E. (2017). Implicit conceptual dynamics and students' explanatory model development in science. In *Converging Perspectives on Conceptual Change* (pp. 105–112). Routledge.

Bub, D. N., & Masson, M. E. (2012). On the dynamics of action representations evoked by names of manipulable objects. *Journal of Experimental Psychology: General*, *141*(3), 502.

Canal, P. (1999). Photosynthesis and "inverse respiration" in plants: An inevitable misconception? *International Journal of Science Education*, *21*(4), 363–371.

Carey, S. (2000). The Origin of Concepts. *Journal of Cognition and Development*, *1*(1), 37–41.

Cartwright, N. (1997). Where do laws of nature come from? *Dialectica*, *51*(1), 65–78.

Craver, C., & Tabery, J. (2019). Mechanisms in science. In E. N. Zalta (Ed.), The Stanford encyclopedia of philosophy (Summer 2019 Edition). Stanford University.

Chandrasekharan, S., & Nersessian, N. J. (2021). Rethinking correspondence: How the process of constructing models leads to discoveries and transfer in the bioengineering sciences. *Synthese*, *198*(21), 1–30.

Cheng, M., & Brown, D. E. (2010). Conceptual Resources in Self‐developed Explanatory Models: The importance of integrating conscious and intuitive knowledge. *International Journal of Science Education*, *32*(17), 2367–2392.

Chi, M. T. H. (2005). Commonsense Conceptions of Emergent Processes: Why Some Misconceptions Are Robust. *Journal of the Learning Sciences*, *14*(2), 161–199.

Clark, D. B. (2006). Longitudinal Conceptual Change in Students' Understanding of Thermal Equilibrium: An Examination of the Process of Conceptual Restructuring. *Cognition and Instruction*, *24*(4), 467–563.

David Wong, E. (1993). Understanding the generative capacity of analogies as a tool for explanation. *Journal of Research in Science Teaching*, *30*(10), 1259–1272.

diSessa, A. A., Gillespie, N. M., & Esterly, J. B. (2004). Coherence versus fragmentation in the development of the concept of force. *Cognitive Science*, *28*(6), 843–900.

Driver, R. (1989). Students' conceptions and the learning of science. *International Journal of Science Education*, *11*(5), 481–490.

Fyfe, E. R., & Nathan, M. J. (2019). Making "concreteness fading" more concrete as a theory of instruction for promoting transfer. *Educational Review*, *71*(4), 403–422.

Glenberg, A. M., & Gallese, V. (2012). Action-based language: A theory of language acquisition, comprehension, and production. *Cortex*, *48*(7), 905–922.

Glenberg, A. M., Goldberg, A. B., & Zhu, X. (2011). Improving early reading comprehension using embodied CAI. *Instructional Science*, *39*(1), 27–39.

Glenberg, A. M., & Kaschak, M. P. (2002). Grounding language in action. *Psychonomic Bulletin & Review*, *9*(3), 558–565.

Glennan, S. (2017). *The new mechanical philosophy*. Oxford University Press.

Glynn, S. M. (2012). Explaining science concepts: A teaching-with-analogies model. In *The psychology of learning science* (pp. 219–240). Routledge.

Glynn, S. M., Taasoobshirazi, G., & Fowler, S. (2007). Analogies: Explanatory Tools in Web-Based Science Instruction. *Educational Technology*, *47*(5), 45–50.

Halliday, M. A. K., & Martin, J. R. (2003). *Writing science: Literacy and discursive power*. Taylor & Francis.

Heath, S. B. (1983). *Ways with words: Language, life and work in communities and classrooms*. Cambridge University Press.

Illari, P. M., & Williamson, J. (2012). What is a mechanism? Thinking about mechanisms across the sciences. *European Journal for Philosophy of Science*, *2*(1), 119–135.

Ioannides, C., & Vosniadou, S. (2002). The changing meanings of force. *Cognitive Science Quarterly*, *2*(1), 5–62.

Johansson, R. (2007). On case study methodology. *Open House International*, *32*(3), 48–54.

Kallery, M., & Psillos, D. (2004). Anthropomorphism and animism in early years science: Why teachers use them, how they conceptualise them and what are their views on their use. *Research in Science Education*, *34*, 291–311.

Kirsh, D. (2010). Thinking with external representations. *AI & SOCIETY*, *25*(4), 441–454.

Krall, R. M., Lott, K. H., & Wymer, C. L. (2009). Inservice Elementary and Middle School Teachers' Conceptions of Photosynthesis and Respiration. *Journal of Science Teacher Education*, *20*(1), 41–55.

Lemke, J. L. (1990). *Talking science: Language, learning, and values.* ERIC.

Liu, N., & Bergen, B. (2016). When do language comprehenders mentally simulate locations? *Cognitive Linguistics*, *27*(2), 181–203.

Machamer, P., Darden, L., & Craver, C. F. (2000). Thinking about mechanisms. *Philosophy of Science*, *67*(1), 1–25.

Mak, M., & Willems, R. M. (2019). Mental simulation during literary reading: Individual differences revealed with eye-tracking. *Language, Cognition and Neuroscience*, *34*(4), 511–535.

Marmaroti, P., & Galanopoulou, D. (2006). Pupils' Understanding of Photosynthesis: A questionnaire for the simultaneous assessment of all aspects. *International Journal of Science Education*, *28*(4), 383–403.

Mashood, K. K., Khosla, K., Prasad, A., V, S., Ch, M. A., Jose, C., & Chandrasekharan, S. (2022). Participatory approach to introduce computational modeling at the undergraduate level, extending existing curricula and practices: Augmenting derivations. *Physical Review Physics Education Research*, *18*(2), 020136.

Mathayas, N., Brown, D. E., & Lindgren, R. (2021). "I got to see, and I got to be a part of it": How cued gesturing facilitates middle‐school students' explanatory modeling of thermal conduction. *Journal of Research in Science Teaching*, *58*(10), 1557–1589.

Mathayas, N., Brown, D. E., Wallon, R. C., & Lindgren, R. (2019). Representational gesturing as an epistemic tool for the development of mechanistic explanatory models. *Science Education*, *103*(4), 1047–1079.

Matlock, T. (2004). Fictive motion as cognitive simulation. *Memory & Cognition*, *32*(8), 1389–1400.

Métioui, A., Matoussi, F., & Trudel, L. (2016). The Teaching of Photosynthesis in Secondary School: A History of the Science Approach. *Journal of Biological Education*, *50*(3), 275–289.

Miranda, M., Gonzalez Campo, C., Birba, A., Neely, A., Toro-Hernández, F. D., Faure, E., Rojas, G. M., Ibáñez, A., & García, A. (2022). An action-concept processing advantage in a patient with a double motor cortex. *Brain and Cognition*, *156*, 105831.

Nersessian, N. J. (2010). *Creating scientific concepts*. MIT press.

Nicholson, D. J. (2012). The concept of mechanism in biology. *Studies in History and Philosophy of Science Part C: Studies in History and Philosophy of Biological and Biomedical Sciences*, *43*(1), 152–163.

Pickering, A. (2010). *The mangle of practice: Time, agency, and science*. University of Chicago Press.

Posner, G. J., & Strike, K. A. (1992). A revisionist theory of conceptual change. In R. A. Duschl & R. J.Hamilton (Eds.), Philosophy of science, cognitive psychology, and educational theory and practice (pp. 147–177). Suny Press.

Pulvermüller, F., & Fadiga, L. (2010). Active perception: Sensorimotor circuits as a cortical basis for language. *Nature Reviews Neuroscience*, *11*(5), 351–360.

Rahaman, J., Agrawal, H., Srivastava, N., & Chandrasekharan, S. (2018). Recombinant Enaction: Manipulatives Generate New Procedures in the Imagination, by Extending and Recombining Action Spaces. *Cognitive Science*, *42*(2), 370–415.

Redish, E. F., & Kuo, E. (2015). Language of Physics, Language of Math: Disciplinary Culture and Dynamic Epistemology. *Science & Education*, *24*(5), 561–590.

Salve, J., Narwal, A., Upadhyay, P., KK, M., & Chandrasekharan, S. (2021). Learning to enact photosynthesis: Towards a characterization of the way academic language mediates concept formation. *Proceedings of the Annual Meeting of the Cognitive Science Society*, *43*(43).

Schleppegrell, M. J. (2001). Linguistic features of the language of schooling. *Linguistics and Education*, *12*(4), 431–459.

Schleppegrell, M. J. (2012). Academic Language in Teaching and Learning: Introduction to the Special Issue. *The Elementary School Journal*, *112*(3), 409–418.

Schubotz, R. I. (2007). Prediction of external events with our motor system: Towards a new framework. *Trends in Cognitive Sciences*, *11*(5), 211–218.

Sfard, A. (1991). On the dual nature of mathematical conceptions: Reflections on processes and objects as different sides of the same coin. *Educational Studies in Mathematics*, *22*(1), 1–36.

Snow, C. (1983). Literacy and language: Relationships during the preschool years. *Harvard Educational Review*, *53*(2), 165–189.

Snow, C. E. (2010). Academic Language and the Challenge of Reading for Learning About Science. *Science*, *328*(5977), 450–452.

Södervik, I., Virtanen, V., & Mikkilä-Erdmann, M. (2015). Challenges in understanding photosynthesis in a university introductory biosciences class. *International Journal of Science and Mathematics Education*, *13*, 733–750.

Spivey, M. J., & Geng, J. J. (2001). Oculomotor mechanisms activated by imagery and memory: Eye movements to absent objects. *Psychological Research*, *65*(4), 235–241.

Stephens, A. L., & Clement, J. J. (2010). Documenting the use of expert scientific reasoning processes by high school physics students. *Physical Review Special Topics - Physics Education Research*, *6*(2), 020122.

Talanquer, V. (2007). Explanations and Teleology in Chemistry Education. *International Journal of Science Education*, *29*(7), 853–870.

Talmy, L. (1983). How Language Structures Space. In H. L. Pick & L. P. Acredolo (Eds.), *Spatial Orientation* (pp. 225–282). Springer US.

Talmy, L. (2000). *Toward a cognitive semantics: Concept structuring systems* (Vol. 1). MIT press.

Thiele, R. B., & Treagust, D. F. (1994). An interpretive examination of high school chemistry teachers' analogical explanations. *Journal of Research in Science Teaching*, *31*(3), 227–242.

Treagust, D., Chittleborough, G., & Mamiala, T. (2003). The role of submicroscopic and symbolic representations in chemical explanations. *International Journal of Science Education*, *25*(11), 1353–1368.

Wilson, N. L., & Gibbs, R. W. (2007). Real and Imagined Body Movement Primes Metaphor Comprehension. *Cognitive Science*, *31*(4), 721–731.

Yee, E., Chrysikou, E. G., Hoffman, E., & Thompson-Schill, S. L. (2013). Manual Experience Shapes Object Representations. *Psychological Science*, *24*(6), 909–919.

Zwaan, R. A., Stanfield, R. A., & Yaxley, R. H. (2002). Language Comprehenders Mentally Represent the Shapes of Objects. *Psychological Science*, *13*(2), 168–171.

Zwaan, R. A., Taylor, L. J., & De Boer, M. (2010). Motor resonance as a function of narrative time: Further tests of the linguistic focus hypothesis. *Brain and Language*, *112*(3), 143–149.