Rethinking Representational Competence: cognitive mechanisms, empirical studies, and the

design of a new media intervention

Synopsis

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Abstract

External representations (ERs), such as diagrams, equations, graphs, etc. are central to the practice and learning of science, mathematics, and engineering, as the phenomena and entities studied in these domains are often not available for direct perception and action. The ability to generate and use ERs in a domain in an integrated fashion, as well as perform transformations on the ERs, is termed representational competence (RC). Many learning difficulties are attributed to difficulties in achieving RC, particularly integration of ERs. RC thus presents a fundamental cognitive difficulty that cuts across different disciplinary domains, making it critical to develop teaching-learning strategies to help learners develop RC.

Most accounts of RC are grounded in the classical information processing model of cognition. In this model, a learner experiences high cognitive load during ER integration, as she tries to 'extract' information from ERs, internalise this information in the mind, and translate or process it to establish connections between the ERs. This characterisation treats ERs as 'vehicles' of information, and therefore does not seek to provide detailed accounts of the cognitive mechanisms supporting ER integration. Models based on this framework thus do not provide specific instructional design principles, for effective development of RC.

Recent theories of cognition have moved away from the information processing model, to develop 'field' theories such as distributed and embodied cognition. Such accounts suggest that ERs, and a learner's interaction with them, play a *constitutive* role in the learning *of* concepts. I extend these ideas in this dissertation, to develop a theoretical model of the cognitive mechanisms underlying ER integration. This model focuses on how the cognitive system interacts with external representations, and the way integration abilities develop through this interaction. This mechanism model predicts that (i) the development of the ER integration ability would result in a reorganisation of the sensorimotor system, and (ii) sensorimotor interaction would support ER integration and its development. To test these predictions, I developed two empirical studies, one based on ER categorisation tasks and eye tracking, and the other based on the design, development, and testing of a new-media intervention. The results from these studies broadly support the theoretical model. Based on these results, I outline some of the broader implications of the model and possible learning interventions.

Graphical abstract
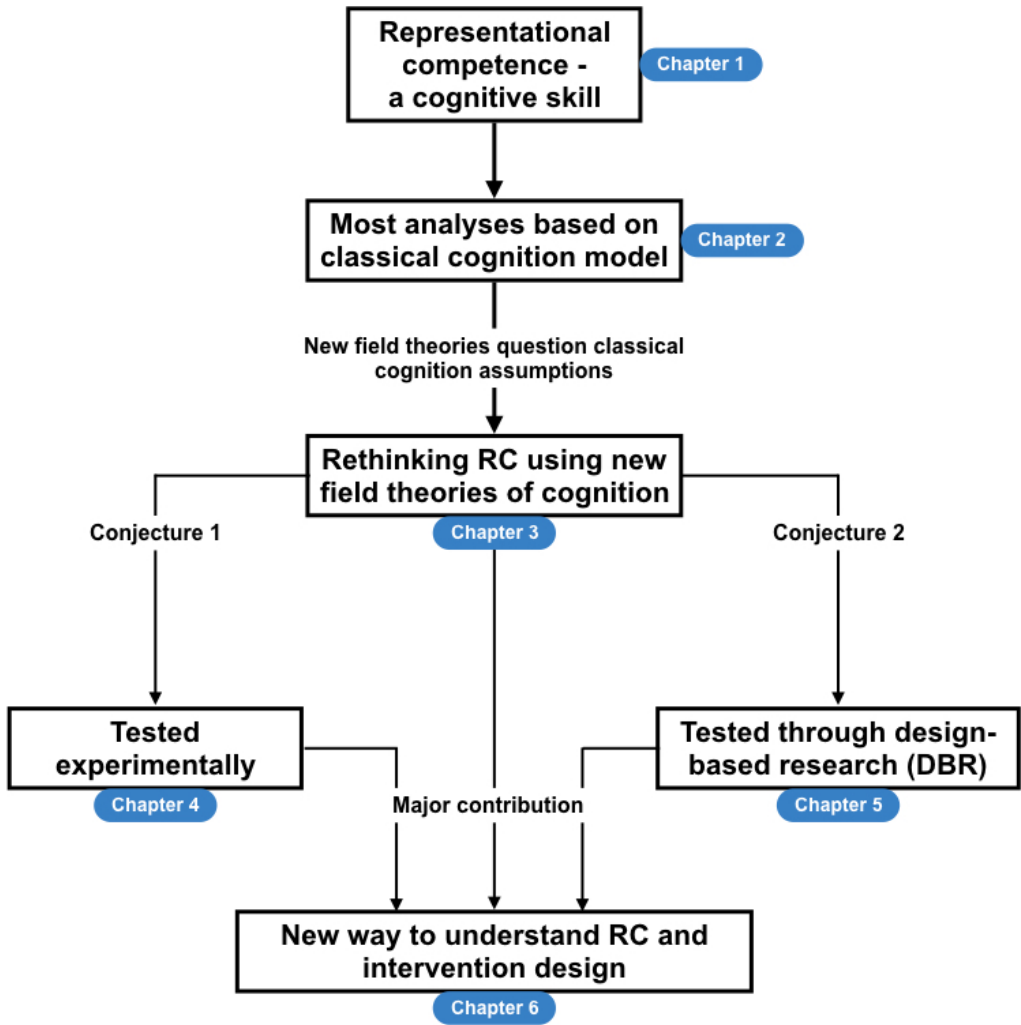
Chapter 1: Introduction

Modern science deals with entities and phenomena that cannot be directly perceived or acted on, because they are too small (atoms, DNA, cells, etc.), too big (galaxies, stars, tectonic plates, etc.) happen in timescales that are difficult to perceive (milliseconds – chemical reactions, millennia – evolution), and are complex (feedback loops between levels and timescales). external representations (ERs), symbolic elements that stand in for the actual entities and phenomena (such as diagrams, graphs and equations), help us in understanding and analysing these imperceptible and complex entities and phenomena at different spatiotemporal granularities. Ideas and information in science are distributed across these ERs (Johnstone, 1991; Lesh, Post, & Behr, 1987; Tsui & Treagust, 2013), and learning and practising science are impossible without gaining expertise in interacting with ERs, thinking and imagining with them, and learning to generate them. The ability to generate and use ERs in an integrated fashion, as well as perform transformations on the ERs, is termed representational competence (abbreviated as RC, Kozma & Russell, 1997 & 2005). RC presents a fundamental cognitive difficulty that cuts across different domains such as science, mathematics and engineering (Pande & Chandrasekharan, 2017), making it critical to develop teaching-learning strategies to help learners in developing RC.

RC comprises of the following non-exclusive interrelated set of skills:

(a) Integrating internal and external representations as well as different external representations

(b) generating ERs appropriate to the situation or problem

(c) communication using ERs

(d) reasoning using ERs

(e) choosing appropriate ERs based on the need of the situation/problem

(f) understanding and describing the different roles of an external representation in relation to other ERs

(g) critiquing ERs in terms of their strengths and shortcomings, etc. (Kozma & Russell, 1997; Kozma & Russell, 2005; Madden et al., 2011).

Figure 1.1 below situates this dissertation in relation to these facets of RC.
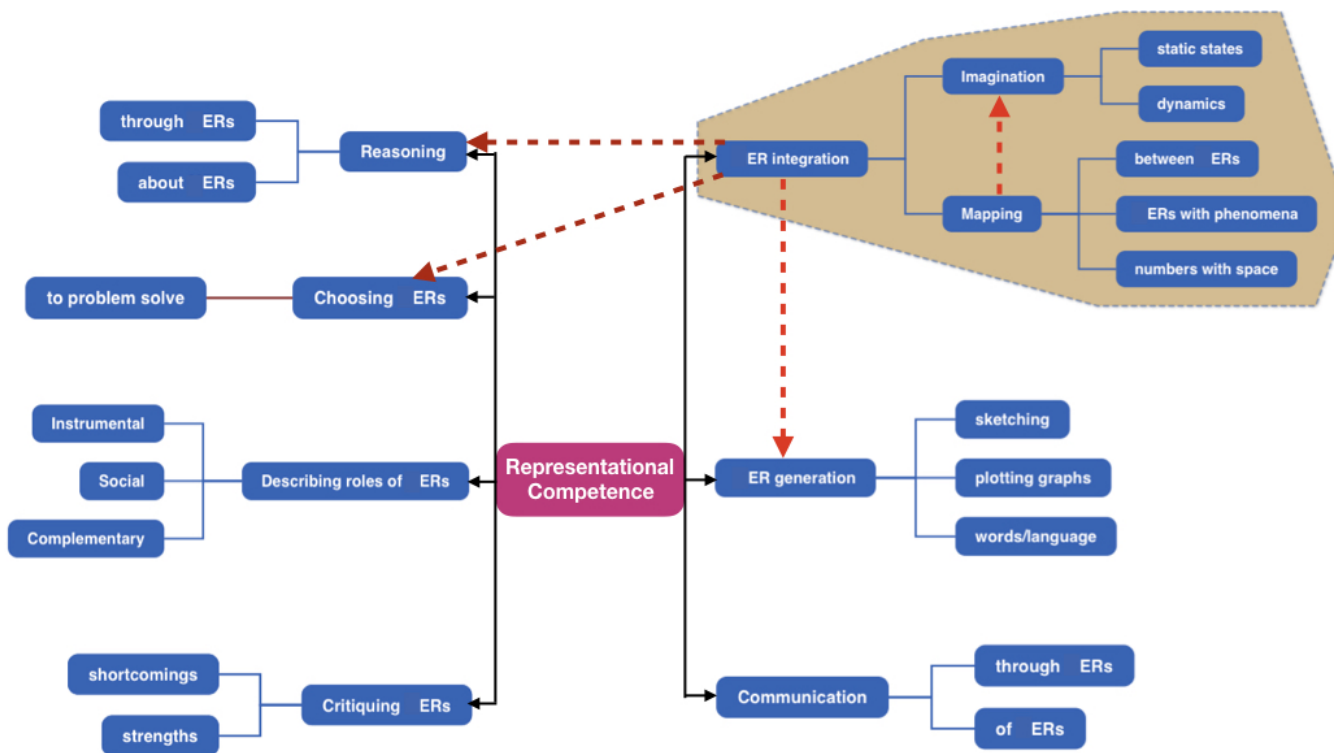

Figure 1.1 The abilities that comprise RC. The scope of this thesis is limited to ER integration, presented in the shaded area. Due to the interconnections between the abilities/concepts (not indicated in the diagram to avoid complexity), the work developed in this dissertation extends to or includes concepts such as reasoning around ERs, choice of ERs or the relationships between them, and ER generation. These implicit relations are highlighted with dotted red arrows.

In this dissertation, I focus on the ER integration sub-skill of RC (see box 1 for definition).

There is consensus in the education literature that many learning difficulties students face in these disciplines are attributable to problems in achieving RC, particularly ER integration (Chi, Feltovich & Glaser, 1981; Johnstone, 1991 & 2000; Johri, Roth & Olds, 2013, Larkin et al., 1980). Expert-novice

studies of RC show significant differences between the two groups, in terms of the ability to understand individual representations, integrate ERs, and use and generate ERs for conceptual understanding, discovery and problem solving (Chi, Feltovich & Glaser, 1981; Larkin et al., 1980; Kohl & Finkelstein, 2008; Kozma & Russell, 1997). While students understand and are able to use as well as generate representations independently (diSessa, Hammer, Sherin & Kolpakowski, 1991; diSessa & Sherin, 2001), they have great difficulty integrating ERs of a phenomenon (Knuth, 2000; Kozma & Russell, 1997; Wu & Shah, 2004).

Box 1: Important concepts used in the document

ER integration is defined as the process of integrating ERs in a domain with the learner's internal (mental) schema, as she uses, understands and transforms between ERs in a domain (Kozma & Russell, 1997; Pande & Chandrasekharan, 2017; Pape & Tchoshanov, 2001).

The **sensorimotor system** comprises of the sensory (related to sensing the different states of the external environment as well as the body and internal organs), motor (related to action or production and regulation of body movement) involved in bodily movements. This system facilitates interactions of the learner's cognitive system with different components of the external environments, particularly ERs.

The sensorimotor system-based interaction (henceforth simply '**sensorimotor interaction**') is made possible due to "the capability of the central nervous system to integrate different sources of stimuli, and in parallel, to transform such inputs in motor actions", called '**sensorimotor integration**' (Machado et al., 2010). For instance, to perform an action as simple as picking up an object (say a box), the sensorimotor system integrates: current state or posture of the body, spatial relations between the body and the object, previous experiences about the object, regulation of body movement, etc. through information coming from the skin, muscles and joints, vestibular system (a system in the ear that tracks body's balance), the motor plan of the action, anticipatory adjustments of posture in relation to the motor plan and the position of the object, etc. (Machado etl al., 2010).

1.1 The information processing model of RC

Performing tasks such as a simultaneous consideration of ERs, seeing the relationships between those ERs, interpreting them, reasoning about them in relation to the represented phenomena, etc. generate tremendous cognitive load on students' working memory (Johnstone 1982 & 1991), and one strand of

literature considers this load to be at the root of the ER integration problem (Hinton & Nakhleh, 1999; Kohl & Finkelstein, 2008; Larkin et al., 1980).

Such cognitive load-based accounts of ER integration difficulties, which are currently dominant in the education literature, are rooted in the classical information processing model of cognition. This model is based on an analogy between computers and the human brain, and assumes that the learner's mind, on encounter with an external representation (input), engages in information extraction (figure 1.2).
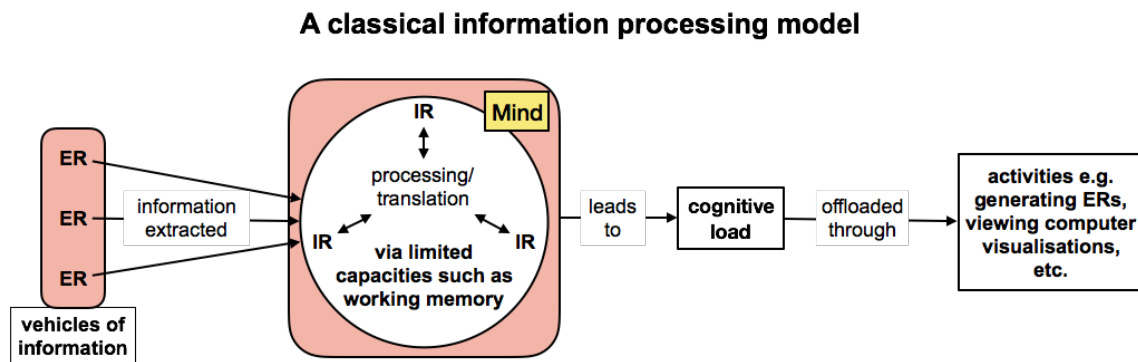
A classical information processing model

Figure 1.2 A classical information processing model of ER integration. In this model, meaning is 'extracted' through amodal syntactic processing of the information contained in ERs.

Correspondences between ERs are established through a translation process based on this extracted information. Such translation processes are considered to establish correspondences between ERs and the phenomena they represent, and also between the learner's mental models (or internal representations, IRs) and the external representation. In this view, ERs act as 'vehicles', tools or transmission media, which carry the information, which is the key element the cognitive system works with. This translation process generates significant cognitive load, and learning difficulties are considered to arise because of this processing load, and limitations of working memory in handling this load. Following from this view, the sole purpose of generating and using ERs during problem-solving is 'offloading' cognitive load. In this model, the extraction and translation of information are mediated mostly through mental capacities such as imagery and modality-independent (amodal) symbolic

processing, as well as working memory (e.g. Gooding, 2006; Johnstone, 1982; Lesh et al., 1987; Tsui & Treagust, 2013; etc.). The limited nature of these processing resources are considered to be the root of problems in achieving ER integration. A central problem with this computer-inspired model is that it advocates that the mind (passively) receives information inputs from the external world, which it processes 'inside' (the skull) in coordination with capacities such as the working and long term memory, and produces an output (usually in the form of an) action.

These assumptions, particularly limited working memory capacity as the central processing bottleneck, have influenced many intervention designs. For instance, visualization software, interactive computer simulations, and virtual laboratories, are all designed to address working memory limitations. Ironically, the software interventions do not seek to augment the student's working memory and processing abilities, but only help offload some of the memory and processing load to the computer screen. Possibly because of this, such interventions have not been very successful in promoting RC (De Jong & van Joolingen, 1998; Rutten, van Joolingen & van der Veen, 2012). Further, by focusing on the "processor capacity" as well as the inaccessible nature of information extraction and translation processes, these models and interventions make the ER integration process, and the cognitive mechanisms underlying it, appear mysterious. Further, these models do not focus on the cognitive as well as practice elements that could lead to ER integration and its development.

1.2 The emerging model

The central assumptions of the information processing approach to cognition – that all cognitive processing is (or is best) done just by neural processes (inside the skull), and that external representations only help 'offload' information – have been seriously questioned by recent empirical and theoretical work in cognitive science, particularly by 'field' theories such as distributed cognition (DC) and embodied cognition (EC).

In the DC view, for instance, Kirsh (2010) outlines seven ways in which the external aspect of ERs, and our interactions with external representations, contribute to cognition:

(1) They change the cost structure of the inferential landscape.

(2) They provide a structure that can serve as a shareable object of thought.

(3) They create persistent referents.

(4) They facilitate re-representation.

(5) They are often a more natural representation of structure than mental representations.

(6) They facilitate the computation of more explicit encoding of information.

(7) They enable the construction of arbitrarily complex structure; and they lower the cost of controlling thought – they help coordinate thought.

"Jointly, these functions allow people to think more powerfully with ERs than without. They allow us to think the previously unthinkable" Kirsh (2010).

This approach mostly focuses on the distributed nature of cognitive processing and its advantages. However, understanding representational competence requires moving beyond just the recognition of the cognitive power of external representations: it needs a model of how new kinds of imagination is made possible by the coupling of ERs with the cognitive system (Chandrasekharan & Nersessian, 2015). This coupling is closely related to integration of ERs. Since different ERs capture different aspects of a phenomenon (Ainsworth, 1999 & 2008), they need to be integrated by the learner to understand the nature of that phenomenon. Any account of how ERs are used in learning, thus, needs to account for this integration process, particularly the role played by interactions with ERs and the cognitive processes involved in this integration.

In a related direction, recent work in embodied cognition by Landy, Allen, and Zednik (2014) articulates a distinction between syntactic/semantic approaches and *constitutive* approaches towards symbolic reasoning. In the first approach, symbols in ERs are considered to be internalised by the cognitive system, and then processed fully inside, i.e. just using neural processes (essentially the classical information processing model). In the constitutive account, the external symbols are part of cognition. Also, the external operations on them, as well as the sensorimotor system-based interaction processes (such as perception, physical manipulation, etc.) involved in these operations, are part of the cognition process. This constitutive view is supported by the fact that most scientific phenomena deal with entities not available to perception and action, and therefore the understanding of these entities is tightly intertwined with the external structures that stand in for these entities. The ERs thus play a twofold constitutive role in cognising these phenomena (stand-ins for imperceptible entities, structures that help constitute concepts), as understanding these imperceptible entities would be impossible without them. And since ERs are external structures, operations done on them are a critical component of understanding the entities and processes they stand in for.

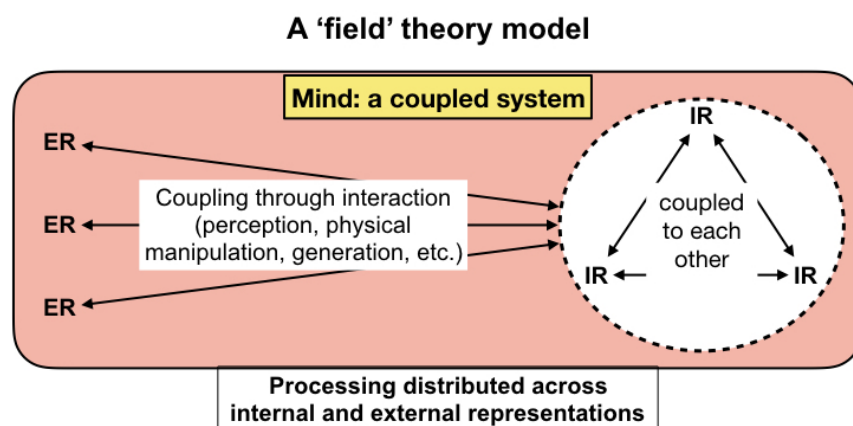Figure 1.3 presents a graphic illustration of these ideas from the DC and EC theories.

Figure 1.3 A general field theory model of cognition and ER integration. In this model, meaning is constituted through (bodily or sensorimotor system-based) interaction with the ERs. The mind is considered to be 'coupled' with ERs, and internal representations of ERs are considered to encode the sensorimotor aspects of the interactions.

The new 'field theories' of cognition emphasise interaction with external structures as the central process driving meaning and understanding. Extending this view to RC, interaction with external representations, particularly based on the sensorimotor system, would be key to ER integration. ER integration and conceptualisation are also build on this sensorimotor integration, as interaction with Ers are based on the sensorimotor system, and such interactions exploit cognitive/brain mechanisms similar to those involved in sensorimotor integration (Pande & Chandrasekharan, 2017).

A good example to illustrate the constitutivity position is provided by Landy and Goldstone (2007) who demonstrated how visual cues, such as spacing the elements in an arithmetic equation differently, or adding lines and circles around equations, influences problem solvers' symbolic reasoning abilities, such as following (or not following) the operator-precedence rule in arithmetic problems. This influence is a result of perceptual grouping, cued by the structural elements added to the equation, suggesting that external structures, and the perceptual as well as sensorimotor mechanisms involved in a problem solver's experiences with those external structures, constitute the processing and overall understanding (internal representations) of the symbols (Kirshner & Awtry, 2004; Landy et al., 2014).

Further evidence in support of the position comes from neurological studies investigating the use of mental abacus. Expert abacus users develop the ability to use an imagined internal abacus, on which they do visual and motor operations while solving complex arithmetic tasks. In contrast, students who are not familiar with the abacus imagine the standard written arithmetic algorithms (learned through paper and pencil operations) while solving the same arithmetic tasks. The interesting finding, however, is that these two operations in imagination (mental abacus, paper/pencil algorithms), which are *constituted* through interactions with different external structures, 'run' in different areas of the brain. f-MRI studies reveal that, in the case of mental abacus, predominantly visuo-motor areas of the brain are ac-

tivated, whereas imagination of the paper/pencil-based algorithms mostly activates frontal areas of the brain (Chen et al., 2006; Hanakawa et al., 2003).

How can one explain this fMRI result using the classical cognition model? According to the classical information processing model, information in both the abacus as well as paper/pencil-based problem solving cases would be extracted in a symbolic form, and processed inside the brain amodally. As there is no visual or motor activity involved in processing the amodal symbolic operations, there should be no activation in the visuo-motor areas of the brain in either of the cases. In contrast, the field theory model, along with our theoretical position regarding the relation between sensorimotor integration and ER integration, suggest that as the mental abacus operations are learned with, and thus rely heavily on, visuo-motor operations, imagination based on stored abacus-based operations would activate visuo-motor areas of the brain significantly. Similarly, the imagined written algorithm operations are based on generating and manipulating text-based images in working memory, so these operations would activate the frontal areas more. This view accounts well for the fMRI data, and suggests that internal representations are generated through interaction, and they encode these interactions. These actions are activated during imagination based on the stored internal representations, such as the mental abacus. This analysis suggests that learning based on different external representations lead to different kinds of stored processes and imagined operations in the brain (figure 1.4).

Extending this view, different operations in imagination would be made possible by different ERs, and integrated ERs. The integration process would also be driven by sensorimotor operations, as in the case of the physical abacus.

The constitutive view does not deny symbols or symbolic relations. In the above example, bead positions in the abacus are symbols that stand in for numbers. However, focusing on this symbolic nature directs the analysis away from the way the mental abacus (a thinking process) is generated from the

physical abacus (a doing process), as the symbolic view would consider both as based on symbols. The constitutive view helps focus on the *processes* involved in this doing-to-thinking shift, as well as the cognitive and neural *mechanisms* involved (Rahaman et al., 2017), which leads to a richer understanding, and consequently, more detailed design directions. A symbol-based analysis would only provide a surface-level view of this change in cognition, and thus design directions based on cognitive load.
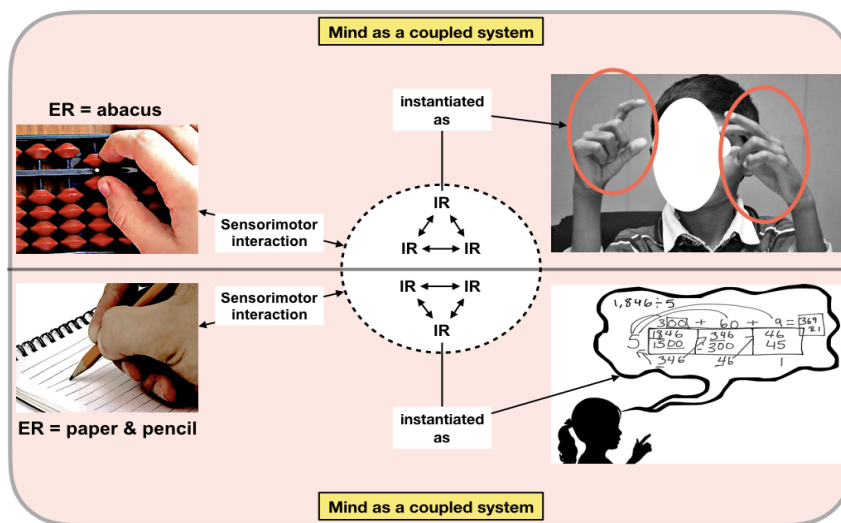

Figure 1.4 Development of different internal representations, based on sensorimotor interaction with different ERs. Expert abacus users develop an internal abacus learned through sensorimotor interaction with the physical abacus. This mental abacus is used to solve arithmetic problems mentally (in imagination), by 'running' the same sensorimotor interactions internally. Some of this covert sensorimotor processes 'leaks' into overt action, leading to gestures similar to the actions on the abacus. Problem-solvers not familiar with the abacus imagine written arithmetic algorithms, learned through paper/pencil-based interactions with the symbols and operations.

The constitutive view offers the possibility of providing critical direction to the design of new computational media for learning, where embodied controllers such as multi-touch devices, Leap Motion, Kinect, Real Sense and Virtual Reality are used to develop new learning experiences, i.e. constitute new ways of integrating ERs (Abrahamson & Sánchez-García, 2016; Borar et al., 2017; Dickes et al., 2016; Karnam et al., 2016; Ottmar et al., 2015, Sinclair & De Freitas, 2014). The interconnections between ERs are considered created by actions, and not by symbolic relations. ER integration is considered driven by the doing aspect, and not by the relations between symbols, even though the relations between symbols contribute to, or even make possible, the doing.

The three aspects of external representations discussed thus far (viz. power of external representations, constitution of concepts, and integration of external representations), are explored significantly in cognitive science and studies of scientific practice, but are not addressed by current work in ER integration and RC, except in some isolated cases.

1.3 Sensorimotor markers of expertise

It is well known across that expertise is marked by specific changes in the nature of cognition and perception, particularly related to problem-solving (e.g. response times, visual attention, etc.; NRC, 2000). These changes have been documented across multiple domains (e.g. chess, science, mathematics, social science, medicine, etc.; NRC, 2000). de Groot (1978), for instance, was among the first to demonstrate how expert chess players could almost instantaneously *see* problems, as well as possible moves to address those problems, when presented with different configurations of pieces on a chess board. Not only were experts quick to respond, they also suggested 'high quality' moves, in contrast to less experienced players. de Groot concluded that training in chess gradually reduced the time and efforts required to abstract patterns, and that the patterns were readily *perceived* by expert chess players, thus marking the replacement of abstraction by perception (de Groot, 1978).

Similar reports have been documented in various other contexts, for instance categorisation of physics problems (Chi et al., 1981) and chemistry representations (Kozma and Russell, 1997). As covered extensively in chapter 2, several recent eye-tracking studies in science and mathematics education have documented objective measures of such differences between experts and novices, in terms of perceptual markers such as gaze. Eye movements and fixations during a task are mostly implicit, i.e. driven by task demands and not completely in the control of the agent, and thus are anchored closely to the perceptual-cognitive processes related to the task (Henderson & Ferreira, 2013; Irwin, 2004). The results from these studies suggest that training, and restructuring of prior knowledge based on training,

reorganises experts' perceptual-cognitive schemas (Cook et al., 2006; Kohl & Finkelstein, 2008). However, many of these existing results have been explained using information processing accounts, such as 'top-down' and 'bottom-up' processes (Gegenfurtner et al, 2011; Lowe, 2015).

Research exploring the notion of constitutivity, and the relationships between sensorimotor activity and ER integration, is relatively recent in education research. Most such studies are situated in the mathematics cognition literature. A number of studies, for instance, have explored how experts differ from novices in the way they pick up information during a problem situation, based on their (sensorimotor) experiences with the symbolic structures involved in that problem (Brathwaite et al., 2016; De Wolf et al., 2017; Kellman et al., 2010; Landy & Goldstone, 2007; Rivera & Garrigan, 2016). Closely related is a considerable amount of research on perceptual learning – a phenomenon characterized by changes in the process of information extraction, and changes in the perceptual-cognitive system (as well as mental models) of a learner as a result of visuo-spatial routines (perceptual manipulations theory; Landy et al., 2014), training and experience (e. g. Goldstone, 1998; Kellman & Garrigan, 2009). Kellman and colleagues (2010) for instance, show how transforming the structure of an algebraic equation affects the difficulty level as well as response times to solve that equation. They argue that people with different experiences with the different equation forms find some forms of equation more relevant than others, and that this relevance is established almost instantly after perceiving the problem, as indicated by response times.

Such markers of sensorimotor changes based on science training, according to the view developed in this dissertation, are markers of changes in cognitive mechanisms associated with ER integration. The work outlined here thus brings together perspectives on ER integration, perceptual learning and constitutivity, and proposes that concepts are constituted through sensorimotor interaction, and this constitutivity process leads perceptual learning, along with other sensorimotor changes.

1.4 Previous relevant work at home institution (HBCSE, TIFR, Mumbai)

Previous studies at HBCSE have examined how students integrate the dynamic structure-function relationships in scientific phenomena and entities through visualisation, as well as the use of gestures and analogies. Subramaniam and Padalkar (2009), for instance, explored how and which ERs are used by adults to reason about astronomical phenomena such as an eclipse involving the sun, earth and moon. They found that adults heavily rely on gestures to visualise and explain phenomena dynamics through static diagrams. Importantly, we benefit not only from the constant dynamic feedback available through gestures, but also from automatic associations gestures build between ourselves and the phenomena. These results indicate the close link between embodiment and RC. Mathai and Ramadas (2009) report similar findings in the context of structure-function relationships in middle-school biology. Padalkar and Ramadas (2009) designed and tested specific manipulative actions and pedagogic gestures to help middle-school students develop an integrated understanding of the dynamics of astronomical phenomena and their static models and diagrams. Building on this work, Srivastava and Ramadas (2013) demonstrated how use of gestures, analogies and perspective taking can together help integration of different external representations (such as 2-dimensional models and diagrams) by inducing mental simulation of 3-dimensional DNA structures.

The work presented in this dissertation integrates previous work across multiple studies done at the centre, by 1) focusing on ER integration as a general learning difficulty cutting across disciplines, and 2) developing a theoretical model of the cognitive mechanisms underlying ER integration based on new field theories in cognition. This work thus tightly connects the ER integration problem, and studies exploring ER integration, with recent cognitive science research.

1.5. Overview of the thesis

Building on the emerging models of cognition, and the three aspects of ERs (cognitive augmentation, constitutivity, integration) as well as the new understanding of the markers of expertise based thereupon, this dissertation develops: (i) a new theoretical model of the cognitive mechanisms underlying ER integration and its development, (ii) empirical studies to test this new model, and (iii) a design that incorporates the model. I begin with reviewing relevant literature (chapter 2), particularly the theoretical frameworks of ER integration and RC, and the empirical studies that investigate the nature of RC and its development in science, mathematics and engineering. This review is an attempt to bring together all the work done in RC, in many disparate areas, and identify commonalities and differences in the research across several themes. The review finds that most research in this area, including intervention development, is either explicitly or implicitly based on the classical information processing model of cognition.

In chapter 3, I develop a distributed and embodied cognition account of ER integration, in contrast to the information processing accounts, for the following reasons:

- One, current models of cognition reject the classical information processing approach; mental processes are now understood as distributed and embodied. Models of ER integration are models of cognition, and thus need to incorporate this theoretical shift, particularly because ERs are external (thus distributed), and working with ERs require sensorimotor interaction (embodied interaction).

- Second, there is a parallel shift in the design of new computational media, where embodied controllers such as Leap Motion, Kinect, Real Sense and Virtual Reality are used to develop new learning experiences (Abrahamson & Sánchez-García, 2016; Dickes, Sengupta, Farris, & Basu, 2016), particularly to integrate ERs. This design approach requires understanding the role of embodiment in ER integration and RC development.

- Finally, the practice of science itself is now understood as distributed and embodied (Chandrasekharan, 2013; Chandrasekharan & Nersessian, 2015; Nersessian, 2010), and any future model of ER integration and RC development need to reflect this shift in our understanding of science practice.

The account developed in this chapter illustrates how ERs are understood by learners through an 'incorporation' process, where they become part of, and thus extend, the cognitive system, while also forming and extending the internal model of the scientific domain. This incorporation process is driven by sensorimotor actions/manipulations performed on the external representations, as well as through the exploration of many states of the external representations. Further, sensorimotor interactions with these ERs (overt as well as covert activation of the motor system) facilitate 'capturing' and 'unfolding' the different states of ERs, and these operations play a central role in ER integration.

Two interconnected conjectures, with empirical implications, emerge from this account:

- In this model, the development of the ER integration ability (expertise) would result in a reorganisation of the cognitive system, particularly the sensorimotor system. This suggests that the process by which learners perceptually access ERs would change after significant training in a domain.

- Interaction, particularly based on the sensorimotor system, would support ER integration and its development.

To test these predictions, and thus also the theoretical model, I conceptualised two empirical projects.

The first project (chapter 4) sought to identify behavioural markers that could track sensorimotor changes as a learner interacts with scientific ERs, leading up to the development of constitutivity and ER integration. In this project, I first established the ER integration abilities of participants, who had

different levels of education in chemistry. This was done by tracking how they related chemical phenomena and their dynamics, when presented with different static and dynamic ERs during a categorisation task. I then looked for patterns in their eye gaze behaviour, and correlated these patterns with participants' ER integration abilities, to identify sensorimotor markers of ER integration. This project contributes to the existing work on the nature of expertise.

The second project (chapter 5) focused on the design, development and testing of a computer interface with fully manipulable ERs of a physical system. Besides being an intervention, the interface was also used as a 'probe into the cognitive processes', to explore how interactivity aids in ER integration.

Chapter 6 summarises the dissertation and presents possible implications and contributions of this work, particularly in relation to new-media designs supporting ER integration and RC development, as well as conceptual learning in science, mathematics and engineering.

The work reported here is among the first to:

(1) Weave together extensive and highly diverse theoretical as well as experimental work on ER integration from different disciplines.

(2) Objectively characterise the sensorimotor changes related to ER integration and RC facilitated by training in a domain.

(3) Design and test a new media intervention based on DC and EC perspectives, exclusively targeting ER integration and RC development.

(4) Analyse in detail the relationship between interactivity, ER integration and learning.

(5) Conjecture that usability and learnability design principles are not enough for the learning of complex representations and conceptual content based on new media.

Chapter 2: Bringing together research on ER integration in science, mathematics and engineering; identifying gaps

This chapter presents a comprehensive review of existing work on ER integration and RC development in science (chemistry, biology and physics), mathematics and engineering. It first examines the influential theoretical accounts, followed by a review of the important empirical studies in education in these fields. This review is an attempt to bring together all the major (interrelated as well as disparate) theoretical and experimental work distributed across more than 170 papers published in more than 35 different venues in education research, cognitive science, learning sciences, educational technology, etc. in chemistry, biology, physics, mathematics, and engineering among several others. The theoretical review amounted to more than 30 different models related to ER integration and RC development. Figure 2.1 outlines the broad categories of the theoretical frameworks that emerged during the review.
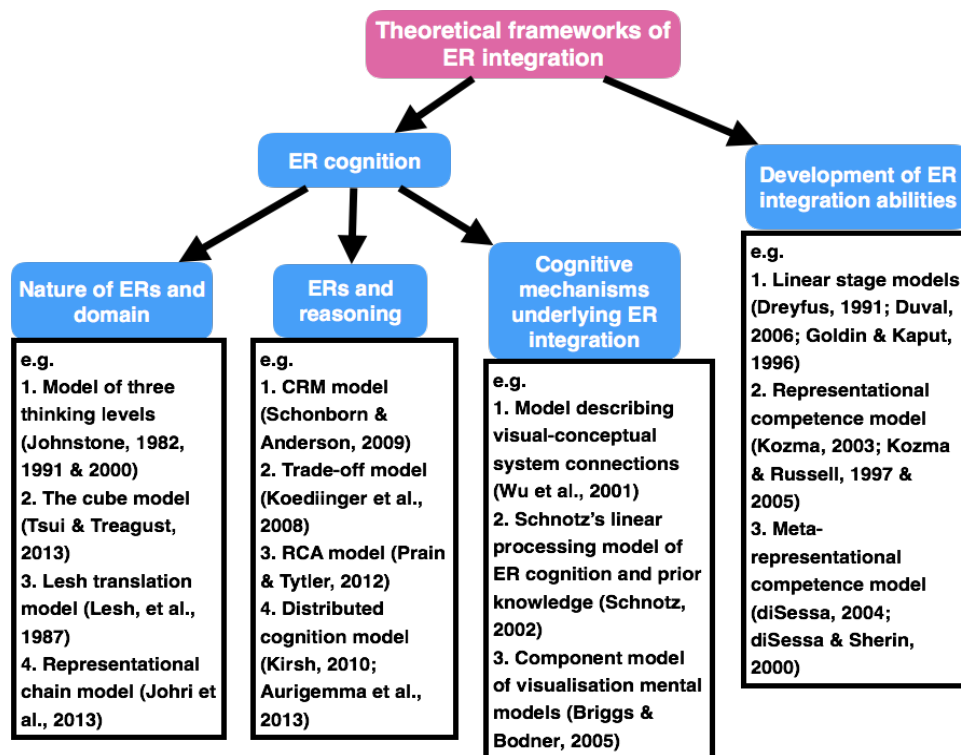

Figure 2.1 Broad categories of theoretical frameworks and models that emerged during the review.

Further, more than 70 research papers reporting empirical investigations are reported in this review to understand the different approaches to ER integration. These theoretical models and empirical studies were compare across disciplines in terms of: problems related to RC, nature of ERs, nature of learning difficulties, research methods employed, and the underlying theoretical assumptions. In figure 2.2, I outline the two categories of empirical studies based on their focus of investigation. These theoretical and empirical studies examine everything from the analysis of children's 'scribbling' on paper, drawing of simple diagrams, making sense of the diagrams, expert-novice differences, to complex modelling of scientific phenomena by practitioners, and working memory models of information extraction, ER interlinking and transformation.

Empirical studies

Linking ERs
Translating between ERs
Transforming between

Student difficulties in linking:
- Math functions with graphs, diagrams, word problems
- Numbers with space

Expert-novice differences in
- Translating between ERs
- Extracting information from ERs
- 'Handling' cognitive load
- Working memory strategies

Relationships between
- Prior knowledge and working memory
- Prior knowledge and gaze behaviour (using eye-tracking)
- Visuo-spatial thinking and ER transformation

Situated cognition and ER integration
- Practice with ER in real-life environments/ contexts
- Gap between real-life and teaching contexts

Distributed and embodied cognition perspectives on ER integration
- Merging perception with imagination
- Building dynamic simulative internal models of phenomena through their ERs

Using computer interventions to foster ER integration

Generating ERs
Representational preferences

Student generated ERs as indicators of:
- Misconceptions
- Internal (problem) representations

Relationships between prior knowledge and:
- Generated representations
- Preferences of representations during problem solving

Expert-novice differences
- Quality and detail of generated ERs (e.g. structural, functional and/or system behaviour information conveyed in sketches)
- Use of analogies between familiar and unfamiliar systems and their ERs
- Generating ERs to tweak working memory

Influence of the nature of representation on problem solving success
- e.g. presenting contextualised ERs as opposed to abstract ones to boost integration

Distributed cognition approaches
- Facilitation of situation reinterpretation through generation of ERs (sketching, drawing, etc.)
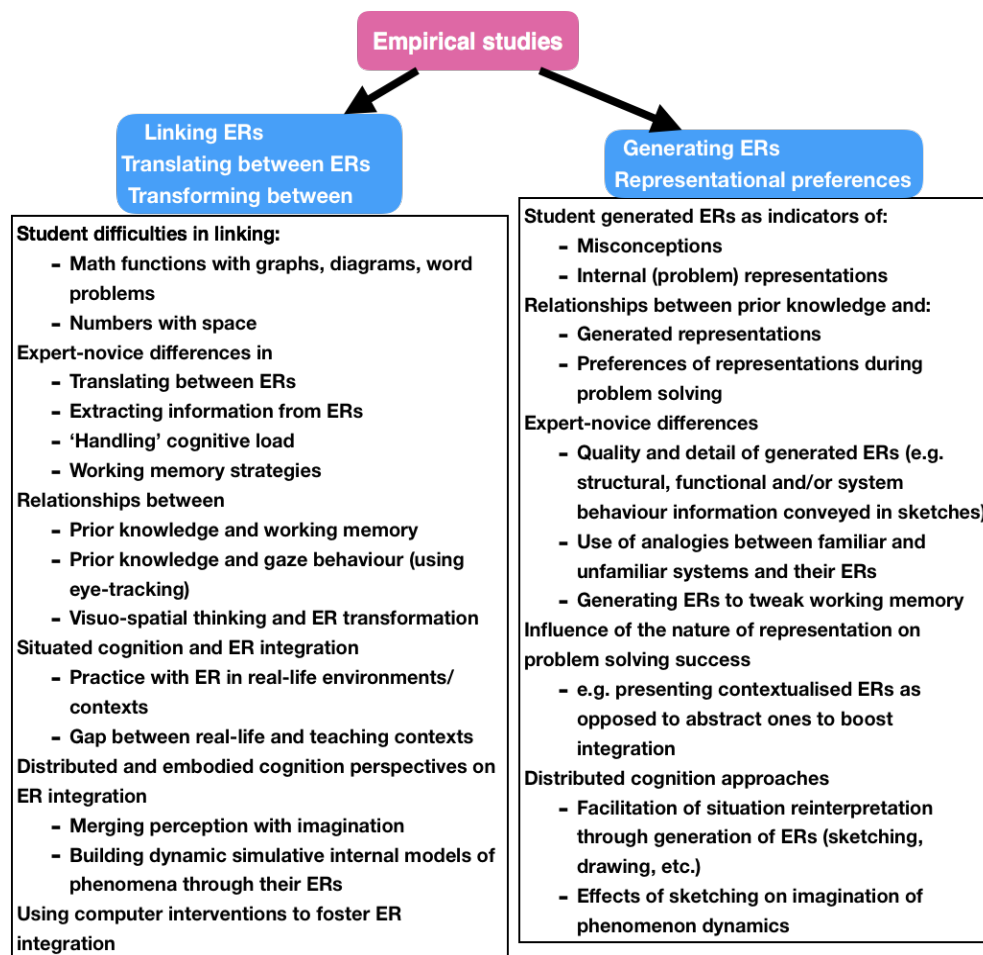- Effects of sketching on imagination of phenomenon dynamics

Figure 2.2 Overview of the empirical studies reviewed.

Based on the review of the models and empirical studies of ER integration and RC, commonalities and differences in the research between disciplines were identified across several themes. The next section presents a set of important findings that emerged out of the review.

2.1 Findings from the review

The following major findings emerged (for comparison data, see Pande & Chandrasekharan, 2017):

2.3.1 Ambiguity in using the term 'representation'

The term 'representation', throughout the literature in education, is often used in an ambiguous manner, where it is unclear if the term refers to internal representations or external representations. Some studies refer to both simultaneously using the term. Notable exceptions to this finding include: (a) Problem solving studies in physics education research (e.g. Chi et al., 1981), and (b) studies which explicitly use the term 'external representations' (e.g. Nakhleh & Postek, 2008), particularly those employing distributed cognition frameworks (e.g. Aurigemma et al., 2013).

2.3.2 Nature of ERs and the RC skill differs across disciplines

There exist subtle discipline-dependent differences in ERs and their affordances. ERs in some disciplines (e.g. chemistry) are more defined, conventionalised and constrained than those in other disciplines, and there is very little scope to freely generate ERs. For instance, there are limitations to the manner of using ERs in chemistry. ERs in biology are relatively more diverse, although biology inherits certain representational systems (ERs) from chemistry. ERs in mathematics are highly conventionalized and rule-based. But unlike chemistry, a single concept in mathematics (e.g. numbers) can be represented in multiple ways. This makes usage of ERs in mathematics more flexible for the learner or practitioner. Physicists employ mathematical ERs in solving physics problems. Use of diagrams in physics is conventionalized, but the learner has enough space to generate diagrams in her

own way; she can scribble and represent situations in multiple ways. Engineering borrows ERs from many of these disciplines, and from areas other than the core scientific domains, such as social sciences, humanities, economics, etc. Engineers thus can flexibly use ERs, prototypes and models.

2.3.3 ERs present a general cognitive difficulty

Despite the differences in the nature of ERs, the ER integration and RC problems can be traced to learning difficulties (e.g. visualisation, transformation, etc.) common to all the disciplines. As a corollary, research shows that these learning difficulties are attributed to difficulties in mastering ERs in a given discipline. This suggests that integration of ERs is a general cognitive difficulty.

2.3.4 Focus on classical information processing model

Most theoretical accounts of ER integration and RC development, as well as empirical studies and interventions across the domains, have been either explicitly or implicitly informed by classical information processing models of cognition (Ainsworth, 1999 & 2008; Johnstone, 1982; Wilensky, 1999). The following assumptions can be identified with these frameworks and studies: (a) The mind extracts information from ERs, which acts as 'vehicles', or transmission media, for the information, (b) ERs and the concepts they represent are linked through some form of information 'translation', and (c) the translation is mediated through mental capacities such as imagery and amodal symbolic forms, as well as working memory (e. g. Johnstone, 1982; Tsui & Treagust, 2013). By focusing on the "processor capacity" as well as the inaccessible nature of information extraction and translation processes, these approaches make the ER integration process, and the cognitive mechanisms underlying it, appear mysterious. Further, they ignore important questions such as: how and why are certain interventions more effective for RC development? What role does practice play in the RC development process? How do internal and external representations interact?

Chapter 3: Towards a distributed and embodied cognition account of ER integration

Here I propose a model of the cognitive processes involved in a generic ER integration problem, and then outline an account of the cognitive mechanisms underlying these processes, using perspectives from recent cognitive theories, particularly distributed and embodied cognition. The explicit departure from classical cognitivist assumptions can be captured as follows:

1. I emphasise the distinction between internal and external representations, considering the two as dynamically coupled through constant interactions between the learner and external representations. My focus is on how different external representations are integrated. But since this integration process is closely coupled with the formation of an internal model of the domain, our model also considers integration of ERs and internal models.

2. I focus on the way the cognitive system *interacts* with ERs, as opposed to the view: that all ERs embed information; that this abstract information is isolated from the external structure and pulled inside by the cognitive system (somehow); and that cognition arises from the manipulation of this information inside the head. My account is thus inspired by the idea of 'constitutivity', which treats external symbols as part of cognition. The external operations on ERs, and the sensorimotor processes involved in these operations, are part of cognizing the concepts ERs embed (Landy et al., 2014).

3.1 The TUF model: capturing the general cognitive processes involved in ER integration

The generic case of integration of ERs in science, mathematics and engineering involves the observed (or described) actual dynamic behaviour of a (physical) system (such as a falling object, a pendulum or a chemical process), an equation capturing the behaviour, and a graph that displays the equation's output for some sets of values. The transition to the equation is often mediated by geometric structures, such as free-body diagrams, and there may be other structural representations involved, such a molecu-

lar models depending on the discipline in focus. Broadly though, the learner needs to develop an integrated internal representation of the three modes – the phenomenon, its equation and the graphs. If other structural representations are present, the integration process has to deal with one or more levels of complexity. An indicator of integration is the ability to transform smoothly between the three modes (Pande & Chandrasekharan, 2017). This transformation is difficult, because it requires shifting between spatial and numerical modes (e.g. graph and equation), as well as dynamic and static modes (e. g. phenomenon and equation). Even the spatial to numerical transformation requires understanding dynamics, as the students need to understand how the values in the equation get translated into a graph, which requires thinking of various values of equations and 'movements' of the graph based on these values. Thus, to integrate the ERs, the student needs to "unfreeze" the static representations, by generating their dynamic behaviour in imagination, and then connect these dynamics with the dynamic behaviour of the phenomenon. In the other direction, students also need to be able to "freeze" the imagined (and perceived) behaviour of real-world systems into equations, so that limit cases and other variations can be explored and combined. A schematic representation of these transformation, unfreezing and freezing processes is presented in figure 3.1. Lets call this generic model as the TUF model, where TUF stands for Transform, Unfreeze and Freeze respectively (figure 3.1).
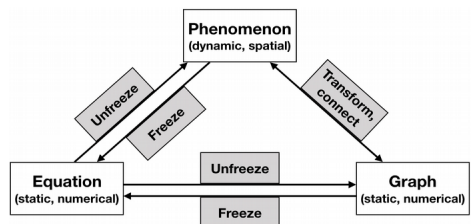

Figure 3.1 The TUF (transform-unfreeze-freeze) model depicting the processes involved in ER integration.

3.2 A DC and EC-based account of the cognitive mechanisms underlying the TUF model

The generic structure presented in figure 3.1 above suggests that a mechanism account of the cognitive processes involved in ER integration would need to address two important questions: *(1) how are ex-*

ternal representations connected with imagination, and (2) how dynamic behaviour could be imagined from static external representations.

Answering the first question requires understanding how external representations are processed by the cognitive system. This question is best addressed within the distributed cognition (DC) framework (Hutchins, 1995a; Hutchins 1995b), which was developed to study cognitive processes in complex (usually technical and scientific) task environments, particularly environments where external representations and other cognitive artefacts are used by groups of people. Most work in DC is focused on understanding how internal and external representations work together to create and help coordinate complex socio-technical systems. The primary unit of analysis in DC is a distributed socio-technical system, consisting of people working together (or individually) to accomplish a task and the artefacts they use in the process. The people and artefacts are described, respectively, as agents and nodes. Behaviour is considered to result from the interaction between external and internal structures.

The canonical example of external representational structures in DC is the use of speed bugs in a cockpit (Hutchins, 1995a). Speed bugs are physical tabs that can be moved over the airspeed indicator to mark critical settings for a particular flight. When landing an aircraft, pilots have to adjust the speed at which they lose altitude, based on the weight of the aircraft during landing for that particular flight. Before the origin of the bugs, this calculation was done by pilots while doing the landing operation, using a chart and calculations in memory. With the bugs, once these markers are set between two critical speed values (based on the weight of the aircraft for a particular flight), instead of doing a numerical comparison of the current airspeed and wing configuration with critical speeds stored in memory or a chart, pilots simply glance at the dial to see where the speed-indicating needle is in relation to the bug position. This external representation allows pilots to 'read off' the current speed in relation to permissible speeds using perception. They can then calibrate their actions in response to the perceived speed

difference. The speed bugs (an external artefact) thus lower the pilot's cognitive load at a critical time period (landing), by cutting down on calculations and replacing these complex cognitive operations with a perceptual operation.

Both the DC and extended cognition (a recent scoping of DC) perspectives focus on memory offloading, but it has been extended in two ways: 1) to show how processing, particularly mental rotation, is lowered using external manipulations that serve as 'epistemic actions' (Kirsh, 2010; Kirsh & Maglio, 1994) and 2) how imagination is augmented by active manipulation, particularly in computational models (Chandrasekharan & Nersessian, 2015; Chandrasekharan, 2014; Marshal, 2007). These studies, and other similar ones showing how external representations are used to generate action patterns (Martin & Schwartz, 2005) suggest that the brain 'incorporates' external representations (Chandrasekharan, 2014) as part of the imagination system, using a mechanism similar to that employed in incorporating tools (Maravita & Iriki, 2004) and other objects (Ehrsson, 2007; Kalckert & Ehrsson, 2012). This incorporation process is considered to be driven by actions/manipulations done on the representations, and the exploration of many states of the representations. This incorporation view is different from classical information processing views, where the information encoded in the representation is extracted by the cognitive system, and all cognitive operations are internal operations done on this extracted information. The new approach suggests that actions and manipulations on ERs lead to the ERs getting incorporated – becoming part of the cognitive system (e.g. the mental abacus system; revisit section 1.2).

The above account provides a rudimentary 'incorporation' model of how external representations connect with imagination (see Chandrasekharan, 2014 & 2009 for details), and brings us to the second question: *How is dynamics generated from static representations?* Embodied cognition research argues that the brain and all cognitive processes developed for action, and the body and the sensorimotor system are therefore closely involved in most cognitive operations. Supporting this theoretical view, there

is evidence that the sensorimotor system is used while generating dynamic information from static images (such as system drawings, see Hegarty, 2004). Common instances of this generation include: judging the sense of speed of a vehicle from its tire-marks (or judging tire-marks given speed), judging the sense of force from impact marks (or judging impact marks, given force), sense of movement speed from photos of action (say soccer), sense of movement derived from drawings, cartoons, sculptures, etc. Experimental evidence for the use of motor system in this process comes from the work on the Two-Thirds Power Law for end-point movements such as drawings and writings. The law relates the curvature of a drawing trajectory with the tangential velocity of the movement that created the drawing/writing. The human visual system deals more effectively with stimuli that follow this law than with stimuli that do not. When the curvature-velocity relationship does not comply with the power law, participants misjudge the geometric and kinematic properties of dynamic two-dimensional point-displays (Viviani & Stucchi, 1989 & 1992). The accuracy of visuo-manual and oculomotor 2D tracking depends on the extent to which the target's movement complies with the power law. This relation allows humans to judge the speed in which something was drawn, using curvature information, and vice versa (judge curvature given speed). This capacity is presumably what we use when we judge speed from tire marks, and also evaluate drawings/paintings. Recent experimental evidence shows that observers simulate the drawing actions of a painter while observing paintings (Taylor, Witt & Grimaldi, 2012) and written text (Bub & Masson, 2012).

Such predictions can also work the other way. For instance, given dynamic traces of handwriting samples (such as *l*, *h* etc.), participants could judge which letter came next to the shown trace, indicating that we can imagine and predict static samples that follow dynamic traces. Kandel, Orliaguet and Viviani (2000) showed that the judgement accuracy increased when the trace followed the Two-Thirds power law, i. e. the angular momentum of writing was related to curvature in a way laid out by the law;

while it went down significantly for traces that did not follow this relation. Based on this and other experiments, Viviani (2002) argues that "in formulating velocity judgements, humans have access to some implicit knowledge of the motor rule expressed by the Two-thirds Power Law". Much of the experimental evidence in this domain is about the replication of biological movements from static images, but everyday experience (such as the tire mark case) suggests that non-biological movements can also be replicated, and it is highly likely that this process also is based on sensorimotor system activation (Chandrasekharan, 2014; Schubotz, 2007).

Box 2: TUF model summary
The TUF account proposes that to integrate the ERs, a student needs to
1. **"unfreeze"** the static representations, by generating their dynamic behaviour in imagination
2. **transform** between phenomena and cues of dynamic behaviour present in the static graphs
3. **"freeze"** the imagined (and perceived) behaviour of real-world systems into equations, so that limit cases and other variations can be explored and combined.
All these processes are mediated by the sensorimotor system.
The cognitive/neural mechanisms involved are: (a) 'incorporation' of the ER, and (b) mental simulations based on covert activation of the sensorimotor system.

This account suggests that the sensorimotor system needs to be activated to start the "unfreezing" of ERs, to generate the dynamic nature of the content captured using the static representation. It is possible that this activation process is difficult to do for novices, and new media interventions that allow manipulations on the ERs could help trigger this activation, thus setting the unfreezing process in motion. Note that this approach is different from the designs suggested by the cognitive load account, where manipulation of ER is not the central feature of the intervention. Also, this approach is in synergy with the 'incorporation' account provided by recent work in distributed cognition (Chandrasekharan, 2014; Chandrasekharan & Nersessian, 2015), as it suggests manipulation of the ERs as a way of promoting incorporation of the external representation, to integrate it with the imagination system. A related idea is that actions done on ERs with dynamic content would help improve integration, as the action system is involved in processing dynamics, and it is also the central integrating system in the body. This view provides an explanation for why interactivity provided by new media helps improve understanding and integration, which are limited with static media (Majumdar et al., 2014).

Given the involvement of sensorimotor mechanisms in the incorporation, imagination and integration processes, as well as the relationships between action-perception-imagination capacities, two interconnected conjectures, with empirical implications, emerge from this theoretical account:
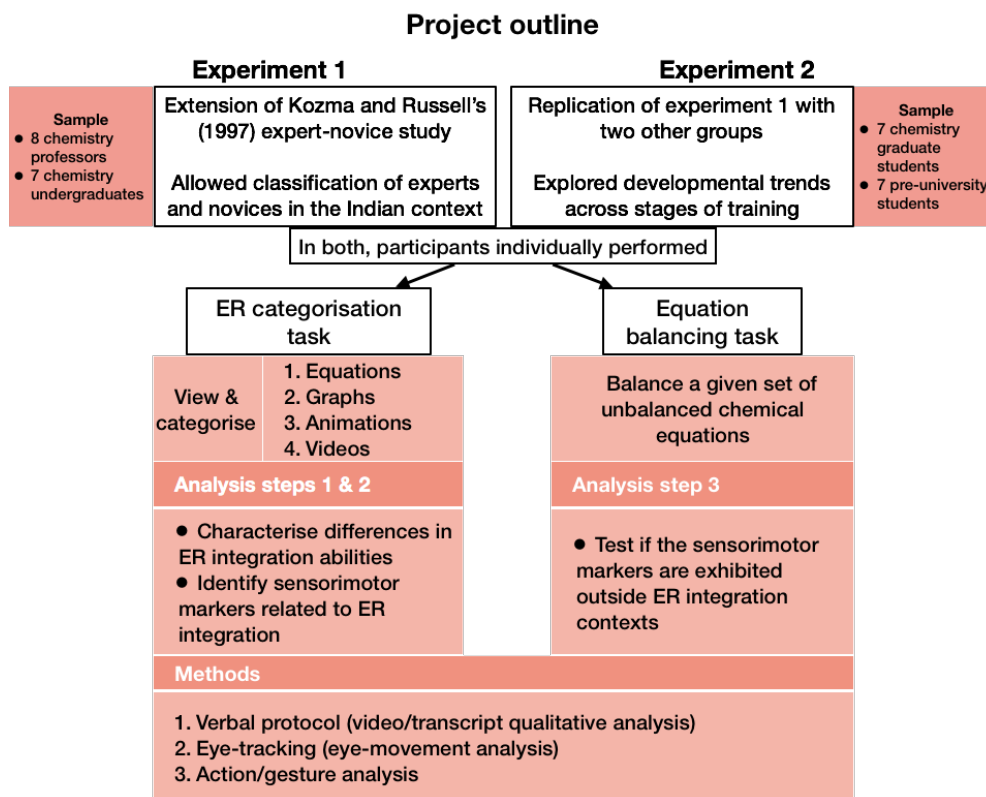
1. In this model, the development of the ER integration ability would result in a reorganisation of the cognitive system, particularly the sensorimotor system. This suggests the way learners perceptually access ERs would change after significant training in a domain.

2. Interaction, particularly based on the sensorimotor system, would support ER integration and its development.

To test these predictions, and therefore also the TUF model, I conceptualised two empirical projects.

The first project is situated at the interface between chemistry education and cognitive science. It sought to identify any sensorimotor changes during chemistry education, related to the development of constitutivity and ER integration. In this study, different groups of participants, with varying levels of education in chemistry, performed tasks with general chemistry ERs, while I capture their gaze behaviour. I then searched for correlations, comparing the level of education of participants with their ER integration abilities, and then patterns of gaze behaviour.

The second project sought to test the second conjecture, by answering the following question: how can the DC and EC-based theoretical account be utilised build effective new-media learning environments that support ER integration? It focused on the design, development and testing of an interactive computer interface, with fully manipulable ERs, developed as an intervention to support ER integration at the middle-school level. This interface provides coupled ERs of a physical phenomenon to a learner, in static as well as dynamic states. Testing the interface contributed to further understanding of the predictions made by the first conjecture.

Chapter 4: Does ER integration based on chemistry training change the sensorimotor system?

Project outline

Experiment 1	Experiment 2

Sample
- 8 chemistry professors
- 7 chemistry undergraduates

Extension of Kozma and Russell's (1997) expert-novice study

Allowed classification of experts and novices in the Indian context

Replication of experiment 1 with two other groups

Explored developmental trends across stages of training

Sample
- 7 chemistry graduate students
- 7 pre-university students

In both, participants individually performed

ER categorisation task

View & categorise
1. Equations
2. Graphs
3. Animations
4. Videos

Analysis steps 1 & 2

- Characterise differences in ER integration abilities
- Identify sensorimotor markers related to ER integration

Methods
1. Verbal protocol (video/transcript qualitative analysis)
2. Eye-tracking (eye-movement analysis)
3. Action/gesture analysis

Equation balancing task

Balance a given set of unbalanced chemical equations

Analysis step 3

- Test if the sensorimotor markers are exhibited outside ER integration contexts

This project sought to test the first conjecture – whether achieving ER integration (expertise) results in changes in the sensorimotor system of a learner. To do this, I first identify expertise (ER integration) related to training. Then markers of sensorimotor behaviour, particularly eye-movements, are identified in relation to the development ER integration, as a learner progressed in her training.

To understand any possible correlation between ER integration abilities and sensorimotor behaviour, I executed the following two steps of analysis:

- Step 1: How do participants with different levels of education in chemistry differ in ER integration abilities?

- Step 2: What are the sensorimotor markers associated with the development of ER integration in chemistry?

I then considered the alternate explanation that any sensorimotor changes seen are always present, and they are thus not necessarily markers of expertise. To test this possibility, I did a further step of analysis.

- Step 3: Are these markers always present, or only triggered while solving tasks related to ER integration?

I conducted two experiments to understand possible sensorimotor changes associated with expertise, and data from both studies were subjected to this three step analysis. In order to obtain as distinct a result as possible in relation to ER integration abilities, the first experiment was conceptualised as an expert-novice investigation, involving chemistry professors (experts) and undergraduate students (novices). These participants (i) viewed and categorised a set of chemistry ERs, while their gaze behaviour was recorded using an eye-tracker, and (ii) balanced a set of unbalanced chemical equations. To understand how ER integration ability, constitutivity and the underlying cognitive mechanisms develop, I replicated the experiment with two more groups of participants, viz. pre-university students and doctoral students (experiment 2), thus making the study a cross-sectional investigation.

4.1 Experiment 1

The first experiment sought to characterise differences in the ER integration abilities of participants with different levels of expertise and education in chemistry. Behavioural markers were then identified and related to those abilities. To ensure that the ER integration abilities (and hence the behavioural markers) between the groups were as distinct as possible, chemistry experts and novices were studied. Chemistry professors (experts) and chemistry undergraduate students (novices) performed two tasks; an ER categorisation task and a chemical equation balancing task.

4.1.1 ER categorisation task

The categorisation task was a replication of Kozma & Russell's (1997) ER categorisation task, which is an ideal tool to establish differences in ER integration abilities between experts and novices. The task also provides researchers the opportunity to observe participants' interaction with ERs, as it involves participants viewing and categorising a set of chemistry ERs into meaningful categories. In the adopted version of this task, I presented to each participant individually on a computer screen different static and dynamic chemistry representations (3D molecular animations and laboratory demonstration videos – dynamic representations; graphs and chemical equations – static representations) of pre-selected general chemical reactions. I also handed over to the participant, after the participant was done viewing each representation, a physical card that depicted the corresponding representation. Once the participant had viewed and collected all the ERs, s/he was asked to meaningfully group the given ERs, and then justify the categories s/he made (see Pande, Shah & Chandrasekharan, 2015; Pande & Chandrasekharan, in preparation).

4.1.2 Equation balancing task

This was a confirmation task. In this task, each participant was presented with six unbalanced chemical equations (presented one after the other) of different general chemical reactions (e.g. Hinton & Nakhleh, 1999; Nurrenbern & Pickering, 1987), and was asked to perform an irrelevant task – balancing those equations, while I captured their eye-movements over the stimuli.

This task exploits an extremely well established and popular experimental paradigm in psychology – interference. If sensorimotor changes are task-general (i.e. not specific to ER integration), the participants, particularly experts, when presented with chemical equations (stimulus similar to one of the stimuli in the ER integration or categorisation task), would exhibit eye-movements (markers of sensorimotor changes) similar to those seen on equations presented during the categorisation task which required doing ER integration.

Note that solving this task did not require imagining the dynamics of chemical phenomena, and hence, ER integration, as balancing equations is purely based on algorithms. This task also intended to test whether such a presentation of a representation (in a problem that does not require ER integration for successful completion) automatically triggers among participants, particularly experts, an imagination of the represented chemical process.

4.1.3 Research questions (RQs)

The conjecture is operationally captured by the following specific research questions:

1. Do groups of participants with different levels of training in chemistry differ in categorising general chemistry ERs and explaining the relationships between them? (Categorisation task; step 1)

2. Do these participants differ in reasoning about the mapping between dynamic and static ERs? (Categorisation task; step 1)

3. What eye-movement patterns do participants exhibit while observing the ERs? What are the between-group similarities and differences in eye-movement? (Categorisation task; step 2)

4. What eye-movements do the participants exhibit while observing static unbalanced chemical equations? How do the groups differ? (Balancing task; step 3)

5. What do these patterns suggest about ER integration and RC development? (both tasks)

4.1.4 Sample and Methodology

8 chemistry professors (expert group, code-named FC; 4 female) and 7 chemistry undergraduate students (novice group, code-named UG; 4 female) from a leading university in mid-western India volunteered to participate in the study. Informed consent was obtained from all participants. Each participant individually performed two tasks during the experiment.

Participants sat in front of a laptop screen which was attached with a Tobii X2-60 eye-tracker. The eye tracker was calibrated for each participant, and he was then asked to solve six unbalanced equations, one by one. Each participant completed the balancing task first, followed by the categorisation task, to avoid any possible priming effects (based on the exposure to different ERs of chemical reactions as well as the act of performing ER categorisation) while perceiving unbalanced chemical equations.

Next, each participant first viewed 19 ERs (images and movies) on the laptop screen, presented one at a time in a predetermined random sequence. The participant then grouped the respective cards into chemically meaningful categories (categorisation task). After grouping, the participant showed the researcher the different categories s/he made, and justified her categorization scheme(s).

The eye-tracker captured fine-grained data on participant's gaze behaviour as they viewed the representations, while video recording of the experiment sessions captured the verbal and gesture data.

4.1.4.1 Data analysis

The nature of the categories generated by the participants was analysed using video recordings, which were transcribed and coded. This analysis scheme is built on the methods reported by Kozma and Russell (1997). Based on the transcripts (participant's category justification), participants' ER categories were coded into five different types: (i) Conceptual, (ii) Mixed (conceptual + feature based, (iii) Feature-based, (iv) media-based, and (v) inappropriate or incorrect. These codes are hierarchical; conceptual categories had the highest weightage while inappropriate combinations had the lowest.

For gaze analysis, raw gaze data obtained from the eye-tracker were filtered using Tobii Studio 3.2 (gaze-data analysis package from Tobii Technology, 2014). Different non-overlapping areas of interest (AOIs) were defined for each static representation (figure 4.1).
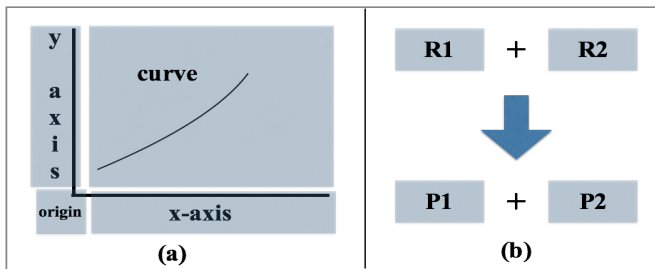
Figure 4.1 AOIs for (a) graph representations, (b) chemical equations. Each shaded box is a separate AOI. AOI shapes and sizes may differ from scene to scene. Four AOIs were created for graphical representations: origin, X-axis, Y-axis, and curve(s). Chemical equations had following AOIs: arrow, reactant-1 (R1), reactant-2 (R2), and so on, and product-1 (P1), product-2 (P2) and so on.

AOI-based fixation data (e.g. sequence of fixations in the different AOIs, number of fixations, etc.; Tobii Technology, 2014) were processed to generate transition data (how the eye moved across AOIs) for graphs and equations. Gaze transitions, i.e. systematic eye-movements between different AOIs, are markers of comparison and integration between two AOIs and representations, and the content they embed. For the graph representations, I discuss transitions with respect to transition diagrams composed of different boxes (representing AOIs) and links between them (representing transitions). For chemical equations, I split the transitions into two types: long jumps or transitions, and short jumps or transitions. Long transitions are transitions occurring between two distantly related AOIs, whereas short transitions are transitions happening over two closely related AOIs. For instance, in figure 4.1b, any direct transition between the two reactants (R1 and R2) or between products (P1 and P2) would be counted as a short transition, while transitions between a reactant (say R2) and a product (say P1) would be long transitions.

Further, two unique overall indicators of the specific gaze activity, inertia and volatility, were defined and calculated using the transition data, where inertia = the number of transitions made to the same AOI/total number of transitions; and volatility = 1 − inertia. Volatility indicates how flexible a participant is in moving between new AOIs and exploring novel relationships between AOIs. Inertia is a measure of how fixated a participant is to one or a limited set of AOIs.

The data analysis protocol for the balancing task was exactly similar.

4.1.5 Major findings and discussion

Table 4.1 shows the categorisation trends for experts and novices across the different schemes.

Table 4.1 Nature of categories for experts and novices

Group/Nature of category	Experts (Mean)	Novices (Mean)
Conceptual	1.5 (1.19)*	0.28 (0.49)*
Mixed	1.83 (0.65)**	0.71 (0.76)**
Surface feature-based	1.16 (0.83)**	3.29 (1.38)**
Media-based	0.67 (1.07)	0.57 (0.53)
Inappropriate	0 (0)*	0.85 (1.07)*

*significant at $p<.05$, **significant at $p<.01$ between the groups.

The categorization task showed that chemistry professors (experts) were significantly more competent at conceptually relating and grouping ERs than novices (RQs 1&2)

During categorisation, some experts used strategies such as spreading the cards on the table, and devised preliminary criteria to arrange the ERs on the table, etc., before proceeding to form finer categories (RQ2). All these actions are identified as 'epistemic actions' which experts in general are known to perform, in order to change the structures of the task environment while searching for a solution or strategy during a task. These actions lower the cognitive load generated by a task (Kirsh, 2010) and also allow seeing newer relationships between ERs (Aurigemma et al., 2013).

Gaze data analysis showed that the differences between the groups for fixation duration, fixation count, mean viewing duration, and frequency of saccades for all the ERs are statistically significant at $p<.01$. Eye-tracking revealed that gaze behaviour of experts is significantly different from that of novices, and is correlated with ER integration abilities (RQ3). These results are similar to eye-tracking results reported by Cook et al. (2008) and Kohl and Finkelstein (2008).

Further, experts made more frequent transitions between the curve (shape corresponds to phenomenon dynamics) and Y-axis (dependent variable – properties of a reaction system), whereas novices transited more frequently between the curve and the X-axis (independent variable) across all the four graph representations. This suggests that the experts coordinated more between the independent variable and the curve, which showed the behaviour of dependent variable given changes in the independent variable. In contrast, novices tried to deduce the end product – a rather static understanding of the reaction (Talanquer, 2013), and face difficulties in inferring effects of independent variable(s) on the behaviour of dependent variable(s) through the shape of the curve (RQ3).

The analysis of volatility (RQ3), a general measure of how flexible a participant is in exploring different parts of a representation in relation to each other, showed that novices (mean = 0.33) had lower volatility values while navigating graphical representations (experts mean = 0.38).

For equations, experts made significantly frequent long transitions (mean = 6.58, S.D. = 1.39; mean proportion = 48.92) than novices (mean = 3.95, S.D. = 1.06; mean proportion = 30.62) at $p = 0.001$. Novices also showed a significantly lower mean volatility index of 0.25 (S.D. = 0.09), in relation to experts' mean value of 0.33 (S.D. = 0.05) at $p = 0.05$, while observing chemical equations (RQ3).

For the balancing task (RQ4), there was no difference between experts and novices in terms of the proportion of long transitions (experts mean percent = 26.82; novices mean percent = 26.4). The proportion of long transitions for both the groups were consistently lower than in the categorisation task. The two groups did not vary in terms of volatility values: For experts, the mean was 0.47 (S.D. = 0.09); whereas for novices it was 0.41 (S.D. = 0.05). However, unlike the long transition values, the volatility values are consistently higher for both the groups than those observed in case of the categorisation task.

4.1.6 Discussion

Experiment 1 results establish the following (RQ5):

1. There are significant differences between the two groups in their attention patterns, nature of transitions and general parameters such as volatility. This suggests that different cognitive mechanisms are at work in the case of experts and novices.

2. Based on the (i) level of training in chemistry, (ii) ER integration abilities identified during the categorisation task, and (iii) differences in the gaze parameters, it can be concluded that experts' gaze behaviour is a marker of the change in cognitive mechanisms leading up to ER integration in chemistry.

3. A comparison of the transition and volatility values for experts across the two tasks shows that the presentation of equations out of the ER integration context does not trigger similar cognitive mechanisms; hence, ER integration is context-specific.

4.2 Experiment 2

The first experiment successfully identified the sensorimotor markers of the changes in cognitive mechanisms during ER integration. Experiment 2 aimed at understanding how these cognitive mechanisms develop through chemistry training. It involved giving the categorisation and balancing tasks to two more groups of participants viz., 7 pre-university students (code-named PU; 2 female) and 7 chemistry graduate students (GS; all male), to identify their ER integration abilities as well as related gaze behaviour, in comparison to the experts (FC) and novices (UG) from the previous experiment.

The tasks, methodology and data analysis steps taken were exactly similar to experiment 1. Data from both the experiments were compared to understand how ER integration ability (RC), constitutivity and changes in cognitive mechanisms develop, thus making the project a cross-sectional investigation.

4.2.1 Major findings

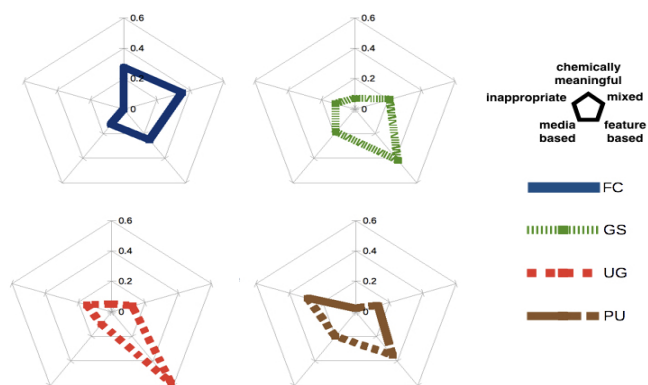Figure 4.2 below presents the overall trends across the groups in the categorisation task.

Figure 4.2 Radar charts showing cumulative proportion trends of category types. Each corner of a pentagon radar plot represents a kind of ER category as indicated in the top right corner.

Starting from participants with less experience in chemistry (PU and UG) to those with more experience (GS and FC), the radar plots show a clear shift from a largely media and feature-based categorisation scheme to a more conceptual one. The doctoral (GS) and undergraduate (UG) students both show clear tendencies towards feature-based categorisation schemes, whereas both the professors (FC) and pre-university (PU) students tend to be more diverse in their categorisation schemes, although in considerably different ways. The comparison of gaze behaviour data between the groups revealed considerable qualitative as well as quantitative differences in ER navigation. For instance, undergraduates recorded significantly more saccades per scene than all the other three groups. In terms of specific saccades, i.e. gaze transitions, across graphical representations, chemistry professors transited more frequently between the curve and the Y-axis by a considerable margin than between the curve and the X-axis, whereas undergraduates showed the exact opposite pattern. However, both the doctoral students and pre-university students transited equally often between X-axis and curve, and Y-axis and curve. FC, thus, appear to be interested in deriving meaning from how the dependent variable

(curve shape) is responding to the independent variable (Y-axis; process dynamics – RQs 2 and 4), while UG may be trying to figure out what would the response be. For GS and PU, the transition proportions are inconclusive, as it is not clear if they are deriving or predicting the behaviour of the curve, by treating values on the Y-axis independent of those on the X-axis. It could also be that they are corresponding between specific features of the curve with values on the X-axis.

While viewing equations, chemistry professors (mean = 48.92, S.D. = 4.23), doctoral students (mean = 51.36, S.D. = 4.08) and pre-university students (mean = 53.08, S.D. = 3.83) performed significantly higher proportion of long transitions than undergraduates (mean = 30.62, S.D. = 1.58). Undergraduates also recorded the least volatility values (mean = 0.28, S.D. = 0.09), indicating that they hesitated to move between different parts of the representations. Chemistry professors (mean = 0.36, S.D. = 0.05) and doctoral students (mean = 0.37, S.D. = 0.1) were moderately volatile, while pre-university students reported the highest volatility index (mean = 0.39, S.D. = 0.07). Though not statistically significant, this difference is indicative of a trend of stability and is consistent with the categorisation trends.

For the balancing task, there were no differences between the groups. The four groups did not differ in terms of volatility measures either, while viewing the different components of unbalanced equations.

4.2.2 Discussion

1. This project brings together perspectives on ER integration, perceptual learning and constitutivity. It holds that perceptual learning could emerge with constitutivity. Markers of perceptual learning based on training in science thus are markers of changes in cognitive mechanisms associated with integration.

2. The categorisation results indicate a clear developmental pattern in ER integration across the four groups. Professors have the highest ER integration abilities, followed by graduate students, and undergraduate students. The pre-university students show the lowest ER integration abilities.

3. The eye-tracking reveals a weak pattern of development. It was expected from the results of experiment 1, and the categorisation trends among the four groups in experiment 2, that the pre-university students would exhibit significantly different values in comparison to the professors. In contrast, undergraduates always exhibited significantly different gaze behaviour in comparison to the other three groups, and were at one extreme of the continuum. The pre-university students often exhibited gaze behaviour similar to those of professors; whereas the graduate students exhibited moderate values across parameters.

How can this pattern be explained? The PU group had just studied general chemistry, so it was fresh in their minds. While in the case of undergraduates and graduate students, the ER integration system appears unstable and undergoing disruptions because of exposure to a lot of new representations and conceptual knowledge. In the case of FC, experiences with chemical ERs have settled into relatively stable internal models. This is perhaps one reason why PU and FC exhibit most stable and less skewed/diverse categorisation trends, while UG and GS are somewhere in between and show strikingly skewed categorisation indicating sharp tendencies towards certain grouping schemes. The development of expertise and ER integration seem to follow a pattern similar to the 'development as a complex dynamic system' model (Smith & Thelen, 2003), which shows that well-learned sensorimotor skills can deteriorate when further skills are learned.
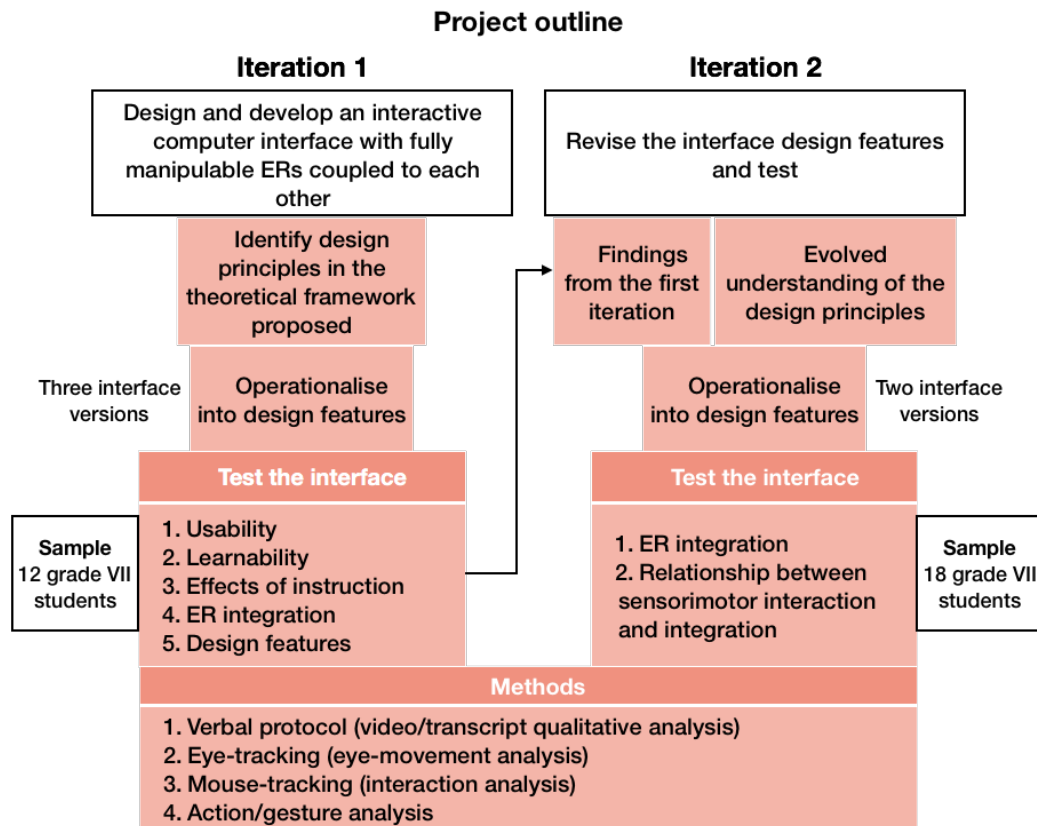
4. Overall, the eye-movement behaviour as well as the instances of epistemic actions suggest that expertise is accompanied by a fine-tuned sensorimotor system, which is: (i) oriented towards picking up maximum information from an external representation, and (ii) recruited for task-specific reorganisation of information to facilitate problem solving. The results thus confirm the first conjecture, that ER integration is accompanied by changes in the sensorimotor system.

5. Once fine-tuned through ER-based training, the sensorimotor system is activated or simulated on encounter with ERs, resulting in distinct sensori-motor behaviour (Barsalou et al., 1999), in this case the gaze. This claim is further supported by findings from the balancing task, which indicate that the revised sensorimotor pattern is not activated outside the ER integration context – thus refuting the alternative explanation of changes in the sensorimotor system as a general epi-phenomenon.

4.2 Limitations

1. Although the study involves collection and analysis of a huge amount of eye-movement data, the sizes of the participating groups are small, so the results are not confirmative from the point of view of statistical testing. The results are thus only indicative.

2. Another major methodological issue is that the eye-movement data in relation to dynamic ERs (animations, laboratory videos) were not considered for analysis. This is because the generation of eye-movement data, as well as processing algorithms, are notoriously unreliable when dealing with dynamic stimuli (ERs), and have recently been shown to perform barely above chance (Andersson et al., 2016). Moreover, analysing this type of data is extremely time, effort and computation intensive.

3. The project attempts to identify sensorimotor markers of the ER integration ability and its development. Similar to most previous experiments, including those replicated in this project, this project does not investigate the influences of (or interferences caused by) conceptual knowledge on ER integration. It is not clear how conceptual knowledge and ER integration are related; that problem is out of the scope of the aims of this project.

Chapter 5: Can manipulation of enactive ERs lead to integration?: exploring the relationships between interactivity and ER integration using a design-based research model

Project outline

Iteration 1

Design and develop an interactive computer interface with fully manipulable ERs coupled to each other

Identify design principles in the theoretical framework proposed

Three interface versions

Operationalise into design features

Test the interface

1. Usability
2. Learnability
3. Effects of instruction
4. ER integration
5. Design features

Sample 12 grade VII students

Iteration 2

Revise the interface design features and test

Findings from the first iteration

Evolved understanding of the design principles

Operationalise into design features

Two interface versions

Test the interface

1. ER integration
2. Relationship between sensorimotor interaction and integration

Sample 18 grade VII students

Methods

1. Verbal protocol (video/transcript qualitative analysis)
2. Eye-tracking (eye-movement analysis)
3. Mouse-tracking (interaction analysis)
4. Action/gesture analysis

This chapter discusses a project to test the second conjecture – sensorimotor interaction would support ER integration and its development. The project involves the design, development and testing of an interactive computer interface, with fully manipulable ERs of a physical system, as an intervention to help learners achieve ER integration. The system allows learners to interact with and control coupled ERs of a phenomenon (oscillation) in their static as well as dynamic states.

The study initially sought to build on the first project, using ERs in chemistry. However, interaction with chemical ERs is complex and counterintuitive, at least for a novice learner (e.g. interaction with real chemicals is often not possible, direct interaction with molecules is impossible; chemical ERs are relatively abstract, and 'acting' on them is a conceptual matter). It thus seems difficult to dissociate

conceptual understanding and ER integration in case of chemical representations. Also, it is nearly impossible to find naive subjects who can process representations in chemistry without understanding any of the chemical concepts. For these reasons, I chose to explore a simple physical system and its representations, where learning the relationship between ERs can happen without requiring conceptual understanding. Oscillation and the ERs related to it were found to be ideal, as one could interact with the ERs physically/virtually at a more everyday world level, in contrast with, say, interacting with molecules. The pendulum is also a physical system with simple dynamics and a trigonometric equation that is relatively easy to understand. The primary motivation for this multi-representational interactive simulation interface is achieving RC or ER integration, and not conceptual understanding, although the possibilities of the latter are not denied.

The interface design focuses exclusively on helping students with ER integration and RC development, based on the conjecture that ER integration builds on (biological) sensori-motor integration. Conceptualisation (used synonymously with conceptual integration in this dissertation) is a more complex process (figure 5.1).
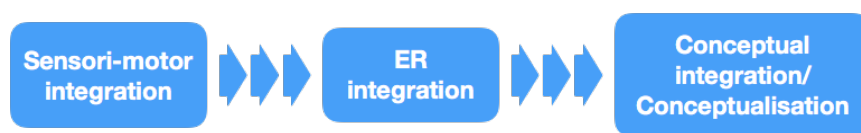
Figure 5.1 Conceptual hierarchy of cognitive processes involved in learning. There may be a continuum of processes with feedback loops in between them.

This conjecture is consistent with our theoretical account, particularly with the idea of constitutivity, in that it expects ERs and a learner's sensori-motor interactions with them to help constitute conceptual understanding. As discussed earlier in section 1.2, sensorimotor integration is entailed in motor actions, and hence also in learners' interaction with the ERs. The idea of constitutivity proposes that ERs, and the sensorimotor interactions with ERs, constitute ER integration and conceptual understanding. ER

integration and conceptual understanding are thus built on one of the most fundamental integrator systems of the body – the sensorimotor system. It is possible that the three processes (sensorimotor integration, ER integration and conceptual integration) are related with each other not directly, but in more complex ways. However, a study of their inter-relationships requires more theoretical work, and is out of the scope of this dissertation.

Grounded in the conjecture relating the three integration processes with each other, we designed an interface specifically for ER integration, and not conceptual understanding, although conceptual learning may happen as a collateral effect. Further, our interface design is rooted in the TUF model, as it interconnects the dynamics embedded in the three ERs of a simple pendulum system: a dynamic simple pendulum, its trigonometric equation, and a frequency graph. Thus, unlike simulation models with similar elements such as Net logo (Wilensky, 1999), PhET (Perkins et al., 2006) and SimQuest (van Joolingen & de Jong, 2003), our design is derived from basic research, particularly education research examining ER integration, and our own theoretical account based on recent models of cognition from the distributed and embodied cognition perspectives (Pande & Chandrasekharan, 2017). One central feature derived from basic cognition research is the full manipulability of all the ERs in the interface, *including equations*, which is a design requirement emerging from the theoretical model, as the model suggests full manipulabiliy would promote integration of ERs. This design principle is derived from an embodied cognition idea – that actions and manipulation, and feedback based on these, i.e. motor control, requires integrating multiple cognitive and perceptual inputs as well as feedback loops, suggesting that actions and manipulations performed on ERs in an interface would trigger/prime the neural processes involved in integration of inputs, which would in turn help in integrating the ERs as well. This line of thinking led to making the equation components manipulable. This theoretical approach also introduces the controller role of the equation, where the full manipulable equation acts as

a controller for the states of the other ERs, a feature not seen in standard simulation models mentioned above, which do not present the equation as a manipulable entity fully connected to other manipulable ERs. In this design, students control and 'enact' the equation, and integration is hypothesized to result from this control feature. Testing the development of ER integration based on this design thus also involves testing these hypotheses, and by extension, the cognitive theory that underlies it.

This study employed a design-based research (DBR) approach, involving iterative cycles of design, development, deployment/testing, analysis and redesign (Wang & Hannafin, 2005). It emphasises an iterative research process, where the theories, design principles and (technological) solutions systematically evolve across iterations, 'leading to a better understanding of the process of intervention' (Amiel & Reeves, 2008). The main research goal of this work was to test whether a naïve student can understand the relationships between dynamically linked ERs and integrate them through embodied interactions. Another major objective of this project was to develop an effective strategy (or set of strategies) to analyse student interaction with the interface, to unearth patterns of behaviour, primarily related to gaze and mouse-control, that could be possibly linked with ER integration/RC. The project involved two design-testing iterations, where findings, specifically related to interactivity-related design features, from the first testing phase were used to revise the design in second iteration.

The following are specific research questions this project sought to answer.

- After interacting with the interface, can naive learners imagine and describe the dynamic relationship between the following ERs of an oscillation system:

    ○ simulation of a physical system and its graph,

    ○ simulation of a physical system and its equation, and

    ○ equation and graph?

- What patterns of interaction are related to successful ER integration? How are interactivity and ER integration related?

- What kind of interactivity is desirable for ER integration?

In the next sections, I summarise the two design and testing iterations.

5.1 DBR iteration 1

5.1.1 Interface design

The first design iteration of the interactive computer simulation interface consisted of three versions (1.0, 1.1 and 1.2). In the dissertation, I explain in detail how each version evolved. The final interface version 1.2 of this iteration includes: (a) simple 2-dimensional representations of a pendulum, (b) a general form of the equation for the motion of a simple pendulum, followed by its specific form where the initial angle and length are variable/manipulable within a defined range, using sliders for each of them (-45 to +45 degrees for angle; 0.1m to 1.5 m for length), and (c) sine-curve presented at the bottom. Figure 5.2 below depicts a screenshot of our interface.
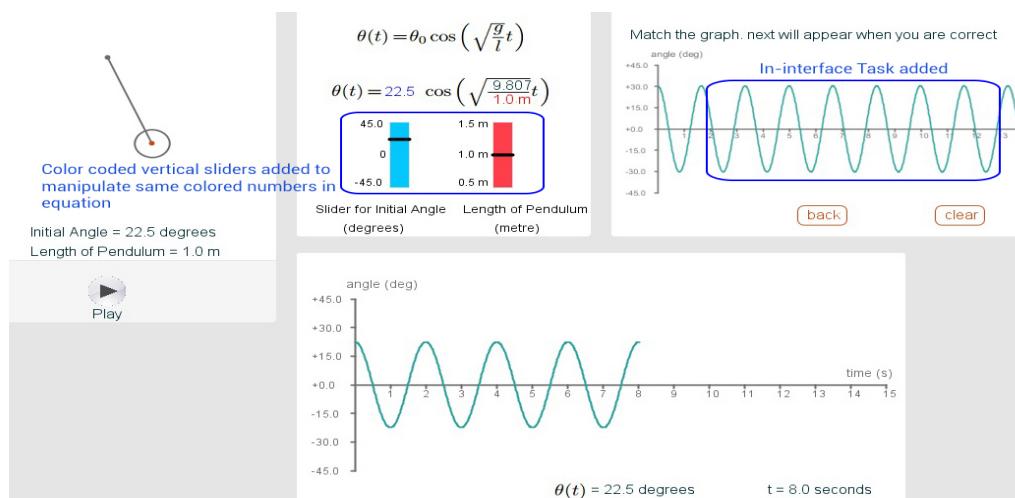
Figure 5.2 Interface version 1.2 with all the three representations and a task (the sine-wave in the top right corner). From screens 1-3, respective instructions would appear in the place of tasks. The colours of the values in the equation match the colours of sliders to maintain uniformity of meaning.

The main design principles were complete manipulability of all the ERs on the interface, and providing a sense of control to the learner (Kirsh, 2010; Kirsh & Maglio, 1994; Chandrasekharan, 2009). They are discussed in Majumdar et al. (2014) and reproduced in Table 5.1 below.

Table 5.1: Design principles and their operationalisation into design features.

Principle	Operationalisation
Different representations provide different but complementary perspectives about a phenomenon (Ainsworth, 1999 & 2008).	The interface has three representations of the oscillation phenomenon – a simple pendulum, an equation and a graph.
External representations allow processing not possible/difficult to do in the mind (Kirsh, 2010).	The interface has three representations. The simulation plots the graph of the equation of the pendulum for various lengths and initial angles of the pendulum in real time, thus simulating the corresponding states of a representation into others.
Cognition emerges from ongoing interaction with the world (Brooks, 1991).	The interface is fully manipulable, i.e., the learner can control the pendulum, equation and graph, to see how change in each affects the other elements.
Action patterns can activate concepts, hence actions and manipulations of the representations should be related to existing concepts (O'Malley & Soyer, 2012).	The learner can interact with the pendulum by changing its length/initial angle by clicking and dragging the mouse. The parameters in the equation can be changed by clicking and dragging the sliders up and down. The interface seeks to make the learners do actions that mimic the behaviour of the system, so that the system can be 'enacted' - the learning is thus through a form of participation with the system.
Features of the world are used directly for cognitive operations. Hence the interface features should support integration directly (Landy et al., 2014).	The interface has the physical system, equation and graph, along with different numerical values. The dynamic nature of elements, and their interconnections are made transparent, so that learners can integrate across spatial-numerical and dynamic-static modes.
The active self is critical for integration of features (Reed, 1988).	The interface is introduced with a task-specific exploration phase in which the learner must perform a set of tasks requiring specific manipulation of the interface. It was hypothesized that these tasks were sufficiently complex in order for the learner to actively engage in the problem solving, resulting in comprehensive exploration and manipulation of the interface by the student, so that the three representations are integrated.
The interface should allow coupling of internal and external representations (Chandrasekharan & Nersessian, 2015).	The task requires student to match a given graph. Learners change the parameters of the pendulum/equation to generate the graph, and visually match the task graph to their graph. This develops learner's imagination and coupling between their internal model and the external representation.

The interface had six screens (The most recent version of the system is available here: http://bit.ly/pendulum_old). Screen 1 displayed the manipulable pendulum. Screen 2 showed the manipulable pendulum and equation/sliders, and screen 3 had the manipulable pendulum, equation/sliders and graph. The remaining three screens – 4, 5 and 6 had learning tasks. In each task screen, the instruction panel was replaced by a task panel, which displayed a screenshot of a pre-

simulated curve (corresponding to different settings/combinations of the length and initial angle of the pendulum), and the learners were required to manipulate the equation and pendulum to generate a curve that matches the given curve by playing/pausing the simulation as required. Screens 1-3 were the 'free-exploration' phase, as the learner is exploring the interface with no specific goal. Whereas screens 4-6 marked the task-specific exploration phase, where the learner explored the interface through the act of solving a task that required specific manipulation.

Grounded in the TUF model, the learning objective behind this interface was to help students develop:

- An enactive understanding of each representation (enaction).

- A dynamic understanding of equations and graphs ('unfreezing' static ERs – imagination).

- An ability to capture in imagination static states of dynamic ERs at will ('freezing')

- An understanding of equations as controllers.

- An integrated internal representation, consisting of the physical system, equation and graph.

5.1.2 Pilot testing

Iteration 1 focused on the evaluation of usability and learning effects of the system, through a two-group controlled study, with the broad goals of understanding: (i) whether an interface with guidance is better, in terms of exploration and integration, than an interface without guidance, (ii) how easy the interface and its features are to use (usability) and to learn (learnability), and (iii) what actions the various manipulation features afford.

12 students (6 female) studying in 7th grade from two urban schools in western India participated in this study. This grade level was chosen because the oscillation concept is not introduced at this level, and

the system thus presents only an ER integration problem to these students, and not a concept problem. Half the students (text-guided group; 3 female) received an interface which had text instructions of how to use the various manipulable features on the interface (e.g. sliders). The remaining students (self-guided group; 3 female) received an interface without these instructions. To understand their interaction process in detail, we recorded student eye movements and mouse movements and clicks using an eye-tracker. Video recordings of the sessions and researcher notes were the other data sources.

5.1.2.1 Methodology

Each participant sat in-front of a laptop, attached with Tobii X2-60 portable eye tracker (Tobii Technologies, Sweden), On calibrating the eye-tracker, the interface window was opened for student interaction. After interaction and the learning tasks, the student was administered six ER integration questions (see appendix 1 for examples of questions), where students were expected to establish correspondences between different static state(s) of representations, to test if s/he imagines or simulates the dynamics of the interface in absence of interaction (Schwartz & Black, 1999).

5.1.2.2 Development of interaction analysis strategies

In addition to how the mouse was moved during interaction with the interface, the focus was also on *the task-oriented movements of the eye* (and not how attention was captured by visual elements). Eye movements, in this approach, are treated similar to mouse movements, and are considered as sensorimotor actions that can lead to integration. Based on this view, a novel analysis strategy of eye movements as actions was developed, in order to understand how interactivity is related to learning. This analysis allows studying action patterns that are correlated with ER integration (as measured by ER integration tasks).

Tobii Studio-3.2 (Tobii Technology, 2014) was used to extract and process the raw interaction data. On the processed data, specific areas of interest (AOIs) were defined to further isolate and capture the gaze and mouse activity happening in those areas (figure 5.3).
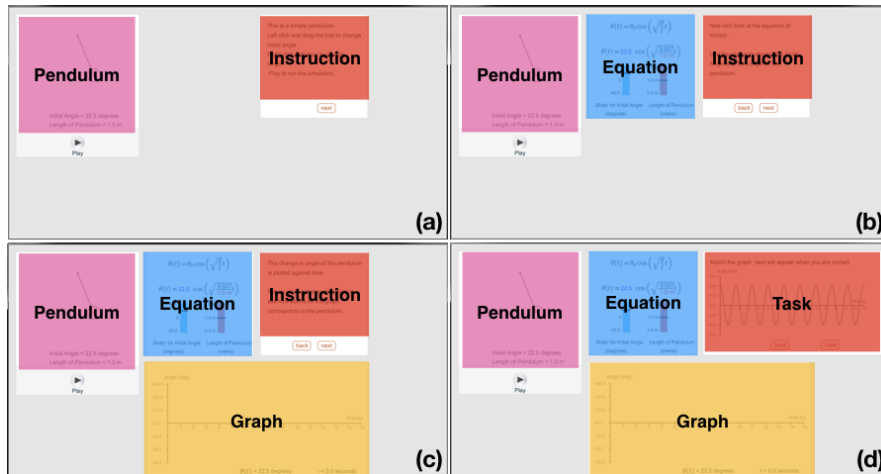

Figure 5.3 AOIs for: (a) screen 1 has two AOIs – pendulum and instruction, (b) screen 2 has AOIs for pendulum, equation and instruction, (c) screen 3 has four AOIs – pendulum, equation, instruction and graph, and (d) screens 4-6 all have four AOIs each – pendulum, equation, instruction and task. For the self-guided group, the instruction AOI was absent.

Using the AOI-based data, four levels of analysis were developed to account for interaction behaviour at different depths and extent of abstraction:

(i) Level 1 analysis provides data on spread of attention (e. g. total visit duration, visit count, mean fixation duration, fixation count, total number of mouse-clicks, mean number of mouse-clicks, etc).

(ii) Level 2 analysis tracked movement of participants from one AOI to the other. Sequences of fixation events and mouse click events are determined, and classified into – a perception-action cycle and a simulation-imagination cycle. It was postulated that, during these cycles, the participant would predict an outcome using a forward model (Schubotz, 2007; Rahaman et al., 2017) of the action (i.e. mouse click) performed during the interaction, as an active effort to understand system behaviour. This expectation can be understood as a mental simulation of the system, mediated by interaction with ERs (Pande & Chandrasekharan, 2017).

(iii) At level 3, level 2 fixation+mouse-click sequence data are processed, to define and compute markers that signify integration. An example of a marker is returns – identified as an A-B-A movement of the eye, where A and B are two different representations (AOIs). Such a movement indicates that the learner is retaining a particular feature in memory and returning to it.

(iv) Finally at the fourth level, process patterns of how the participants interacted with the interface are generated from level 3 data, using a graph theoretic framework such as a transition diagram, wherein the AOIs are the nodes and the transitions between the various AOIs are the weights of the branches. Level 4 in the present analysis also focuses on defining and computing interaction parameters specific to the simulation/imagination cycle of interaction (e.g. volatility-like measures).

5.1.3 Major findings and discussion

The results of our evaluation are reported in detail in the thesis, and also in Majumdar et al. (2014), Kothiyal et al. (2014) and Pande et al., (in preparation). Briefly, eye and mouse tracking data showed that learner exploration is richer and more diverse (i.e. learners manipulated all the elements) when there are instructions on the interface than when there are no instructions. Learner exploration during the performance of tasks was richer and more diverse than learner exploration before the tasks were presented (table 5.2). Student manipulation increases when the task is presented, which we hypothesise facilitates ER integration. Instructions and specific tasks, thus, were critical to rich learner interaction with the interface.

Table 5.2 Relative explorations of participants in text and self guided conditions in comparison with an ideal case. Direction of the arrow indicates frequency (up = increased, down = decreased).

Exploration	Screens 1-3 (free-exploration)		Screens 4-6 (learning tasks)	
Activity	Look	Click	Look	Click
Good/ideal	↑	↑	Focused ⬤	↓

Text-guided group	↑	↑	↑	↓
Self-guided group	↓	↓	↓	↑

Learners tended to focus more on certain representations, possibly because of familiar and more intuitive features (e.g. pendulum), while ignoring other representations, perhaps because of the difficulty to discover the various affordances or action possibilities offered by those features (e.g. sliders).

In addition, it was decided to add a qualitative follow-up interview component to the study and revise the ER integration questions to further probe our goals, as the six questions seemed insufficient in capturing student imagination. These tasks could also be integrated into the interface for easy deployment, without altering the actual settings of the experiment, and for digitally logging the answers provided, which can then be subjected to an automated analysis.

5.2 DBR iteration 2

The results from the first iteration showed that in order to motivate desirable exploration of the interface (where learners explore and manipulate all representational elements), and to effectively test integration, changes were needed in the interface. Some of the required changes are summarised below:

(a) The interface needed instructions regarding the manipulation affordances of all the representational elements.

(b) The learners needed specific tasks, doing which would require participants to manipulate all the representational elements.

(c) All the interaction affordances must be equally familiar (or unfamiliar) to the students so that they don't gravitate towards using one.

(d) More ER integration questions needed for effective testing.

(e) These questions should be integrated within the interface for perceptual compatibility reasons.

Figure 5.4 below presents the redesigned interface (version 2.1) from this iteration. Highlighted in red-coloured borders are the new or modified features informed by findings from iteration 1.

Figure 5.4 Screenshot of the computer interface version 2.1 with all 3 representational modes and a task. The instructions and back, next and clear buttons, the bevel buttons (as opposed to sliders from the earlier interface version), the learning task are highlighted with red borders. Clicking and dragging the bevels would change respective values in the equation.

5.2.1 Testing methodology

18 students (9 female, age range ~11-13 years) studying in 7th grade from an urban school in western India volunteered to participate in the study. All the participants preferred Marathi as the language of instruction during the experiment. Written consent was obtained from at least one parent of each child.

The experiment protocol was similar to the pilot study, except that detailed interviews were conducted this time with all the students, to further probe students' reasoning and cognitive processes involved in solving ER integration questions. Below is the schematic of the experiment sequence:

Start >> Introduction to the setup >> Eye-tracker calibration >> Interaction with the interface >> Relax >> ER integration questions >> Relax >> Interview >> End.

During the interview the researcher walked the participant through each question and reminded her about the answer she provided, while the student reasoned about why s/he chose that answer.

5.2.1.1 Data analysis strategies

A coding scheme was developed to analyse the interview transcripts (statements tagged with gesture/action data) to identify the accuracy as well as patterns of reasoning while answering ER integration questions. Three categories of student reasoning, in relation to the learning objectives of the interface, emerged out of the transcript analysis: (1) Simulation-based reasoning involving descriptions of ER dynamics and correspondences between them, (2) Feature-based static understanding of the ERs and their relationships, and (3) Static understanding based on spatial operations performed on the ERs such as superimposition, spatial extension, etc. These categories are hierarchical. Students were categorised into three performance categories: Good, intermediate/partial and poor integrators.

For the gaze data, we report analysis only at levels 3 and 4, as these are directly related to understanding (inter)action patterns. Two general measures at level 4 were devised: (a) Average spread = average number of AOIs visited between mouse clicks, and (b) elasticity = 1*(average number of A-B-A returns)+2*(average number of A-B-C-A returns).

5.2.2 Findings

The good integrators extensively reported the dynamics of ERs while mapping between the pendulum and the graph. These students exhibited a good understanding of the behaviour of different graphs that were shown during the ER integration questions, including those not related to oscillation. In a few cases, dynamic behaviour of ERs or the system was reported verbally even when answering the question did not require doing so. The partial integrators relied more or less equally on the three reasoning categories, whereas most poor integrators exhibited either a feature/number mapping-based

reasoning or performed irrelevant spatial operations on the ERs to establish relationships between them, without any attempts to map spatial and numerical components with the system behaviour.

Between-group gaze data comparison at levels 3 and 4 revealed the following three major findings:

5.2.2.1 Integration is correlated with interactivity

The interactivity values for levels 3 and 4 parameters suggest that good integrators had the richest interaction with the interface, followed by poor integrators, whose values are slightly lower. The average integrators had the least diverse interaction with the interface. Figure 5.5 presents how the overall spread+elasticity patterns varied for the three performance categories as the student interaction with the interface progressed. Across screens and tasks, good integrators exhibit a strong trend, with a drop in interaction during the learning tasks, as compared to screens 1 and 2. For average and poor integrators, although the overall nature of their interaction with the interface does not seem to vary significantly between the screens and tasks, a weak pattern exactly opposite to that of the good integrators is noticeable, with an increase in activity after transit from screen 3 to task 1.
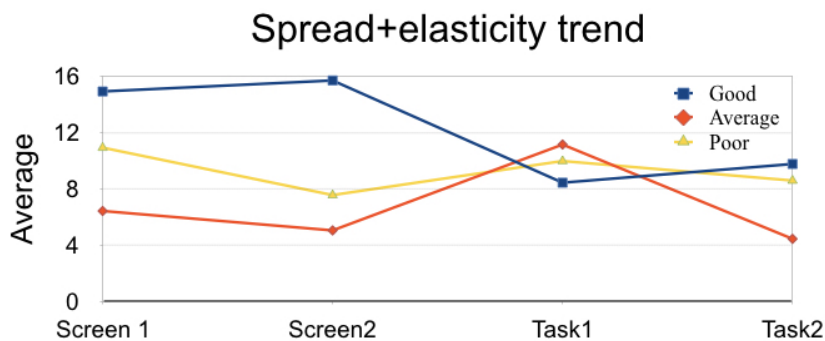

Figure 5.5 Average spread+average elasticity trends of good, intermediate and poor integrators.

The trends match the ideal gaze behaviour patterns (revisit table 5.2), suggesting that interactivity and ER integration are positively related, and interactivity is necessary for integration.

5.2.2.2 Interactivity does not guarantee integration

To dig more into the correlation between patterns of reasoning and patterns of interaction on the interface, four participants (2 good and 2 poor integrators) who were able to articulate the reasons for their answers clearly were selected for detailed interaction analysis at level 4, in terms of transition and return networks (similar to those presented in section 5.1.5). This was because such computer interfaces are expected to develop learners' implicit understanding of the target domain, and we wanted to examine learners who were able to make their implicit knowledge explicit, and describe what they had learned from the interface.

No differences in the A-B transition and A-B-A return networks were observed between the good and poor integrators. Both low and high performers were found to have similar interaction patterns, indicating that participants who could not integrate ERs interacted with the interface in ways qualitatively similar to those employed by good integrators. This suggests that high interactivity did not always lead to integration.

5.2.2.3 Integration has no unique pattern of interaction

The return patterns of these four students showed that their interaction patterns varied qualitatively in terms of emphasis laid on the different representations and the sequence of looking and clicking. Importantly, these are individual variations and not just variations between the performance categories. These strong individual differences within groups suggest that there are multiple patterns of interaction among good integrators as well as poor integrators. This suggests that not only are there multiple patterns supporting integration, but also that the same interaction pattern can lead to different integration performance (good or poor). The results imply that there is no unique or "ideal" interaction pattern that can guarantee integration.

In summary, these findings indicate that the relationship between sensorimotor interaction and ER integration is more complex than assumed in conjecture 2, and may involve other factors such as facilitation by a teacher, context, etc.

5.3 Limitations of the study

1. Students in this study experienced a simulation intervention for about ten minutes with minimal instruction. Future studies could investigate whether (a) a longer exposure to the interface would help ER integration more, and (b) would it be possible for a teacher to integrate this computer interface with the existing classroom dynamics, to scaffold ER integration.

2. The intervention and assessment modules are presented separately in the current interface. Students interact with dynamic ERs but are presented with static ERs during the assessment (ER integration questions). This design allows investigating how students imagine based on the static ERs, but does not provide information on how they would use interactions in the simulation to solve the problems. An ongoing revision of the design seeks to include both static image based tasks and simulation based tasks.

Chapter 6: Concluding remarks

6.1 Summary

The theoretical and empirical work reported in this dissertation focuses on ER integration, which is central to RC – a critical skill in learning science, mathematics and engineering. I argue that a theoretical account of ER integration, based on recent developments in DC and EC, taking into account the constitutive character of ERs, is needed, particularly to (a) understand the cognitive mechanisms underlying ER integration, and (b) develop design guidelines for developing new enactive media interventions. As a first step to develop such an account, I reviewed the theoretical frameworks proposed for ER integration as well as RC development, and related studies within and across the STEM domains (chemistry, biology, physics, mathematics, engineering). The review revealed that existing accounts and approaches to ER integration are primarily rooted in information processing theories of cognition, particularly cognitive load-based models. Such accounts make the development of ER integration appear mysterious, as they do not seek to unravel the underlying cognitive mechanisms. Further, the computer interventions based on such frameworks consider ERs merely as tools to achieve conceptual understanding, and ironically end up helping offload some of the learner's cognitive processes to the computer screen.

To address the need for a state-of-the-art understanding of the cognitive mechanisms that support ER integration, I outline a theoretical account extending the idea of constitutivity. This model (the TUF model) focuses on the interaction between internal cognitive processes and external representations, applying and extending recent advances in distributed and embodied cognition theory. The account illustrates how learners incorporate ERs, by interacting with them using sensori-motor mechanisms. ERs thus gradually become part of, and thus extend, the cognitive system, as well as form and extend the internal model of the scientific phenomenon they represent. Further, activations of the sensori-

motor system during interactions with these ERs, or simulations thereof, facilitate 'freezing' and 'unfreezing' the different states of ERs in imagination.

These ideas predict that:

(1) The development of the ER integration ability (expertise) would result in a reorganisation of the cognitive system, particularly the sensorimotor system. This suggests the way learners perceptually access ERs would change after significant training in a domain.

(2) Sensorimotor interaction would support ER integration and its development.

To test these predictions, I developed two empirical projects. The first explored behavioural markers of sensori-motor mechanisms associated with ER integration. The second developed a novel interaction-based learning environment, and tested it extensively to understand the role of interaction in ER integration. Both empirical investigations treat eye-movements (or gaze) as actions similar to hand movements.

Project 1 concentrated on identifying gaze and other behavioural markers across various expert and novice populations, to understand the development of ER integration in chemistry. The results confirmed that, among the multiple variables at work, a sensorimotor change is critically associated with the development of ER integration. This sensorimotor component, in our sample, was identified as a tuning of the perceptual system, in the process of novices turning into experts (marked by changes in eye movements and gaze patterns while viewing ERs). This tuning helps in quickly and effectively picking up relevant information from the ERs. Interestingly, experts also appeared to 'simulate' the chemical phenomenon dynamics during their context-based encounters with chemical ERs, suggesting that expertise is supported by a close coupling between perceptual and imagination systems, thus

confirming the first conjecture. This study is among the first to objectively characterise the sensorimotor changes facilitated by training in a discipline.

The DBR project reported two design-development and testing iterations of a fully manipulable, interactive multi-representational computer interface. It was conceptualised to support integration of ERs at the middle-school level, based on the concept of oscillation. Results revealed that although sensorimotor interaction in general facilitates ER integration, high interactivity does not always lead to integration. As a corollary, there is no unique interaction pattern leading up to ER integration. This indicates that the relationship between sensorimotor interaction and ER integration is more complex than assumed in conjecture 2.

6.2 Educational implications

This research, particularly its unique perspectives on the problem of science learning, has many different implications. A few major points are discussed below.

Firstly, the conjecture that concepts are constituted by interaction with many ERs, and the converging results corroborating this model based on theoretical and empirical work, indicate that sensorimotor interaction supports ER integration. This suggests a shift towards manipulative-based pedagogies, particularly those utilising the potential of new-media as they make possible manipulation of ERs and observing effects in real time. They also allow coupling static and dynamic states of ERs at will.

Secondly, the proposed model provides theoretical justification for action-based learning. Recent research argues that (embodied) interactivity leads to learning, particularly manipulation based on new-media. But it is not clear how manipulation contributes to learning. One proposal is that the process of interaction associates the self with perception and memory, and this leads to better cognition (Hung et al., 2014). A second approach argues for constructionism (Papert & Harel, 1991), which is considered

as a new epistemology, where the central role of interactivity is the support it provides for collaborative building, of mathematical objects (using Logo) and complex systems (using NetLogo), based on manipulation-based programming. A recent third approach considers gestures in new computational media as similar to the process of gestures during the mathematical discovery process, which are hypothesised to be part of the mechanism that helps shift body-based intuitions (about possible results) into external symbolic proofs built using known and accepted mathematical structures (De Freitas & Sinclair, 2014; Sfard, 1991 & 2000). The constitution view argued for in this dissertation suggests that actions done on manipulatives help in learning because actions are inherently integrative in nature. Every action requires a complex integration process, bringing together objects, forward models and feedback from various channels (visual, tactile, proprioception). This integration process would be primed when manipulatives are used to interact with symbolic entities, and this priming would help integrate different symbolic components in imagination.

While this research suggests that interactivity is necessary for ER integration, it also shows that interactivity may not be sufficient. Our computer interface was very useful in understanding the 'controller' role of equations, where it is used to set the initial value of the variables. Once the oscillation starts, the equation works as a 'descriptor', as the variable values change as the simulation progresses, and this change is captured by the graph. However, the general equation embeds a third aspect, where it describes an idealised system that is true of all natural number values of the variables. This idealisation, and the process by which it is derived using modelling and deductive thinking, are not supported by our interactive system. This is because the system only presents an instantiation of the general description provided by the equation, and this simulation of the general system illustrates the oscillation behaviour for a range of values. The illustrated oscillation behaviour can be considered similar to the way teachers embody and simulate the dynamic behaviour using the blackboard and

gestures. This process may allow the student to extend the illustrated specific cases, to reach the general case. However, there is another process the teacher illustrates, where she derives the oscillation equation, where such inductive extension does not work. This process is not supported by current interactive systems. It is an open question whether the model-based reasoning involved in this process can be supported by interactive media, as the reasoning here proceeds using uninstantiated variables and general principles. These are integrated by the imagination process. This capacity may well be a unique affordance of the imagination process.

Finally, this research contributes to the work on the nature and markers of expertise. It also provides a possible way to interpret and explain the results from past as well as current studies on expertise.

6.3 Other contributions of the dissertation

1. The empirical projects reported in the dissertation are among the first to objectively characterise the sensorimotor changes facilitated by training in a domain. Findings from these projects and their conceptual background provide a fresh perspective towards theories of ER integration and expertise.

2. Our fully manipulable interface is one of the first theoretically motivated interventions targeting ER integration, by using interaction features emerging from DC and EC theories. It is among the few DBR projects studying the development of RC using eye and mouse tracking.

3. The idea of making equations manipulable, and using equations as controllers, is first proposed and developed in this work. All other existing simulation systems hide equations in code, and only allow discrete parameter changes. This feature leads to the fundamental insight that formal systems are best understood as dynamic systems that capture dynamic real-world behaviour continuously.

4. This work is the first study to systematically examine the relationships between interactivity, ER integration and learning. In contrast, most existing computer interventions assume interactivity is good,

based on design principles coming form usability and learnability paradigms in HCI (human-computer interaction) and educational technology design. The analysis presented here shows that usability and learnability design principles cannot be applied directly to the problem of learning complex representations and conceptual content.

5. The empirical work reported here led to the development of novel interaction-based methods to study problem-solving, using gaze and (inter)action tracking. The interaction analysis methods described in the dissertation are state-of-the-art, and emerged from dedicated collaborative work over the years with contributions from cognitive scientists, educators, computer scientists, teachers and students.

6.4 Limitations and future work

The work reported here only provides indicative data to support the conjectures related to the theoretical model, as the studies have the following set of limitations.

Firstly, when using eye-tracking technology, it cannot be known for sure if looking at something equals (consciously) processing it, as the gaze behaviour captured by eye-tracking may not always be related to the subject's cognitive processes. Inversely, changes in the cognitive processes may not always reflect as changes in gaze behaviour. Secondly, the statistical outputs of eye-tracking often contain systematic errors to a certain degree, arising out of individual differences in the calibration accuracy and precision. Finally, there is often loss of gaze data points due to several unavoidable factors such as blinks, proximity to the laptop screen, rapid head-movements, etc. However, such errors do not undermine the results as long as they are within a certain range, depending on the context of the experiment.

Secondly, part of the work reported is based on the conjecture that ER integration is cognitively more fundamental, as well as simpler, than conceptualisation. This conjecture grants that the process of conceptualisation, in relation to sensorimotor and ER integration, may involve many feedback loops, and that there may be many different phases in-between. Further research is needed to test this conjecture systematically, to answer questions such as: should instructional tools provide perceptual experiences related to learning content, before introducing concepts, to help students have a concrete cognitive base for better comprehension?

Finally, from a technology point of view, our interface design allows real-time (visual) observation of the changes in the ER or system behaviour resulting from manipulation. However, with the emergence of more embodied and immersive new-media platforms, the underlying instruction design principles and interface features can be fused with gesture-based control (Kinect, Wii, LeapMotion) and haptic devices, in order to imitate the kinaesthetic movement that students can feel in real time. This can result in a more holistic (multimodal) experience when they interact with physical objects. Further studies are need to compare the results reported here with those based on such different new-media platform-based interventions.

List of publications and awards

1. Pande, P., Kothiyal, A., Majumdar, R., Agarwal, H., & Chandrasekharan, S. (*in preparation*). Interactivity is necessary, but not sufficient, for imagination-based integration of external representations. **(Chapter 5)**

EARLI Travel Grant and Klaus Jacobs Foundation Grant 2017 (paper presentation at EARLI 2017)

2. Pande, P., & Chandrasekharan, S. (2017). Representational competence: towards a distributed and embodied cognition account, *Studies in Science Education*, *53*(1), 1-43. UK: Routledge. **(Chapters 2 & 3)**

Most viewed article from the issue

3. Pande, P., Shah, P. & Chandrasekharan, S. (2015). How do experts and novices navigate chemistry representations – an eye tracking investigation, In *Proceedings of EPISTEME-6,* 102-109, HBCSE-TIFR, Mumbai, India. **(Chapter 4)**

4. Pande, P., & Chandrasekharan, S. (2014). Categorization Of Multiple External Representations By Chemistry Undergrads: An Eye-Tracking Study, In *Proceedings of the International Science Education Conference 2014,* 1393-1415. NIE-Singapore. **(Chapter 4)**

Springer Best Paper Award Finalist 2014

5. Pande, P., & Chandrasekharan, S. (2014). Integration of multiple external representations in chemistry: a requirements gathering study, In *Proceedings of the 22nd International Conference on Computers in Education,* 732-737. Japan: Asia-Pacific Society for Computers in Education. **(Chapter 4)**

APSCE Merit Scholarship Award 2014

6. Kothiyal, A., Majumdar, R., Pande, P., Agarwal, H., Ranka, A., & Chandrasekharan, S. (2014). How Does Representational Competence Develop? Explorations Using a Fully Controllable Interface and Eye-tracking, In *Proceedings of the 22nd International Conference on Computers in Education,* 738-743. Japan: Asia-Pacific Society for Computers in Education. **(Chapter 5)**

7. Pande, P., & Chandrasekharan, S. (2014). Eye-tracking in STEM education research: limitations, experiences and possible extensions, In *Proceedings of The 6th IEEE International Conference on Technology for Education,* 116-119. Kerala: IEEE. **(Chapters 4 & 5)**

8. Majumdar, R., Kothiyal, A., Pande, P., Agarwal, H., Ranka, A., Murthy, S., & Chandrasekharan, S. (2014). The enactive equation: exploring how multiple external representations are integrated, using a fully controllable interface and eye-tracking, In *Proceedings of The 6th IEEE International Conference on Technology for Education*, 233-240. Kerala: IEEE. **(Chapter 5)**

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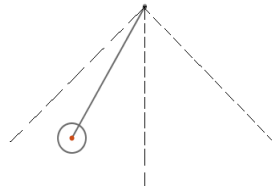
Appendix 1

Examples of ER integration questions in iteration 1 (printed sheet was presented to the student).

Example question 1: Where will be the pendulum when the end of the graph is as below?
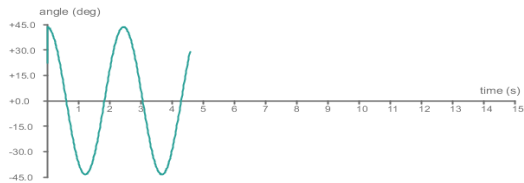
(a) 30 degrees left, (b) 30 degrees right (c) 30 degrees vertical (d) Exactly horizontal

Example question 2: The pendulum is at the point shown in the figure below. Where is this point on the graph?

You can mark the point(s) below: