INVESTIGATING MULTIMODAL INTERACTIONS FOR THE DESIGN OF LEARNING ENVIRONMENTS:

A CASE STUDY IN SCIENCE LEARNING

by

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To Thomas, who prompted me to strive for my dreams…

ABSTRACT

This thesis focuses on multimodal interactions for the design of a learning environment. The process of designing such systems involves studying the benefits of multimodal interactions in learning. Therefore, it analyses the structure of the interactive space between the learner and the content to be learnt, and introduces and tests a framework to structure it. It proposes that multimodal interactions can encourage rhythmic cycles of engagement and reflection that enhance learners' meaning construction in science concepts, such as 'forces and motion'.

The framework was the outcome of an iterative process of analysis and synthesis between existing theories and three studies with learners of different ages. Through these theory-informed studies, the significance of physical manipulation of objects and symbols through the employment of multiple modalities was emphasised as a way to facilitate learners' meaning construction, engagement and reflection.

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The words real-world and sensory modalities are used interchangeably.

The words symbolic and communicative modalities are used interchangeably

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Chapter 1 Introduction

This thesis focuses on designing a multimodal learning environment. The process of designing such systems involves studying the benefits of multimodal interactions in learning. Therefore, the thesis analyses the interactive space between the learner and the learning resources when technology is used. Learning can be influenced by interactive technologies, and this thesis studies the effects that multimodal interactive environments can have on learners. In particular, it proposes that physical manipulation with symbolic entities can augment learners' meaning construction.

For this thesis, learning is mainly approached from a constructionist point of view where learners 'dive' into situations to construct meaning. Additionally, learning is not considered as a merely cognitive activity, but also a physical activity, particularly as it requires the employment of multiple sensory and communicative modalities. Bearing in mind that linguistic and visual information has been studied by research in multimedia, this thesis studies the contribution to learning of additional types of information, such as information coming from other sensory modalities.

Whilst interacting with the world, people employ their sensory modalities; they may also need to employ these modalities while interacting with a supportive technology. In the educational domain, pupils may also be facilitated to understand scientific concepts when employing multiple modalities and these modalities are not only visual or linguistic. In particular, the use of touch and kinaesthesia is proposed as beneficial for learners when studying forces and motion.

A starting point for this research was that multimodal interaction is a crucial condition for the design of the technology that would support some types of learning. To explore such condition, a categorisation of modalities is proposed which purposefully organises and highlights the significance of sensory modalities in learning. Additionally, a theory-informed framework for multimodal interaction is put forward which investigates the circumstances that would prompt individuals to be engaged in specific learning tasks and exercise their reflective abilities. This framework synthesises research from a diverse, interdisciplinary background: research on needs and practices of education and more particular of the science classroom, educational technology research, considerations on human sensory modalities as well as the tools that computer engineering can provide, including research on human factors while interacting with technology.

The framework for multimodal interaction aims to structure the interactive space to be influenced by technology. From this structure, implications for designing learning environments are proposed, which are reinforced through experimental studies via a movement tracking technology.

1.1 The research approach

This research has followed a user-centred approach to the design of a learning environment. The user-centred design approach poses questions regarding the user, the task to be accomplished and the environment where the user will act (Faulkneur 1998). It also aims to define requirements of users, based on theoretical and user studies, and bases subsequent design decisions on these requirements (Noyes and Baber 1999). The user in this research is the learner of science. The task is to learn about 'Forces and motion' which is part of the national curriculum. The learning environment could be anywhere: the school lab, the summer camp, the park. However, a setting that is related to traditional education, i.e. a school lab, can enhance the student's ability to concentrate on an activity.

The research is centred on the learner. To understand learners' requirements, there is a need to understand what the learner has to do regarding the content to be learnt, the skills to acquire and the practices used already to achieve these skills. In particular, the specific questions to address are:

- From the curriculum requirements regarding learning about 'forces and motion', which are the specific issues which cause learners problems, and how are these problems dealt already within the science classroom (see section 2.3.1.1)?
- How is technology used already to facilitate the existing learning practices (see section 2.3.3)?
- How can science learning be supported by technology in a way that would keep learners engaged and provide them with opportunities to reflect (see section 2.4.2)?

Addressing these questions involves conducting a review, from which the use of combined multiple modalities emerges as key feature of science learning. Therefore, how the employment of multiple modalities has been considered by two research communities is explored: the Human Computer Interaction (HCI) community and the Educational Technology community (see 2.5).

In an attempt to accommodate the usage of the term 'modality' from both Human Computer Interaction (HCI) and Educational Technology (ET), a categorisation is proposed that distinguishes between the 'sensory' or 'real-world' modality and the 'communicative' or the 'symbolic world' modality (Chapter 3). Science learning at school is considered as an instance of the real world in which learners are introduced to the symbolic world. It is argued that for learners to interpret scientific symbols and concepts, their senses and real-world objects have a significant role. Such argument is explored through a framework which studies real-world interactions and symbolic-world ones (Table 1-1). It aims to structure the interactive space between the learner and the learning task with the aid of digital technology. Such interactions would happen in a different world, namely, the multimodal digitally enhanced world (M-DEW).

It is argued that M-DEW could support the interplay between concrete and abstract understanding. It is related to computational environments where "meanings can be constructed from an intersection of resources mobilised by actions, in which ideas become connected to existing understanding and activities" (Noss and Hoyles 1996). M-DEW could facilitate learners in constructing and negotiating emerging ideas, and in creating links between concrete understanding and abstract thinking.

<table>
<tr><th>Worlds / Modalities</th><th>Real World</th><th>Symbolic World</th><th>Digitally Enhanced World</th></tr>
<tr><td>Full access to real-world modalities</td><td>Manipulation of objects and understanding</td><td rowspan="3">Thinking of Representations and understanding</td><td>Physical manipulation of representations and understanding</td></tr>
<tr><td>Restricted access to real-world modalities</td><td>Watching and understanding</td><td>Watching dynamic representations being manipulated and understanding</td></tr>
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Table 1-1: The framework for multimodal interactions. Real-world modalities do not necessarily influence the symbolic world.

A series of experimental studies were also conducted aiming to study the interactions in real world and in M-DEW with different access to sensory modalities. These studies are explained in the next section.

1.1.1 Theory-informed studies

To specify a multimodal digitally enhanced environment and identify required features, data from learning situations is needed. Towards this end, three sets of studies with learners took place to reinforce the multimodal framework and specify the special features of the technology and the learners' activity. Initially, pilot studies aimed to familiarise the researcher with the procedures of each study and ways participants may be approached. Each pilot study led to a main study that explored specific issues of the multimodal framework proposed below. The contribution of teachers was important in all studies, both with suggestions of the content delivery and in checking the difficulty of the tasks.

The experimental studies are based on a comparison among learners who had full access to real-world modalities, those that had restricted access to real-world modalities and those that had even more restricted access to real-world modalities. The full access to real-world modalities consisted of physical manipulations, looking at the affects of their manipulations and reading and answering questions on the subject. A restricted access to real-world modalities consisted of looking somebody else manipulating, looking at the effects of the manipulation and reading and answering questions. Finally, the students that have even more restricted access to real-world modalities had to read about an action and its effects.

All studies had three phases: the initial questions, where the prior ideas of students were captured, the teaching session, where students did activities and recorded what they were doing in a recording sheet and, finally, a written test where the students answered questions about the learning aims of the study providing a summary of their learning. The final test was also the main means of analysis. The students' answers were marked and statistically compared in pairs based on non-parametric tests.

The results showed that learners who had the least access to real-world modalities had the poorest results: using static visual and linguistic cues was not enough to provide learners with enough cues to understand the learning task. On the other hand, learners with full access to real world modalities were able to reach the learning aims without difficulty and performed better than the previous group. Additionally, learners with restricted access to real-world modalities were in between: they tended to be better than learners with the least access and worse than learners with full access to real-world modalities. Such results suggest the multimodal framework can successfully describe learners' performance where learners with full access to real-world modalities have a richer and more enjoyable experience.

1.2 The aim of the thesis

The aim of the thesis is to propose how multimodal interactions with technology can benefit learners in their efforts to understand scientific concepts, such as 'forces and motion'. In particular, the significant role of real-world modalities has been identified which should be combined with symbolic modalities. For both set of modalities to be combined, a contribution of interactive technologies is suggested. Through multimodal interactions within a digitally enhanced world environment, learners have access to real-world and symbolic modalities that are related to the subject to be learnt. This multimodal digitally enhanced world (M-DEW) would augment real-world interactions with the ability to physically manipulate entities of the symbolic world. It would be a real world in which the learner can see digital effects; a conceptual environment where symbolic entities have direct referents to the real world.

To fulfil the aim of the thesis several steps need to be undertaken. An initial step is to set up research questions that would address the specific aims of the thesis. Then, there is the effort to answer them. The first research question refers to the task of science learning. To understand what learners have to do, there should be an understanding of the practices of science teaching and of the issues that confuse learners. So a question that arises is:

How do people learn science in the classroom and where do they face difficulties?

The second research question aims to describe the task of science learning through the perspective of multiple modalities. In particular the second research question would be:

How can multiple modalities be organised so that the task of science learning is described?

For the design of an environment to support science learning, a framework needs to be introduced to describe learners' interactions. So the third research question would be:

Can a Framework for Multimodal Interaction inform the design of learning environments to support science education?

One of the fundamental conditions for learning, which is also apparent in science learning, is learners' engagement with the learning task and their abilities to reflect. Therefore, learners' efforts to understand scientific concepts are related to their ability to be engaged to the learning task and to reflect on their activities. It is expected that learners' sensory and symbolic modalities have a significant role in learners' engagement and reflection. So the next research question would be

Do multiple modalities have an effect on learners' engagement and reflection?

The following chapters aim to answer the above questions. The starting point is Chapter 2, where a literature review of the constructionist approach in learning and computer-based learning is conducted. The aim is to explore how constructionist learning environments already facilitate learners. Furthermore, a survey of the classroom learning and teaching of science is conducted and how IT contributes to learners' meaning making. The aim is to address what modalities are used when and with what effects. Comparing multimedia to classroom learning, the richness of the latter appears to be due to the employment of not only symbolic but also sensory modalities. Thus, technologies designed from the multimodal perspective may be able to enrich the learning environment. The next section deals with multimodality and how the term 'modality' has been used by Human Computer Interaction and Educational Technology communities.

Aiming to associate existing usages of the term 'modality', a taxonomy is proposed in Chapter 3, which puts modality into different 'worlds' or environments where learners have to act or construct meaning. Such categorisation is viewed essentially as a useful model for facilitating the design of learning environments. Therefore modality in the real world would refer to sensory modalities through which everyday interactions take place. Modality in the symbolic world would refer to representations which are usually limited to be visual or linguistic. It is argued that there are more representations, e.g. kinaesthetic, tactile, etc. that could enrich interactions with the symbolic world.

Learning occurs in any of these worlds. 'Real world' learning could be seen as situated, informal, lifelong. 'Symbolic world' learning could be seen contextually as any learning situation which needs or uses symbolic descriptions of the real world. It involves abstraction as the main vehicle for manipulating it. From all the range of situations where learning can occur, classroom learning has been considered significant since it is a 'real world' situation where learners are introduced to the 'symbolic world'. Within the science classroom, in particular, pupils need to link descriptions of the real world to 'scientific' or symbolic terms. Science learning refers to the understanding and manipulation of symbols that represent aspects of the real world. Thus, some of the problems that learners have in science learning could be partially due to their problematic transition between real-world and symbolic world understanding or between concrete and abstract thinking.

For learners to interact with symbols and objects via their senses, a digitally enhanced world could be introduced. It is an environment where learners can interact not only with the technology provided but also with other, not digital, resources available. It would need to incorporate real-world interactions that create digital effects of how instances of the symbolic world are affected. The modalities of this world would be a range of real world and symbolic modalities that are important for learners' meaning construction.

Furthermore, in Chapter 4 the focus shifts from 'worlds' to learners' interactions within each world. The starting point of this framework is real-world interactions. Learners' interactions with objects are studied through research in object manipulation, and their impact in engagement and reflection. Subsequently, learners' interactions with the symbolic world are studied through research in external representations. The view of mental interactions with symbolic representations is extended to include physical interactions with them. It is argued that for situations where the representing concept is about changes in the environment, learners that are employed physically with representations will be engaged and able to understand the real substance of the concept.

For learners to be able to interact physically with symbolic entities, they could be supported by interactive technology. For learners to be able to interpret symbols' meaning and understand their usefulness in describing aspects of reality, they also need support on their activities. One of the focal points in learners' support of interactions is to strengthen the link between real world and symbolic world interactions. Coupling the physical activity with the relevant symbols and linking physical changes to symbolic variables is identified as a way to facilitate the smooth interplay from the real to the symbolic world and vice versa. To provide learners with access to such information, a synthesis of modalities from the real and the symbolic world within a digitally enhanced learning environment is suggested. In this multimodal digitally enhanced environment (M-DEW), learners have access not only to the teacher and the content material but also to information that fits personally to them through the use of their own modalities. Thus, to study physical interactions with symbolic representations, we focus on multimodal interaction within the digitally enhanced world. The technology employed within M-DEW does not have to be 'new'. As a matter of fact, existing technologies could be instances of M-DEW if coupled with activities to support the linking between real-world and the symbolic. Three issues are studied: the transition between real-world and symbolic world interactions, the impact of M-DEW in learning and the impact of M-DEW in the symbolic world. M-DEW is related to learning environments where actions and other resources facilitate meaning construction in which ideas become connected to existing understanding and activities (Noss 1997)

Finally, for the design of learning interactions within M-DEW, a set of features have emerged. These features provide requirements for learners' interactions that refer not only to technology but also to activity.

The issues proposed in chapter 4 are reinforced by experimental studies that are described in chapters 5, 6 and 7. In particular, Chapter 5 describes a study that took place in a school camp with 11-year-old children who manipulated objects to learn about the abstract concept of force. It regarded the usefulness of the categorisation of learning objects proposed in chapter 4 as well as the contribution of sensory modalities in children's engagement and ability to reflect.

The experimental study described in Chapter 6, took place in a school lab with 14-year-old pupils. The study investigates how the employment of multiple modalities can facilitate learners in constructing relations among movement and scientific symbols of motion within an instance of M-DEW. It investigates if links are built when learners physically manipulate symbols and how meaning is constructed through the coupling and the de-coupling of movement and its symbolic representation. Additionally the contribution of multiple modalities is explored in learners' engagement and reflection.

The experimental study described in Chapter 7 took place in a university lab with undergraduates. It addressed the ability of students to interpret kinematics graphs and link between two different representations of the same movement within an instance of M-DEW. Again the contribution of multiple modalities is studied in learners' engagement and in their abilities to reflect.

Finally, chapter 8 summarises the conclusions of this research and the answers to the research questions. It concluded that physical manipulation of objects and symbols can indeed facilitate learners' meaning construction, through the employment of multiple modalities which augment learners' rhythmic cycles of engagement and reflection. Additionally, interactions with the symbolic world could be enriched if they are augmented by real-world manipulations which could be synthesised within M-DEW: a model of an environment where learners can physically interact with symbolic entities.

Chapter 2 Learning and Multimodality: an interplay

2.1 Introduction

In this chapter, a literature review is conducted. Starting from constructionism, it examines constructionist educational technologies (microworlds), since it is suggested that have been designed to support learners' engagement and ability to abstract.

Furthermore, a review is conducted of the practices of the science classroom, the laboratory and when interacting with information technologies. It aims to illustrate that interactions in the classroom are mainly based on language and symbols to manipulate abstract data, whereas laboratory activities involve interactions with multiple modalities to handle real data.

Additionally, multimedia are explored since they aim to augment classroom learning by providing visual and verbal support by learners. Advantages and problems of learning with multimedia technologies are also explored: the advantages are related to interactivity, and complementarity. The problems are related with the extraction of generic principles for the design of multimedia environments.

In attempts to facilitate learning with computers, multimodal technologies may be able to enrich learning environments in ways that existing technologies could not by providing access to physical interactions and to information that was previously difficult to obtain. As an example of such interactions, data-logging activities are reviewed.

However, what is meant by the term modality is explored based in two interdisciplinary fields: HCI and educational technology. From these definitions, the need to build a bridge among the different uses of the term 'modality' is suggested and further explored in the next chapter.

2.2 About learning

For this thesis, learning is considered to be an active process in which the learner uses interactions with the environment and constructs meaning out of it. The learner, who is active (Dewey 1916) instead of a passive knowledge recipient, constructs meaning through interacting with the environment by using those modalities that are related to the learning task. Pupils have the constructivist role that many educationalists propose: they are people who decide what is meaningful and worthwhile to learn. To do so, learners need to know 'the reasons why' they have to learn these subjects, that is, they need to realise the relevance of the subject to their life and interests. Unless they contextualise the learning material, they may not be involved in using the knowledge that is to be constructed by them (Perkins 1992; Duffy and Jonassen 1992; Bruner 1973).

This thesis does not consider learning as the acceptance of knowledge, which exists "out there", but it involves the learner relating what they knew previously to the concepts under discussion. The learner needs support towards learning to learn, that is, the ability to ask questions, evaluate their strategies for answering them and develop answers to questions of the content domain. It is a kind of discovery learning but the 'knowledge' to be discovered is in the learners' activity, not in the text (Duffy and Jonassen 1992). So the learners could be engaged in scientific processes of discovery where they could apply successfully their understanding.

In such a constructivist learning environment, the available resources can scaffold learners' activity. Scaffolding refers to the gradual assistance by an adult to support learners to explore successfully a setting. However, the scaffolding metaphor could imply that there is a rigid structure that is used to construct, which could support the objectivistic idea that there is a specific knowledge that needs to be passed on the learner (Duffy and Jonassen 1992). In this thesis, scaffolding is considered as a type of support that facilitates the growth of the learner: through the ability to ask questions, evaluate strategies and produce answers, learners are learning how to approach problematic situations in a beneficial way (Bruner 1983). By realising that learning is about inquiry, learners are more likely to be personally engaged and interested in the activity and thus, construct their own meaning.

Additionally, the idea of "building knowledge structures" could be enriched by the idea of the learner being consciously engaged in constructing a public entity, whether it is a sand castle on the beach or a theory of the universe (Papert 1991). This idea has been shaped under the theory of constructionism initially proposed by Papert (Papert 1980).

Constructionism and constructivism have some common aims: they both highlight the processes by which people outgrow their current views of the world, and construct deeper understandings about themselves and their environment. However, constructionism extends constructivism by adding the additional feature that an external, shareable artifact is created. It stresses the connection between understanding and personal experience, particularly with respect to creating and experimenting with objects to learn about abstract concepts. Constructionism evokes the idea of learning-by-making (Papert 1991). It studies how knowledge is formed and transformed within specific contexts, shaped and expressed through different media, and processed in different people's minds (Table 2-1). Constructionists argue that learners are more likely to become intellectually engaged when they are working with personally meaningful activities and projects. Forming new relationships with knowledge is equally important as forming new representations of knowledge (Kafai and Resnick 1996).

	Constructivism (Piaget)	Constructionism (Papert)
Commonalities	children are the builders of their own cognitive tools, as well as of their external realities; knowledge and the world are both constructed and constantly reconstructed through personal experience; knowledge is not merely a commodity to be transmitted, encoded, retained, and re-applied, but a personal experience to be constructed; the world is not just sitting out there waiting to be uncovered, but gets progressively shaped and transformed through the learner's personal experience; the conditions under which learners are likely to maintain or change their theories of a given phenomenon through interacting with it during a significant period of time are studied.	
Differences	Construction happens 'inside' the learner's head	construction is publicly stated which can be manipulated and reflected upon with others
	the genesis of internal mental stability in terms of successive plateaus of equilibrium	dynamics of change stresses the fragility of thought during transitional periods points toward this fragility, contextuality, and flexibility of knowledge under construction. how different people think once their convictions break down, once alternative views sink in, once adjusting, stretching, and expanding their current view of the world becomes necessary
	looking at situations from a distance	stresses the "diving into" situations; Becoming one with the phenomenon under study is a key to learning and thus put empathy at the service of intelligence; studies how knowledge is formed and transformed within specific contexts, shaped and expressed through different media, and processed in different people's minds.

Table 2-1: Commonalities and differences between constructivism and constructionism (derived from (Papert 1991; Ackermann 2001)

2.2.1 Computer aided learning

Both constructivist and constructionism learning theories have provided the basis for the design of many learning technologies. According to Kearney and Treagust (2001), there is a shift towards constructivist software where learners are engaged collaboratively in open ended, exploratory learning environments and have the opportunity to construct meaningful knowledge. An example of such software makes use of interactive digital video clips of appropriate Physics demonstrations as part of a predict-observe-explain sequence (Kearney and Treagust 2001), so the learner is supported through interactivity and cognitive scaffolding.

Educational technology research offers many opportunities for learning-by-knowledge-constructing (based on constructivism) or learning-by-making (based on constructionism) by placing the focus not only on technology but also on pedagogical considerations. Whenever there are new ways to present information to the learner, technology provides education with more resources for learning. However, technology may be useless unless it is combined with pedagogical enquiries, which would inform technology designers about the ways learners need to be supported. Having access to information is only one requirement; the information would not become knowledge unless it is retrieved, evaluated and integrated by the learner. Educational technologies can be adaptive to the learner who would be guided, advised and offered explanations to 'discover' knowledge-bearing activities. Keeping in mind the limited resources of teachers, such technologies can support their efforts and offer assistance to promote one-to-one interaction with each student (Laurillard 1995).

An example of constructionist based technology is 'microworlds' a term initiated by Papert (1980), to describe children's interactions with a technology that focuses on the transfer habits of personal lives exploration to the formal domain of scientific theory construction (Papert 1980). The key feature of microworlds is the ability to build things and provide a crucial organising distinction between systems that put learners in the role of builder and thinker and those that place him or her in the role of listener or receiver (Hoyles et al. 2002). The early use of the term 'microworld' described the use of Logo programming language by the learner, however, later microworlds and other similar environments have been created using other computer languages and they did not involve programming by the learner (Edwards 1998). Such evolution, however, created debates about the usefulness of programmability as a vehicle for creativity and constructionist learning (Hoyles et al. 2002).

Microworlds are open-ended, exploratory computer environments where students need to translate mathematical or scientific regularities into computational procedures and objects. Computational objects stand on the boundary between the physical and abstract; learners can see them, move them, put one on top of the other. Yet, they are symbolic constructions (Turkle and Papert 1990). Through this translation students can explore abstract concepts, e.g. proportionality, in multiple ways: they can inspect and transform each tool and operation of the microworld in ways that make learners both users and designers (Hoyles et al. 2002). Text-based programs have been seen as the symbolic representations of mathematical functions as well as the glue that bounds all the representational modes together. If these functions can be accommodated by other entities, i.e. direct manipulative visual objects, that do not restrict learners' expressive power but broaden it, then the idea of microworlds has been evolved (Hoyles et al. 2002).

Microworlds aim to reveal and challenge students' current and partial understanding about a domain. They offer access to ideas and phenomena that students may not otherwise easily encounter (Edwards 1998). Learners' exploration is necessarily constrained by the model of knowledge domain that underlies the microworld, but such constraints are designed to promote learning (Noss and Hoyles 1996). Knowledge is not simplified but it is recognised as complex, interrelated and evolving in action (Noss and Hoyles 1996). Edwards (1998) has approached 'microworlds' in two views: the structural and the functional. The former focuses on design features that an instance of 'microworlds' has and the latter focuses on the ways that learners are actually use these environments. In particular, the structural features of 'microworlds' are summarised below:

- A microworld has a set of computational objects aiming to reflect the structure of mathematical or scientific concepts.
- A microworld links more than one representation of the underlying mathematical or scientific concept. A common feature of microworlds is to link symbolic and graphical representations.
- A microworld includes a set of activities which may be pre-programmed into the environment or instantiated in worksheets or verbal instructions, through which the learner is challenged to use the entities and operations to reach a goal, solve a problem duplicate a situation or pattern, etc.

Additionally, according to the functional approach, learners are expected to:

- Manipulate objects and execute operations instantiated in the microworld aiming to induce or discover their properties and constructing an understanding of the system as a whole. To reach such goal, learners would have to experiment, to generate hypothesis and test them or engage in open-ended explorations.

- Interpret feedback from these manipulations in order to self-correct their understanding of the domain. This feedback is often provided through linked representations.
- Use the objects and operations of the microworld to create new entities or to solve specific problems and challenges (Edwards 1998).

Considering the structural features of microworlds, they aim to provide learners with means to facilitate abstraction. The functional approacah on the other hand, seems to focus on ensuring that learners would be able to abstract and be engaged to the learning task. This experimentation-feedback cycle, which is a hallmark of computer microworlds when viewed from the functional perspective (Edwards 1998), can be seen as an interplay between engagement and reflection: while experimenting they are engaged and while interpreting the feedback they are reflecting. Learners can try out different relationships and evaluate them through the systems' feedback. The system's feedback is of great importance since it can be a fertile ground to embody the mathematical concepts into the turtle graphical environment (Papert 1980). However, feedback is not a panacea, as showed by later research. It is not necessary that the linkage between the concepts and the behaviour of computational objects, such as the turtle, will be associated, nor that learners will keep a distance from the environment to think ahead of problem solutions (see (Simmons and Cope 1997) for more on the effect of different feedback on learners).

To summarise, starting from theories about learning, microworlds were studied as a way to support learners' meaning construction through reflective and engaging activities on visual and symbolic objects. These environments have focused on mathematics and science as a testbed of their usefulness and effectiveness. In the next section, science education and the way it is communicated to learners at school is studied. The aim is to reveal the means of communication to learners and possible problems that they face during science learning tasks.

2.3 Science learning at school

This section studies how science is currently taught at schools: initially there is a review of practices in the classroom, followed by practices of practical work and IT in science. These have been identified as the main ways though which science is communicated to students; their problems indicate opportunities for intervention through interactive technologies.

In particular, in the classroom, interactions among learners and the teacher are mainly verbal which are augmented by graphical representations and manipulation of symbols through mathematics. Data handling occurs through abstract variables which are related to reality through the teacher. In the laboratory, on the other hand, interactions involve multiple modalities –including sensory ones – and data are collected and handled by pupils. Data however is not always successfully connected to the theory taught in the classroom. Many assumptions are taking place that could alter the experience of learners to simple testing which is not directly related to real life. Again it is the role of the teacher to ensure that such relations are strong.

Therefore a proposed computational environment to support science learning would focus on providing interactive features to employ multiple modalities as well as relate the collected data to abstract variables and the ways they describe real-world situations.

2.3.1 Teaching in the classroom

Teaching in the classroom involves a great use of language, either in a spoken or written form. It can have the form of questions and answers, generally the questions posed by the teacher and the answers given by pupils. Questions can be closed, involving factual recall, checking comprehension or if the pupil can directly apply the knowledge recalled. Closed questions require a short answer and rely on linear processes and logical reasoning, providing no opportunity to stray from the teacher's path. Questions can also be open where a number of different answers could be accepted. They provide greater opportunity for pupils to contribute an appropriate answer and therefore, are not threatening (Amos and Boohan 2002). They can also be diagnostic, to elicit what pupils already know or to check if pupils are following the teacher (Wellington 2000).

In classroom, the discourse of science contains many types of words - scientific, semi-scientific, non-technical - and for many students, the main obstacle in science is to learn its language (Wellington and Osborne 2001). Science education involves dealing with many words that gives them meanings in new contexts. Force in science, for example, is measured in Newtons and causes objects to change their state of motion or shape. In everyday life it has a much broader meaning as in 'she forced me to do it'.

Highly abstract ideas have no visual concrete referent and acquiring their meaning takes pupils a long time and a lot of practice. Acquiring abstract concepts' meaning is associated to their cognitive development and teaching should take into account the need to pay careful attention to abstract concepts' names (Wellington and Osborne 2001).

Apart from the ability to learn the scientific language, explanations are also an important aspect of the science classroom. A great deal of teachers' effort is to create a repertoire of different explanations. Explaining involves the ability to convey difficult scientific ideas without distorting their meaning or telling lies. It requires breaking down a complex idea or process into its smaller components, which involves identifying the underlying or prerequisite ideas and then sequencing them in a coherent way (Wellington 2000). Explanations aim to open a gap of understanding and create a difference e.g. between what is already known and what is new. It can use analogies or metaphors to transform ideas. Explanations do not use only language: they accommodate diagrams, gestures and any other resources the teacher decides to employ (Ogborn et al. 2002). Through explanations, the symbolic world is introduced to the pupils: it is not merely explaining familiar entities doing familiar things but also describing the unfamiliar in familiar terms, explaining unfamiliar events with familiar occurrences or introducing unfamiliar entities doing unfamiliar things (Wellington 2000). Explanations provide students with the resources they need to explain phenomena not explaining phenomena per se (Ogborn et al. 2002) in order to attribute personal meaning to specific phenomena.

Additionally, students not only need to understand concepts and phenomena in a personal way, but they also need to be able to express it clearly. According to Wellington and Osborne (2001), apart from problems that pupils have with individual words, they also have problems putting words together in a paragraph. Writing in science education is mainly in the form of reports, expressed in passive voice, and occurs mainly by the teacher. However, for students to become competent in writing, narratives can be of great value. Students can express their thoughts in writing using a familiar genre, one that shows anthropomorphised entities and endowed with agency (Wellington and Osborne 2001).

2.3.1.1 Difficulties when learning about forces and motion

One of the problems mentioned in learning the scientific language was regarding the 'concept' words. This is due to the fact that pupils bring ideas into the classroom that are not easily addressed from the teacher. For example, everything in shops is weighed in kilograms, yet kg is a unit of mass. Children need to realise that mass is a constant and weight is a changing force. This force is measured in Newtons and is produced by the effect of gravity.

Furthermore, when learning about kinematics graphs interpretation, there are indications that students lack the ability to connect among representations and between representations and phenomena (Kozma, R. 2003). In particular, McDermott et al. (1987) have grouped the difficulties in two categories: difficulties regarding connections between graphs and physical concepts and difficulties connecting graph to the real world. They gave an account of the difficulties pupils have in connecting kinematics graphs to physical concepts, which are:

- discriminating between slope and height of the graph
- interpreting changes in height and changes in slope of the graph
- relating one type of the graph to another which is mainly a confusion around variables: they expect the distance-time and the velocity-time graphs to be identical.
- matching narrative information with relevant features of a graph

Additionally, the difficulties connecting graphs to the real world movements refer to:

- separating the shape of the graph from the path of the motion (picture-like effect),
- representing movement as a continuous line,
- representing negative velocity on a velocity-time graph and
- accepting that the same motion can be represented by graphs of different shapes (McDermott et al. 1987)

When learning about kinematics, pupils often ignore the abstract concept of the graph and think of the graph as a picture of motion (Beichner 1990; McDermott et al. 1987), i.e. a line parallel to the time axis of a distance-time graph could be erroneously assumed to describe a horizontal movement and a line going upwards describes a vertical movement. By using a sensor on their hand to collect data for drawing a graph, pupils can negotiate this conception: they relate their actual movement to the appearance of the graph. Additionally, regarding the slope and height confusion, students can confuse the slope of the line with a certain *point* on the line, usually the highest or lowest point (Beichner 1990; Brasell 1987; Mokros and Tinker 1987). What is more, some students tend to incorrectly superimpose upon the graph existing knowledge about a phenomenon (Mokros and Tinker 1987).

Bearing in mind that these difficulties have been made specific, there are several ways that focus on challenging them. These difficulties are usually addressed through practical work and the use of interactive technology.

2.3.2 Practical work in science education

One of the purposes of practical work is to build a bridge between the realms of objects and observable properties on one hand and the realm of ideas on the other (Millar 1998). When in the laboratory, students should be encouraged to make links between things they see and handle, and ideas they entertain which might account for their observations.

The existence of practical work gives support to the physical aspect of learning. It also offers a demonstration of the students' need to accommodate multiple modalities while learning. Practical work in laboratories first appeared at the late 19^{th} century in a few grammar and public schools in UK, although it was introduced in larger-scale curriculum reform movements in 1960s. The Nuffield Physics Project was a pioneer of the time, aiming to make science intelligible and accessible to pupils of (selected) comprehensive schools (Maddox 1966), and promote investigative activities that would lead to pupils' vicarious experience of scientific discovery. However, as the need for non-selective comprehensive education arose in combination with the need for assessing not only theoretical achievement but also practical skills, the activities within the laboratory became routinised, based on 'scientific-content' and depended on pupils' literacy (for extensive historical retrospection see (Jenkins 1998)).

Practical work offers many more opportunities than the classroom for satisfying curiosity, individual initiative, independent work, working with one's own time and obtaining constant feedback regarding their actions (Tamir 1991). Practical work is associated with students' increasing motivation since they can find out about things through experimentation which is the very essence of science (Parkinson 2002). They can 'play' with 'new toys', e.g. Bunsen burners, chemicals, which can make science exciting and different. According to Wellington (1998), the reasons for including practical work in the National Curriculum can be grouped into three main domains: the cognitive, the affective and the skill acquiring. In particular, practical work can improve pupils' understanding and facilitate their conceptual development by allowing them to try out the laws and theories of science; it can illustrate, verify or affirm 'theory work' (cognitive domain). Practical work can also be motivating and exciting; it generates interest and enthusiasm; it helps students to remember things (affective domain). Finally, through practical work, students can exercise not only manipulative or dexterity skills (e.g. setting up apparatus) but also transferable skills such as measuring, predicting, observing and inferring which are also useful for their out-of-school life at home or later at work (Wellington 1998).

However, this extrapolation is not always successful since students' learning is often compartmentalised and doesn't link one subject to the other. Additionally, when a strategy of inquiry is generic enough to be applicable in a range of disciplines and problems, it can hardly be also sufficient in the solution of a problem at hand (Ausubel 1964 as cited in Wellington, 1998). Practical work is not only able to clarify or aid understanding but also to confuse students especially when there are 'wrong' results that are not explained to the students. Additionally the discussions that take place in the lab tend to be procedural and relate to carrying out rather than analysing the task (Barton 1997).

In reality, scientists propose theories of how the world may work. By manipulating theoretical entities, they make predictions that can be tested by manipulating physical entities in the real world. In schools, it is difficult for pupils to manipulate theoretical abstract entities and so there is a tendency to overemphasise the manipulation of physical entities omitting their relevancy to theory and downgrading the importance of practical work (Boohan 2002).

Practical work is also considered as an opportunity for less 'hard thinking' or catching up with the gossip (Parkinson 2002). Additionally, considering school management, practical work is expensive both in terms of time and resources which are always limited; not to mention the arising safety implications and the possibility of litigation.

The problems arisen from the practical work can be opportunities for designing learning environments. The reason for failing to extrapolate from the lab activity to theoretical activities, for example, could be due to lack of coupling between the actions of the two situations. Thus, a question that arises is how can the task of the practical work be de-cluttered and data handling can be improved by giving access to data from real-life situations which can be handling without being confusing? Furthermore, how to make the equipment at hand less complex so that students' practical work can focus on understanding science concepts and appreciate the methods of science?

2.3.3 ICT in science education

As an attempt to answer the above questions, simulations and other computer models have been developed. Additionally, since science can be viewed as content, e.g. the laws, theories, facts, and as processes, e.g. measuring, recording, processing data, information and communication technology (ICT) in science education aims to support both (Wellington 2000).

Simulations and modelling offer a wide range of opportunities by either describing reality or simplifying it to aid conceptual interpretation (Boohan 2002). Simulations refer to models that are created by others; modelling refers to models that are created by pupils. Simulations can show phenomena and processes that might be too slow or fast to do in the school lab; they offer access to non-existing entities, e.g. the frictionless body, they model activities that would be dangerous or expensive to carry out by pupils (Wellington 2000). Through simulations variable can be easily controlled and teachers can focus on theoretical issues instead of dealing with managing the lab.

Simulations, however, are not panacea for learning science: easy manipulation of variables may lead to misunderstanding that this happens in reality, models are hidden from the pupils which results pupils to be able to manipulate only factors within this model, cannot question the model and they might confuse the model with reality. Additionally, some models are better than others and some models are caricatures of reality rather than representations of it (Wellington 2000). It is the teacher that can safeguard such confusions by stressing the fact that simulations are models and emphasise their limitations (Wellington 2000).

In general, ICT systems are useful for collecting and storing large amount of data, performing complex calculations on stored data rapidly, processing large amounts of data and displaying it in a variety of formats, helping to present and communicate information (Wellington 2000). Computers can be used for a variety of reasons, as a word processor, a spreadsheet, a database, desktop publishing and graphics, to interact with multimedia software, to browse the Internet, to log data. However, the use of ICT in schools has shown weaknesses (BECTA report, 2002): the objectives are sometimes unclear, there are low expectations of written outcomes, glossy computer-generated effects are accepted without extending pupils' abilities, allowing students to reproduce information rather than analyse it.

2.3.4 Summary

Reviewing practices in the classroom, practical work and ICT in science education, gives insights of ways that they can be improved either through organising the learning activity or through the use of technology.

The identified problems that students have from the way the science curriculum is taught in the classroom could be summarised as:

- The ability to understand and use the relevant terminology.
- The ability to provide students with appropriate explanations that would provide them with the resources they need to explain phenomena in a personal way.
- The ability of students to write narratives related to their (practical) work.

The identified problems related to practical work in the science curriculum are related to:

- the ability to extrapolate from the procedures of practical work to theoretical concepts,
- interactions with data that is not always connected to symbolic entities and their descriptions to aspects of real world,
- confusions due to 'wrong' results that are not explained to pupils,
- discussions that tend to be procedural instead of analysing the task, showing an overemphasis to manipulation without relating to theory,
- the ability to link one scientific concept to another,
- expensive resources and time management.

2.3.5 Learning with multimedia

The review of the practices that take place in the classroom, and the laboratory revealed problems which could be addressed by information and communication technologies. Attempting to enhance classroom learning in science or other subjects multimedia were introduced employing multiple representations while interacting with a learning technology. Moving from the book to the computer there is the opportunity for greater interactivity and novel ways to think about a learning activity. Technology provided more ways to represent concepts through different media formats, e.g. animations, narratives, text and graphics and their combinations. Such advances in technology ask for pedagogical enquiries to confirm the usefulness of such new activities in facilitating learning.

However, the findings are often conflicting, even though there is a plethora of empirical studies investigating the advantages and disadvantages of learning from single or multiple representations of information with the aid of computers (Rogers, Y. and Scaife 1996). The large number of variables involved, individual differences, varied use of testing measures, the research environment are just a few examples that blur the conclusions of multimedia research (Jones, S. and Scaife 2000). It is generally assumed that learners who have access to multiple representations enhance their comprehension, learning, memory, communication and inference (Tversky et al. 2002).

Pedagogical considerations argue for the importance of structuring the instruction for learners as well as the importance of scaffolding thoughts and reasoning that are salient to the tasks. Kozma (1991), for example, considers learning with media and argues that learners will benefit more if the instructional methods provide, perform or model cognitive operations that are salient to the task and the situation. Learners will also benefit more if they cannot or do not perform or provide for themselves the operations provided by these representational media (Kozma, R. B. 1991). Additionally, Narayanan and Hegarty (2002), argue that providing the learner with a sound structure and content is more important than providing them with interactivity and animation afforded by new media. Comprehension and learning require a sound content and structure of instructional material, and not new media or types of representation (Narayanan and Hegarty 2002).

Furthermore, as Dubois and Vial (2000) argue, the combination of text and image is effective when the information provided is complementary and adapted to each presentation (Dubois and Vial 2000). Adding another presentation mode is not necessarily valuable if the added information does not promote in-depth processing of information. Making connections from multiple representations depends not only on the presentation mode and the construction of the interrelations between the multimodal items but also on the characteristics of the task (Dubois and Vial 2000).

Additionally, Tversky et al. (2002) have studied the advantages and drawbacks of animations. In particular, they argue that animations may be hard to perceive: even when motion is simplified to the path or trajectory of a single object rather than the complex interaction of moving parts, perception may not be accurate, e.g. the legs of galloping horses was conceived wrongly before the stop-gap photography. Animations may also be comprehended discretely instead of continuously: when motion is conceived of in discrete steps then the natural way to convey it is to portray it in discrete steps than in continuous animation. What is more, for an animation to facilitate learning they should lean toward the schematic and away from realistic and may need the use of arrows or highlighting to direct attention to critical changes and relations. Additionally, learners should be in control of the speed of animations and can view, review, stop start, zoom in and out and change the orientation of parts and wholes of animations at will. They conclude that carefully crafted animations can facilitate learning (Tversky et al. 2002).

2.3.5.1 Advantages of multimedia learning

Learning environments that provide learners with multiple representations offer opportunities for greater interactivity, and complementarity. There are implications about the importance of interactivity (Scaife and Rogers 1996; Healey et al. 2002; Tversky et al. 2002), and complementarity (Ainsworth 1999) in the literature and some of them are analysed below.

Animations and virtual environments can emphasise the key-components of the phenomena under study, can highlight the underlying processes explicitly and provide feedback to learners' actions (Scaife and Rogers, 1996). Interactivity has been defined by Narayanan and Hegarty (2002) as a facility by which a user acts on a computer presentation which in turn interprets the user's action and produces the appropriate response. Interactivity gives learners the opportunity to re-inspect and facilitate their perception and comprehension through zooming, controlling of speed and viewing alternative perspectives (Tversky et al. 2002). However, learners still need to learn to 'read' the content of the animations in relation to the information presented verbally or as text and to assimilate it with their current understanding of the domain (Scaife and Rogers 1996). It cannot just be assumed that the interactive representations are better than non-interactive ones.

Complementarity refers to the ability to present information or a structure in multiple equivalent ways. Thus, it can refer to both complementary processes and complementary information. When there is complex information to be shown or when there is no single representation that would sufficiently carry all the necessary content, multiple representations can be useful (Ainsworth 1999). These representations can have different or partially redundant information: different information to facilitate understanding of complex information and partially redundant to support new interpretations of the same domain (Ainsworth 1999). Additionally, when employing multiple representations, learners can benefit from the different complementary processes that each representation supports: they can use more than one strategy and have the chance to exhibit preferences (Ainsworth 1999).

2.3.5.2 Considerations on learning with multimedia

Multimedia enables novel ways of representing information but a pervading assumption seems to be that the more explicit depiction of motion offered by animation the better for learning (Jones, S. and Scaife 2000). However, a comparison between animated and static diagrams reveals that multimedia representation can lead to cognitive overload due to too much information available, problems in having to integrate multiple representations that are not always available concurrently, an unmanageable increase of the available information especially where multidimensional dynamics are involved (Jones, S. and Scaife 2000).

On the other hand, when researchers are trying out different types of representations they might propose some rather undeveloped notions of multimedia, e.g. the need to incorporate flashy presentations, the truism of an image worth a thousand words (Mayer and Gallini 1990). In particular, despite the potential problems of learning with multimedia, Mayer and Moreno (Mayer and Moreno 1998, 2002; Moreno, R. and Mayer 1999; Moreno, R. and Mayer 2000) have been trying different combinations of images, text and sound effects to form design principles for educational presentations. Based on different cognitive theories i.e. the dual-coding theory (Pavio 1991), the cognitive load theory (Chandler and Sweller 1991; Sweller 1994; Mousavi et al. 1995) and constructivist learning theory, they have proposed the following principles, which were validated by user studies:

- The *multiple representation* principle: it is better to present an explanation in words (narration) and pictures (animation) than solely in words.

- The *contiguity* principle: it is better to present words and pictures simultaneously (contiguously) rather than successively (separately)
- The *coherence* principle: eliminate unneeded words and sounds.
- The *modality* principle: it is better to present words through an aural narration than as visual on-screen text when pictures are engaging the visual channel.
- The *redundancy* principle: present narration and animation rather than narration, animation and on-screen text (Mayer and Moreno 2002).

Mayer and Moreno aim to promote constructivist learning from passive media. They argue that constructivist learning is not synonymous with hands-on activities or social collaboration. The main aim of computer-aided learning, according to them, is the appropriate cognitive activity, which is not necessarily fostered by the use of highly interactive hands-on experiences. They claim that if words are heard instead of read, then learners benefit more from the multimedia presentation (Mayer and Moreno 1998, 2002; Moreno, R. and Mayer 1999; Moreno, R. and Mayer 2000).

Focusing on the format of the information to be presented to learners without considering the content, as Mayer and Moreno do, may not be appropriate for the design of an educational technology. According to Rogers and Scaife (1996), generalisations about the use of different media in interactive multimedia offer little help for determining what to make explicit and salient about a domain in a particular representational form. Even though operationalising multimedia effects on learning can be quite useful in some cases, such conclusions can also be dangerous: the coherence principle, for example, could be argued that is needed due to the multiple representation principle: suggesting too general principles, such as using words and pictures together, could lead to misunderstandings that give reasons for urged designers to show off their designing skills. Specific learning tasks could be benefit more or less from specific words and pictures.

Additionally, Mayer and Moreno tested the contiguity principle by comparing students presented with animation and narration with students presented with narration only. However, research on animations argues that before concluding for the usefulness of animations for learners, we should focus on an appropriate comparison. For the comparison to be eligible, animations should be compared to graphics that do not change in time since ‘change in time is what animation adds’ (Tversky et al. 2002).

Other educational technologists and educators have been considered the *contiguity* principle from a different perspective. Showing information contiguously or successively could be a matter of showing complementary and relevant information to learners. Depending on the learning content, both of these processes need supporting (Dubois and Vial 2000; Ainsworth 1999).

Regarding the *modality* principle, Tabbers et al. (Tabbers et al. 2001), showed that learners using audio instead of text were less successful which contradicts the modality principle. Replacing visual text with audio does not easily generalise in non-laboratory settings. In studies where the modality effect was demonstrated (Moreno, R. and Mayer 1999; Mayer and Moreno 1998), the authors claimed that the reduction in extraneous load of the multimedia instructions resulted to a more efficient use of the available memory resources. However, Tabbers et al (2000) showed that the results obtained in their experiments could also be largely attributed to the difference in visual complexity (Tabbers et al. 2000). In particular, Mayer and Moreno (1998; 1999) cut their explanatory texts in smaller pieces, reducing the visual search to a minimum. Additionally, in their experiments the instructions were presented as system-paced animations. Students could study the instructional material only a few minutes, and the maximum study time was always based on the time that was needed to hear the narration. Therefore, learners in the bimodal condition could use this limited time more effectively because they could look at the picture and listen to the text at the same time, while the learners in the visual-only condition had to spend their time searching between text and picture.

To summarise, learning with multimedia can be really helpful for learners but it depends very much on the learning task, the settings and the available resources. Creating generic design principles for the presentation of the learning content runs the danger of omitting details that are necessary for learners' meaning construction.

Interactive multimedia for learning purposes have made an important difference in the way in which learners could learn but there are still problems in students willingness to stay devoted to the learning task, and in their ability to extrapolate the learning outcome. One of the reasons for this may be that many multimedia programs are designed for a "…single focal point teaching through a linear sequential process" (Stoney and Oliver 1999). In other words, when programs are designed around old teaching paradigms, students are confined to a narrow learning experience.

Additionally, multimedia environments focus on the employment of multiple visual and verbal representations. Bearing in mind that these are the main representations used in the classroom, multimedia learning environments seem to facilitate classroom learning. Practical work, however, is not necessarily facilitated. Even in cases focusing on practical work, having images of the lab instruments and interacting with them via the mouse or keyboard are not necessarily as helpful as physically interacting with them in the lab.

2.4 Multimodal Learning

Bearing in mind that multiple representations provide some advantages for learners to learn, but that there are still problems, there might be a need for a different approach to computer-aided learning. Studying the importance of multiple representations while learning with computers shows an overriding focus on 'visualising to be able to cognise'. Viewing multiple ways of presenting concepts, stresses the importance of vision in understanding, ignoring the effects that other senses can have while in a learning activity. This thesis stresses that learning is not only a visio-cognitive activity but also a physical one particularly as it requires the interplay among multiple sensory modalities and representations.

The literature is mainly talking about visual and linguistic representations, which are beneficial for specific tasks but they might not be appropriate for the whole spectrum of the learning activities. Learning is closely related to experiencing life and in life we employ all of our senses -not only vision. Apprenticeship and situated learning are trying to address issues related to life but they focus on the social aspect of learning omitting issues about abstracted phenomena and ideas (Daniels 2001; Laurillard 1993). This thesis focuses on the individual and investigates whether the contribution of his/her sensory modalities not only situates them in the learning activity but also provides them with the willingness to reflect.

Considering that computers until recently were on the desktop, learners had to sit next to them and interact with the input and output devices provided. As computers become more ubiquitous, there is an opportunity for learners to leave the keyboard and mouse on the desktop and interact with the computer with different means from pointing and text-typing.

For learners to be engaged into a subject, they need to relate themselves and connect their everyday life to the learning material; in other words, they need to be situated. Such relationships could be generated by following an alternative approach to learning: one that incorporates learners' multiple modalities and the available instruments of the environment including the multiple representations provided by books or multimedia software. Such an approach is argued to be multimodal learning.

2.4.1 Multimodal Learning: the educational perspective

A multimodal approach to the classroom highlights the important use of multiple modalities in real learning environments (Kress et al. 2001). Children select or negotiate the meanings conveyed from modalities to construct conceptions about the world. Each modality contains information that is a resource for pupil's meaning construction. Each modality covers a different aspect of phenomena which could challenge prior conceptions of the world and provide resources to imagine and think with. Thus, within the classroom, the use of multiple modalities offers a rich range of resources for pupils to employ while learning (Jewitt et al. 2001).

Science learning in a classroom is one scenario that can be supported by multimodal learning. By manipulating a spring, for example, children's understanding of force or weight can be supported and reinforce the teacher's lesson. In this scenario, the spring and the teacher's talk and actions are resources through which meaning can be conveyed. According to Kress et al. (2001), teachers often use gestures together with speech to draw attention to images and other references within the classroom. In particular they argue:

> "[… in science teaching] a variety of modes are interacting and interplaying: gestures, drawings, speech, objects. […] Each mode contributes to meaning construction: […] speech to create a difference, [...]an image on the blackboard to get a visual backdrop, […] manipulation of an object to locate the discussion in the physical setting, […] action to make clear the dynamic nature of the concept […and] the image in the textbook to do a stable summary. […]cohesion is achieved through repetition, synchronisation, similarity and contrast. The affordances and constraints of the different modes help the communicator to decide what will be selected to do what. The selection of [modes]

> also makes meaning: the metaphorical path will be different in each case. […Each mode] plays a different role in the construction of the entity at hand. Each mode requires the pupils to do a different type of work in order to understand (Kress et al. 2001)".

2.4.2 Multimodal Learning: the contribution of technology

Considering that the interactions in science education are multimodal, the next consideration would be how these interactions could be enhanced by the contribution of technology. Bearing in mind that pupils might want to study outside school, or that the teacher is not always available to every pupil, technology could support their efforts.

Kress's analysis of how cohesion is achieved in learning is not alien to the advantages of multimedia learning. In particular, repetition could be related to complementarity: complementary information could be either redundant or different (Ainsworth, 1999): redundant information and repetition can be seen as identical and they can both support new interpretations of the same domain. Synchronisation could be related to interactivity: synchronising information from different modes gives the opportunity to re-inspect the situation at hand and extend their comprehension of phenomena, which are the effects of interactivity according to Tversky (2002). Finally, similarity and contrast could also be related to activities that multimedia environments prompt learners to do.

Nonetheless, Kress's analysis could be seen as a starting point for employing technology differently: by incorporating the links between someone's actions and their effects on phenomena, e.g. by supporting one's gestures or other actions in an attempt to augment learners' meaning construction. The support of links between learner's actions and their effects has been studied by microworlds but there is always a *transitional object* (Papert, 1980) that mediates the experience: the turtle. The question is whether such links can be supported without the mediation of virtual objects but real ones or the actions themselves.

2.4.2.1 An example: data logging

This section reviews a particular area of science lab activity as an example of illustrating the linking of learners' actions and their effects through the employment of multiple modalities in a learning task. Data-logging activities are used in the science lab for almost two decades but the advantages of it have mainly focus on the importance of easy data collection and presentation. Data logging activities in this thesis are seen as opportunities to couple physical actions to symbolic representations. They are used to illustrate that learner's engagement and reflection could depend on information which is not only visual.

The use of data-loggers makes data capturing less tedious as a sequence of readings can be obtained automatically under the control of computer software. This increases the productivity of the class and encourages higher quality work (Kennedy and Finn 2000). Data-loggers can capture data over very short periods of time to very long periods of time and display the information in any format. They are more accurate than pupils; they can retain a vast body of data and access it on request, they can keep on logging without stopping; they can present data concurrently to collection and the collected data can be re-presented it in a variety of ways including graphs to enhance the communication of meaning to the observer (Wellington 2000). With data-loggers, pupils can make immediate observations of data, ask questions about it, look for links with other information, make comparisons, predict patterns, look for trends (Rogers, L. 2002).

Data-logging activities can take away routine activities of practical work that can consume time or provide inaccurate data and shift the focus on the interpretation of results (Rogers, L. and Wild 1996; Parkinson 2002). The change of emphasis away from the routine process of logging to the use of interpreting skills can enhance scientific thinking, creativity and problems solving (Wellington 2000). Additionally, the presentation of the graph as pupils carry out their experiment has the potential to help them relate the graphical image to the observed experimental events. This assists in the linking of the abstract and the concrete: since the data-logging system can take the necessary readings and do the calculations, the mental work for the pupils may be devoted to understanding the experiment and exploring how the outcomes relate to the science questions being considered (Kennedy and Finn 2000).

Furthermore, Rogers L. and Wild (1996), noted that the extra time resulting from automated data-logging could be used by the teacher to encourage discussions and investigative activities among pupils. It can also benefit weaker students as the reduced manual effort in obtaining graphs, gives pupils of lower ability better access to analyse data. Pupils of higher ability, on the other hand, can manipulate the data, present it in a variety of ways, change variables and predict the effect of these changes (Kennedy and Finn 2000).

However, teachers have been sceptical about data-logging with technology: it has been pointed out that perseverance, ability to organise data systematically, and calculating skills are part of science and that students should go through these practices in practical work' (Wellington 2000). Nevertheless, the educational benefit from using data-logging technologies does not lie on collecting data: there are other technologies to support such activities, e.g. spreadsheets and databases. The advantages of using data-logging activities focus on skills such as interpreting, discussing and hypothesising. In particular, the skills for interpreting graphs could be categorised as the ability to

- view the graph's details, i.e. scales, point of origin,
- read its values,
- describe the shown variables,
- relate between variables,
- make predictions,
- translate descriptions into mathematical forms (Rogers, L. 2002).

Data-logging activities deflect attention from numbers and points and support reading patterns, manipulation of variables and prediction of change.

As pupils and teachers become confident in the use of sensors and modern programmes, they are encouraged to take decisions and to investigating the results by altering some of the variables in the experiment. More cycles of "predicting, observing, hypothesising" are possible due to ease of capture of data and the saving of time allowed by the data-logging approach to science teaching.

Additionally, data-logging extend pupils' powers of observation, improve the quality of measurement, provide calculating and analysing aids for investigating data, and motivate pupils through prompt feedback (Rogers, L. and Wild 1996). Graphical analysis skills are in a very dynamic state when using a data-logging activity and pupils' rapid progress can be observed over the period of only one session. Experiments can be readily repeated, generating more data for analysis and students can manipulate parameters of the experiment and re-run then, allowing more investigative styles of working.

With data-logging, not only the plotting is accurate but the speed of plotting enables graphs to be treated dynamically and interactively (Rogers, L. 2002). This real-time data acquisition and graphical display emphasises the time variable of the graph because it becomes a more prominent feature of the graph than in a 'static' graph produced after the event in traditional laboratory settings (Newton 1997). The graph need no longer to be regarded as the end-product of an investigation as often occurs in conventional practice (Rogers, L. 1997).

However with such technology the discussions between the teacher and pupils can be very different from those of traditional practical work. This time, discussions could aim at scaffolding pupils' understanding. Barton (1997) urges teachers to be accommodative to this opportunity for enhanced interactions among pupils, technology and themselves. This interaction is not always verbal but is evident by watching pupils expressions and actions (Barton 1997).

Even though there are only a few studies that compared the effect of data-logging in pupils' ability to interpret graphs with traditional laboratory sessions, Rogers and Wild (1994, 1996) provide a few exceptions. In a number of studies they compared data-logging activities with traditional practical work. In 1994, they did not get any favourable results towards data-logging because the tests to measure achievement were 'conceived in the context of traditionally laboratory work which did not reward changes in learning achieved with IT' (Rogers, L. and Wild 1994). In 1996, the type of activities that dominated each experiment with IT was so diverse that the results were not conclusive.

Rogers and Wild (1996) suggested that it is too simplistic to look at the effects of data-logging in a bland general way without regard to the context of use. They argued that the contextual factors were: a. the quality of exploitation of the computer tools, b. the physical nature of the topic under investigation, c. the learning objectives, and d. the teaching style.

In particular, the computer tool could be exploited greatly when pupils learn how to use the tool: if pupils focus not only on the ways of using the tool but also on understanding about the application of the computer tool and its potential as an analysing aid through testing hypothesis, discovering patterns in data or obtaining other useful information about data. The physical nature of the topic under investigation refers to the tasks that pupils have to carry out during the experiment. In some case pupils are busy manipulating the computer tool, in other cases pupils have less to do and they have plenty of time to extrapolate the meaning of data: the latter offers more opportunities to think about the science involved, e.g. potential pupils' mistakes in data collection. One of the properties of data-logging is the reduced manual effort and errors in data collection which gives extra time to the teacher: thus the learning objectives and the management of the pupils' activity has to be re-considered so that the representation of data becomes a tool for exploring and thinking about the data. Finally, the teaching style has a great influence on the ability of pupils to ask questions. In situations where the teacher followed an investigative approach, the use of data-logging was associated with more discussion either among pupils or between pupils and the teacher (Rogers, L. and Wild 1996).

Full exploitation of data-logging requires developing goals to extend its use beyond data collection to data interpretation. Achieving this shift will require identification of further opportunities to exploit aspects of data-logging software for developing higher order interpretative skills in experimental science. Increasing familiarity with software may itself facilitate identification of further needs which are well served by the technology and consequently lead to development of new goals.

Data logging technologies that present real-time graphs have been considered by researchers outside UK under the name of microcomputer-based laboratories (MBLs). Especially in the US, several studies have been carried out in school laboratories where whole classes used the technology to collect data and learn how to interpret graphs. As Thornton and Sokoloff (1990) described, "MBL has a motion detector which uses a sonic transducer. The motion probe, essentially a SONAR unit, transmits short pulses of high frequency sound then amplifies and detects the echo. The computer is programmed to measure the time between transmitted and received pulses and calculate position, velocity and acceleration of the object causing reflection. Any one of these quantities may be graphed as data are taken or any one or many can be seen on display after the data is taken. The motion detector can accurately detect objects that are o.5 and 6m away. It detects the closest object in a roughly 15^{o} cone" (Thornton and Sokoloff 1990).

In particular, Nachmias and Linn (1987) assessed the extent to which students critically evaluated computer-generated graphs and examined the effect of an extensive use of MBL on pupils' critical evaluation skills. They argued that critical evaluation of data requires a. knowledge to test the data against, b. ability to relate the data to other information and c. inclination to test the data. Through an extensive study they concluded that without special instruction, students tend to evaluate computer-generated graphs uncritically much as they assess textbook-presented graphs and other information, which relates to what (Rogers, L. and Wild 1996) argues about the teaching style: if pupils are not used to ask questions they will not start doing so when they use the technology. Through a semester-long program, students gained experience in critically evaluating graphs which was associated with the ability to identify graphs with extraneous influences (attribute slopes or shapes of the graph to features of the technology) rather than mistakenly relate them to features of the nature of the phenomenon (heat and temperature). However, pupils were not always successful in explaining what factors were causing problematic graphs: they were able to evaluate correctly data from wrong graph scaling of probe set up but not from inappropriately calibrated probes or probe sensitivity (Nachmias and Linn 1987).

Other researchers have proposed the following advantages of using such a technology:

- Movement in the visual display tends to capture students' attention and prompts them to attend selectively to the important features of the graph (Brasell 1987).
- Graphs allow humans to use their pattern recognition capabilities and see trends and spot subtly differences in shape (Mokros and Tinker 1987).
- By viewing the real-time graph being formed during the experiment, it is more likely that students will see the graphs as dynamic relationships rather than static pictures (Linn et al. 1987) as cited in Beichner, 1990).
- Real-time graphing lets the students process the event and its graph simultaneously rather than sequentially. (Beichner 1990)

However, data-logging experiences have not been without problems. Barton (1997) suggests that the computer screen where the data is displayed has a focusing effect on pupils. During a data-logging activity, pupils watched and frequently pointed to the screen throughout the activity. They used the screen when tried to explain their interpretations and ideas. The same effect was described as problematic by Newton (1997): "whilst many pupils particularly liked handling the equipment, they also disliked passively watching the experiment". Teachers can help pupils think critically of their data instead of just watching it, by asking them open questions that encourage pupils formulate their own responses (Newton 1997).

There are additional worries due to the fact that data-logging activities support students in creating qualitative narratives of their actions. Describing what happens could be beneficial to pupils but without practice in the use of the appropriate vocabulary, it might be difficult for students to progress from these qualitative descriptions to quantitative descriptions of variable relationships (Newton 1997). Again it is suggested by Newton (1997) that it is the role of the teacher to make sure that pupils are sharing more scientifically acceptable verbal translations of the graph.

To summarise, data logging as a type of interactive technology could provide learners with a mediated activity to facilitate the transition from concrete to symbolic understanding. The benefits of data logging activities consider

- the speed and ease of capturing data,
- the clear presentation of data which can be easily manipulated,
- the shift of learning outcomes from gathering data to interpreting data,
- the encouragement of active learning by developing problem-solving skills and
- encouraging students to question, predict and hypothesise about the results of their laboratory practical work.

Students are involved in planning experiments, measuring variables, analysing results, and evaluating experimental methods. With the introduction of such technology and its related activities, however, the role of the teacher needs to be reconsidered. Teachers need to encourage pupils to think critically of their data and experiment with the equipment to find out new configurations of data.

2.5 Towards a definition of Multimodality

For multimodal interactions to be incorporated into a computer based learning environment, there is the need to explore the interactive means that technology can offer. Research in human-computer interaction is exploring many different ways to communicate information to the computer through the concept of multimodality.

The term multimodality is used to refer to the employment of multiple modalities, interaction styles, and sometimes even interactive devices. For this thesis, multimodal systems are characterised by the modalities they are using. The concept of modality has been interpreted in different ways both across disciplines and within a single discipline. Depending on the definition of the word modality, multimodal technologies can provide users with a range of advanced interactive means: from interactive suits to interactive animations. Table 2-2 expresses the different usages of the term modality. From this categorisation, the concept of multimodality emerges as the alternate or simultaneous employment of more than one input or output human or computer modality. However, we need to keep in mind that input and output modalities are not always separate in humans, e.g. when we taste something bad, we have an immediate facial expression before we swallow. Furthermore, for computers, input might be divided into two or more activities in order to be processed, for example Bolt's 'Put-that-there' system involve one modality to identify the object by pointing at it and another modality (speech) to issue the command (Baber and Mellor 2001).

Computer scientists often do not discriminate between human and computer modalities (Blattner and Glinert 1996) and thus refer to different devices or processes as sensory modalities. Additionally, researchers usually do not always provide a clear distinction between input and output modalities, resulting in a greater confusion. Noteworthy exceptions to this attitude are the research conducted for AMODEUS (see (Nigay and Coutaz 1993; Coutaz et al. 1995) and MIAMI (Bernsen 1994b, 1994a).

MODALITY	Input	Output
Human	Sensory processes	Response processes
	Touch (pressure, texture)	Hand/head/body movement
	Kinaesthetic (force feedback)	Gestures
	Audition (speech, music)	Facial expressions
	Vision	Lip movement
	Taste	Eye movement
	Smell	Sounds/speech
Computer	Interaction Processes	Feedback processes:
	Speech recording/recognition	Visual
	Audio sensing	Auditory
	Visual sensing	Voice feedback
	Position and Motion sensing	Sounds
	Gesture recording/recognition	Tactile: force feedback
	Head/body/hand/lip tracking	Kinaesthetic: moving feedback (robots)
	Force or tactile sensing	
	Neural sensing (through EEG)	

Table 2-2: A categorisation of modalities

The following sections study the usage of the term 'multimodality' in the field of human computer interaction (HCI) and in Educational Technology. From the initial stages of this study, it became apparent that 'modality' cannot be separated easily from the term 'medium'. Thus, the usage of both terms is discussed under the two fields.

2.5.1 The approach of multimodal HCI

Human–computer interaction can be multimodal as well as unimodal. Multimodality refers to the concurrent or alternate use of more than one modality to send and receive information (Carbonell 2001; Baber and Mellor 2001). In a multimodal interaction, someone may receive information by vision and respond by speech or movement. Multimodality could be contrasted to 'unimodality', which is based on the use of only one modality to receive and sent information. An example of unimodal activity could be watching an animated presentation on a computer without responding.

Research on multimodal interfaces is based on the naturalness of the communication between the user and the system (Marsic et al. 2000; Oviatt 2000; Sharma et al. 1998; Oviatt et al. 2001). Naturalness refers to a human-computer communication that would closely resemble human-human communication. Based on the fact that natural communication among humans involves multiple concurrent modes of communication, multimodality is the way to aspire such naturalness in human computer interaction (Sharma et al. 1998). Multimodal systems aim to provide people with more advanced interactive means than conventional graphical user interfaces: they can provide ease-of-use, increase productivity and exploit the abilities of humans to express themselves during the interaction with the computer (Flanagan and Marsic 1997) as well as minimise the need for specialised training (Oviatt 2000; Sharma et al. 1998). Multimodal systems support a combination of modalities that can be matched to the task or the environment.

Multimodal interfaces aim to enhance the communication between humans and the computer since they can provide the means to increase accessibility for users of different ages, skills levels, sensory and motor impairments, or even native languages. Multimodal interfaces also can offer the means to be used in natural field settings and during the changing conditions of mobile use. Additionally, multimodal interfaces increase the robustness of the recognition systems because of the synergistic blend of complementary modalities (e.g. pointing and speech are complementary when saying 'put that there' and pointing to the desired place), which results in the mutual disambiguation of the incoming message (Oviatt 2000).

Additionally, Baber and Mellor (2001) argue that multimodality in human-computer interaction can have two perspectives: the human-centred and the technology-centred. According to the human-centred perspective, multimodal systems should support more than one sensory and response modality of the users. The technology-centred approach defines that a multimodal system supports concurrent input or output usually with more than one device (Baber and Mellor 2001).

2.5.1.1 Modality and medium

Within the human-computer interaction field, the definition of modality can refer to a complex-property entity characterised by the medium of expression with a specific profile (Bernsen 1994), the communication channel to acquire or convey information (Nigay and Coutaz 1993), to environmental sensors/effectors and related perceptual process (Maybury, M. T. 1998) or to ways of exploiting specific media (Martin and Julia 1998).

Modality should not be confused with the medium although both notions are related to the form of the message. A single medium may support several modalities. A single modality may be supported by multiple media. Many media may support many modalities: e.g. a multimedia document which includes text, graphics, speech, video effects visual perception of images (still and moving) and auditory perception of natural language (Maybury, M. 1993).

A medium refers to the carriers used to transfer information, ranging from the human perceptual organs to coaxial cable and radio waves. It sometimes refers to a physical device which enables the information exchange between the user and the system (Martin and Julia 1998). A modality, on the other hand, refers to input and output processes aiming to produce and interpret information. For example, speech is a modality which is transferred via sound (the medium); vision is a modality and a graph is carrying information, therefore it is a medium.

In accordance to the above approach are Maybury's (1993) definitions, where modality refers primarily to the human senses employed to process incoming information, e.g. vision, audition. Medium refers both to the material object (paper, video) as well as the means by which information is conveyed (a piece of paper with text on it, the human eye that reads it), which could be generalised as the carrier of information.

2.5.1.2 Multimedia in HCI

Multimodality and multimedia are closely related. Lee (1996) argues that multimedia systems refer to the presentation of information. Multimodal systems refer to processes of interpretation and regeneration of information presented in different media (Lee 1996). Turk and Robertson (2000) transfer the comparison to the user interface and provide a technology-centred distinction. They base the distinction between multimedia and multimodal user interfaces on the system's input and output capabilities which does not fit to the distinction made earlier. According to them, a multimodal user interface supports multiple computer input and output, e.g. speech together with pen-based gestures with visual and audio feedback. A multimedia user interface supports multiple outputs only, e.g. text with audio or tactile information provided to the user. As a result, multimedia research is a subset of multimodal research (Turk and Robertson 2000).

2.5.1.3 Interaction styles

Interaction styles offer an alternative category for exploring multimodal systems in the human-computer interaction community. Bearing in mind Table 3, interaction styles refer to computer input and output capabilities. They offer a cohesive way of organising the system's functionality, of managing the user's input and of presenting information (Newman and Lamming 1995). Examples of interaction styles are direct manipulation, form-filling, menu-based user interfaces, natural language, WIMP (Windows, Icons, Menus, Pointers) etc.

Considering interaction as a dialogue between the user and the computer, interaction styles can have a profound effect on the nature of this dialogue (Dix et al. 1998). Thus if users can interact with system by filling in forms and receiving feedback in natural language from the machine, the system can be regarded as multimodal. McMillan and Crawford (1998), provide a categorisation of interaction types based on the mediating artifact. They propose the *linguistic style* which includes command-line interaction and text-based natural language, the *key-modal style* which comprises of menu-based interaction, question & answer, and function-key interaction and finally the *direct manipulation style* which consists of graphical user interfaces (GUI) and forms (McMillan and Crawford 1998).

Bearing in mind that computer input can be divided into two or more activities to make information easier (Baber and Mellor 2001), interaction styles are generic descriptions of how this processing occurs. Additionally, they focus on the visio-linguistic human processing abilities and do not incorporate other sensory or response processes from which humans acquire information. Thus, it is considered that are covered from the other sections.

2.5.2 The approach of Educational Technology for multimodality

Usually educational technologists refer to multimodal information or presentation which locates modality to the 'computer visual output' of Table 3. They suggest that different types of visual representations provide multimodal information to learners (Stenning and Inder 1995) and multimodal information is the one presented in verbal or visual modalities (Narayanan and Hegarty 2002). Considering modalities as either verbal or visual, they show an emphasis on the importance of linguistic communication while, at the same time, they underestimate the importance of other communicative means, e.g. body language, gestures, or other actions. Additionally, they exclude different types of representations i.e. aural or kinaesthetic which can provide learners with extra information supporting their engagement and reflection (see Chapter 3, for more details).

2.5.2.1 Modality and medium

Modality in educational technology is related to information presentation and the most common distinction is between text and graphics (Narayanan and Hegarty 2002; Stenning and Inder 1995; Scaife and Rogers 1996). Media in educational technology can be defined as a representation, e.g. sound, text, image, movie (Scaife and Rogers 1996), static or dynamic representation (Narayanan and Hegarty 2002), as the physical context of a representation and the way it is perceived (Stenning and Inder 1995), sometimes even as a modality of communication or multisensory interaction (Dubois and Vial 2000; Mayer and Moreno 2002). In particular, modality for Stenning and Inder (1995) is an interpretation function that relates a representation to a representation. Different interpretation functions have different consequences for the tractability of computations based on them (Stenning and Inder 1995). Therefore, modality for Stenning and Inder (1995) would be a means by which representations can be manipulated.

Kozma (1991) additionally, differentiates among media based on their technology, symbol systems and processing capabilities. Technology, which is the main characteristic, consists of the mechanical and electronic aspects that determine its function and to some extend its shape and other physical features of the medium. Symbol systems are notations based on appearance or sets of elements (words, picture elements) that are interrelated within each system by syntax. The processing capabilities of the medium refer to its capability to process or operate the available symbol systems. They can complement the capabilities of the learner, in that the medium can facilitate the learner in performing specific tasks or do them for the learner (Kozma, R. B. 1991).

Furthermore, Narayanan & Hegarty (2002) categorize media according to their behaviour over time and the modality they employ (Table 2-3). Therefore, multimedia mean that information is presented in different modalities (i.e. visually or verbally) using computer-based dynamic media.

MEDIA / MODALITY	Dynamic	Static
Verbal	Animated text, aural narratives	Text (passive do not interpret users' actions)
Visual	Animations, video	Diagrams, pictures, photographs

Table 2-3: A categorisation of media proposed by Narayanan & Hegarty (2002)

2.5.2.2 Multimedia in Educational Technology

The definitions of media mentioned in the previous section resulted in different perceptions of multimedia in educational technology than HCI. A common conception is that multimedia are resources that make effective use of computer technology by providing simulations, multiple representations, and informative and immediate feedback to learner's actions at the interface (Morris et al. 2002). While interacting with well-constructed multimedia programs, learners can explore the learning environment in the own time, at their own pace and in their order of choosing (Stoney and Oliver 1999). Multimedia applications for learning purposes usually accommodate verbal and visual representations with the use of dynamic or static information. When sound is used, it usually involves a recorded voice saying something: such information lies on the verbal modality. Less often there are other sounds used, e.g. to indicate changes in the computing environment through hearing button clicks. In such cases, learning environments are focused on the stimulation of the distant senses, vision and audition, neglecting the stimulation of the near senses which could provide learners with crucial information for understanding, engagement and reflection.

2.5.3 Summary

Even though there is not a full agreement in HCI research, modality usually is considered as a means by which humans communicate sensory information, i.e., a sensory and response process via which information is passed from or to a person (the first row of Table 3). Modalities can provide either the input or the output of information and can be used individually or in combination.

When the term 'media' refers to the communication artifact, multimedia systems provide to the user enhanced communication means. The user interacts with the system through employing multiple modalities.

Modality in ET usually refers to the type of representations employed, being verbal or visual. When the term 'media' refers to the representation of information, multimedia systems are equivalent to multi-representational systems. The user interacts with the system using the conventional media and response modalities e.g. mouse clicking, keyboard typing.

In this research, multimodality is studied as an approach to human-computer interaction applied in learning settings. It focuses on the interaction between the human and the system from the human perspective. It investigates the human and the employed modalities whilst interacting with a system. Instead of concentrating on the user who is familiar with a computing system, e.g. how to operate the mouse, it concentrates on the human who is interested in accomplishing a particular learning task. It is a human-centred approach that investigates the modalities used in a task and provides the interactive means to employ them. Multimodality is concentrated on how the human interacts with a system more effectively regarding a particular task.

It could be argued, on the other hand, that multimedia research in HCI focuses on the interaction between the user and the system from the system perspective: it studies how will the system present the information to the user, e.g. through text, synthesised speech, and what devices will the system use, e.g. mouse, pen. Even though it is also a useful perspective, it is not the focus of this thesis.

2.6 Conclusion

The literature review presented in this chapter started from constructionism and examined how microworlds have been designed to support learners' engagement and reflection. Furthermore, a review of the science classroom literature was conducted, which explored the practices of the science classroom, the laboratory and the use of information technologies. It was argued that learning in the classroom referred to abstract data and interactions are based mainly on language and symbols; learning in the lab, on the other hand, involve interactions with multiple sensory modalities but data is not always related to symbolic entities and to theory.

Additionally, multimedia learning environments were explored as means of enhancing classroom learning by providing visual and verbal support to learners. Learning with multimedia technologies can provide greater interactivity and complementarity which is an advantage for learners. Yet, there are also problems with multimedia learning which are related to the extraction of generic principles for the design of multimedia environments. Additionally, multimedia learning environments do not consider the employment of multiple sensory modalities which could have an effect learners' engagement and reflection.

An alternative perspective to learning with technology was suggested to be multimodal learning where the employment of multiple sensory and communication modalities enriched learners experiences. The strength of such employment is augmented by learners' engagement and reflection as a result of teacher's successful effort. Later, the example of data logging activities was explored as a way to illustrate the importance of employing multiple modalities and being physically interacting with entities of the learning task.

Multimodal technologies may provide a rich interactive experience but there is a need to clarify what is meant by 'multimodality'. Therefore, the term 'modality' was explored as it is used in HCI and Educational Technology. From these definitions, the need to relate the different use of the term 'modality' is noticed. A way by which these uses could be combined is explored in the next chapter.

Chapter 3 A categorisation of modalities

3.1 Introduction

In the previous chapter, the different ways by using the word 'modality' were identified. In the chapter, a categorisation of modalities is proposed as an attempt to relate the HCI and ET terminology. In particular, this chapter studies aspects of modality that are seen into different 'worlds'. Each 'world' is an environment where students have to learn to act and acquire specific skills.

Initially, an aspect of modality is studied consisting of the means to interact with the real world, that is, the place where everyday interactions take place (first column of Table 3-1). It is later contrasted with the notion of modality of the symbolic world (second column of Table 3-1). Both worlds have a crucial role in learning: learners gain from both the direct situated experience of the real world and the description of that experience that is represented in the symbolic world. Additionally, bearing in mind its value as a tool of scientists, the symbolic world has a substantial role when learning about science because it provides a notation for understanding and communicating natural phenomena.

Subsequently in the chapter, it is discussed how the real and symbolic modalities are part of the science classroom and laboratory (third column of Table 3-1). Bearing in mind that real-world equipment is employed in the science laboratory, interactions with it are not always connected to theoretical concepts and how they describe aspects of reality. Looking for ways to keep interactions close to reality, the use of digitally enhanced features is suggested.

The last section explores how activities can be augmented within a digitally enhanced world to facilitate the interplay of real-world interactions with symbolic ones (forth column of Table 3-1). The notion of a multimodal digitally enhanced world (M-DEW) is introduced, as a real-world learning environment which employs modalities from the real and symbolic world interactions through digital interactive features provided by technology. The aim of M-DEW is to ensure that real-world interactions would create a link with entities of the symbolic world; in other words, to support the interplay between concrete understanding and abstract thinking.

	Real world	Symbolic World	Science Classroom	multimodal Digitally Enhanced World
Modalities		Language (verbal) Written	Language Written	Language Written
	Vision Spatial reasoning Pattern recognition Colour perception Depth perception	Visual representations e.g. images Graphs Animations, etc	The visual Drawings Book's illustrations Book's text	Vision Static Graphs Dynamic (Online) graphs
	Audition Sound recognition, Sound localisation, Loudness perception, Noise masking etc.	Aural representations e.g. Music Spoken language Other sounds, etc	The aural Spoken language	Audition Spoken language
	Touch Kinaesthesia Haptics	Kinaesthetic representations	The actional Gestures Object manipulation	Action Hand movement
	Smell	Other		
	Taste			

Table 3-1: The term 'modality' as used in each sub-section.

3.2 Modalities of the real world

The real world is considered as the physical environment where learners act. It mainly involves everyday interactions with people and artifacts and results in learning about everyday issues, i.e. table manners, safety, hygiene. It could be related to Laurillard's 'everyday percepts' (1993), which afford learning from situated environments.

When modality is considered in relation to the real world, it is regarded as a sensory channel to perceive the world. Perception refers both to properties of the physical world and those of the perceiver (Sekuler & Blake, 1994). The nature of the environment determines what is there to perceive. Stimulation from the environment comes in various forms of physical energy: thermal, mechanical, acoustic and electromagnetic. The nervous system of the learner converts the patterns of this physical energy into neural events. It does so through his/her sensory modalities (Sekuler & Blake, 1994).

The different modalities, thus, are regarded as being vision, audition, touch, smell and taste. Instead of focusing on the sensory organs, the focus is on the act of sensing, that is, seeing, hearing, touching, etc. Depending on the task or the detail of the study of someone's interactions, there could be a more detailed description for vision which could be seen as pattern recognition, spatial reasoning, or other; or for audition which could be divided into loudness perception or noise masking; or for touch, there could be tactile and kinaesthetic channels (see Table 3-1). Touch detects properties of objects such as their firmness, shape, smoothness. Kinaesthesia provides information about movement and the position of limbs. When an object is manipulated, however, there is coordination of tactile and kinaesthetic information which is regarded as haptic information (Sekuler and Blake 1994).

Perception usually requires some action. To see, someone has to look, searching the environment until the desired object of regard is located. When someone touches an object, it is more easily identified if he/she explores it with the fingers. These examples recall what Gibson has argued, that perception is an active process which guides activity, thereby stimulating more activity (Gibson 1966), as cited in Sekuler & Blake 1994). The orientation of perception's action raises a distinction among the different sensory modalities regarding the proximity of the perceiver to the object to be perceived. Touch and taste require a direct contact with the stimuli and thus are considered as near senses. On the contrary, audition and vision can pick up information coming from remote sources and thus are regarded as distance senses (Sekuler and Blake 1994). It can be noted that virtual learning environments have been focused on the stimulation of the distance senses, neglecting the stimulation of the near senses which could provide learners with crucial information for understanding, engagement and reflection.

Although perception begins with the responses of the sense organs, it draws also on the perceiver's knowledge of the world. Knowledge permits categorisation, controls attention, guides acquisition of sensory data and supplies context for sensory data (Sekuler and Blake 1994). Familiarity can sharpen perception. Thus, with appropriate training, learners can perceive properties, patterns, and distinctive features that previously had been undiscriminable (Sekuler and Blake 1994). Extrapolating into the perspective of learning about science, when pupils look at graphs they do not necessarily see: they need to learn how looking at the graph can provide them with information, that is, they need to learn to interpret a graph. Forms of visual interactions develop and stabilise in interactions between people and objects (Stevens and Hall, 1998). The same could apply to other relationships between senses and science concepts: manipulating objects of the real world could help learners understand specific scientific concepts, i.e. force.

Steven and Hall (1998) argued for 'disciplined perception': learning situations could be seen as sequences in which people assemble and coordinate aspects of visual displays to make relevant objects visible to themselves and co-participants. Through active and embodied practices, people bring the heterogeneous elements at hand into coordination. Coordination between fine-grained actions are assembled to comprise distinct states of understanding (Stevens and Hall 1998).

3.3 Modalities of the symbolic world

The symbolic world describes aspects of the real world through symbols or signs. Each symbol is attributed with specific meaning in order to be manipulated and study their changes. Symbols can refer to any level of the real world: they could be thought as belonging to a continuum from imaginary signs to specific relationships of underlying laws of matter. The continuum can accommodate any symbol which requires interpretation and represents a description of the real world.

Representations are the main entities of the symbolic world that could be communicated through more than one sensory modality. Language, for example, can be heard, read or felt (if it is in a Braille form). In contrast, the diagram as a representation is highly associated with the visual modality even though it could have been acquired by another sensory modality (Eysenck and Keane 2000). Apart from visual or verbal representations, however, there are other representations, i.e. aural and kinaesthetic, which could explain features of the real world. It is argued that when designing learners' interactions with technology all of the above representations need to be considered: each one can facilitate understanding differently and, depending on the learning content, each one has different contribution in supporting engagement and reflection.

The symbolic world has been used greatly by scientists in their attempts to explore the relations between phenomena and study their interdependencies. Through representations, they can describe physical, chemical, or other phenomena and can denote the abstract concepts that are of their interest. The diagrammatic representation of force, for example, is shown by an arrow to describe its magnitude and direction.

These symbolic descriptions of the world devised by scientists create an unnatural environment in which Laurillard's learning 'precepts' are constructed (Laurillard, 1993). Learners of science are required to be able to understand these 'precepts' and learn how they operate and change.

When modality is considered in relation to the symbolic world, representations become the main interest, which result in a completely different idea of modality. Language, for example, is a way of representing information; but it also attributes meaning and structure to it. Any meaningful representation of information, such as a diagram or an image, has a specific structure which is communicated via a certain type of notation. So modality could be seen as a representation that gives structure to information and makes it meaningful. Modalities of the symbolic world are focusing on communication, thus verbal language and other representations are communicative modalities and they are different from the sensory modalities of the real world.

Apart from visual representations, aural representations can refer to something different than utterances. They could be used, for example, to refer to something that is not visually present in the particular settings of the event (van Leeuwen 1999). The sound of an ambulance on TV, for example, could be associated with emergency without the ambulance being visible. A piece of music, also, could be a type of aural representation that is associated to specific meaning or feeling. Music as a symbol has been used greatly by politicians to create a common feeling among their supporters, an example being Verdi's 'Nabucco' as a symbol of Italy's struggle for freedom and unity in the mid 19th century.

Sound has specific characteristics that can demonstrate different meaning depending on the context. Morse code, for example, can be heard as noise or it can have specific meaning for someone that knows how to interpret it. Morse code is communicating words through short and long tones. Untrained people can be completely ignorant to its meaning but experts can group the sounds not only in letters but also in words and phrases.

Van Leeuwen (1999) distinguishes between representation and presentation of sound to explain the difference between the sound that is accompanied by visual stimuli and the sound that stands alone. He draws examples from cinematography to show how the director uses aural stimuli to communicate extra information that is not visual.

Additionally, apart from visual, verbal or aural representations, there are also kinaesthetic representations that lead us to specific movement or action. This is associated with specific artifacts or tools that exist in the environment and the movements depend on the context of use. The pen, for example, is for writing and it is associated with the specific grip that enables us to write. However, even if the pen is for writing, it can also be a pointing device during a conversation about a written text. Thus the same tool can raise different movements depending on the context of use. Tools function as external representations which are related to the types of grips and the range of postures for using the tool as well as the type of action to be employed and the material to be acted upon (Baber 2003). Thus, objects of the environment represent a range of actions: from actions related to innate experiences (i.e. not to touch a burning hot surface) to those related to selecting ways of using a tool and where to act upon.

Representations can be re-structured and create different entities that still represent the same idea or concept. They would be in a different format, which could trigger different sensory modalities. Therefore, a visual representation could change to aural and kinaesthetic and vice versa. These representations could be associated with different modalities. Aural representations, for example, can have multiple visual notations, e.g. the stave with notes that represents both the musical sound and the movement through which to accomplish it. It can also be represented kinaesthetically by the specific gestures that the orchestra director makes. Likewise, kinaesthetic representations also have a visual notation e.g. choreography, instructions of how to assembly furniture, or how to play sports. Also a checklist for maintenance represents a key for a set of actions.

Just because representations can be translated not only based on their format but also on their sensory modality, these different representations are not necessarily equivalent. Larkin and Simon (1987) categorised representations according to their informational and computational equivalence. Informationally equivalent representations carry the same amount of information; computationally equivalent representations take the same effort to be processed (Larkin and Simon 1987). When considering representations for learning purposes the designer should consider representations that are informationally equivalent and easier or more direct to process.

Additionally, even though all representations require inferences about the represented world, some representations are more explicit than others: some representations provide a direct mapping to a meaning, e.g. the minor key denotes melancholic music. By contrast, Morse code provides a less direct mapping to a specific meaning since it corresponds to specific letters; one has to translate the code to natural language to interpret its meaning. This mapping between the representation and the represented object has to be explicit when the users of the representation do not carry it as part of their expertise (Stenning and Oberlander 1995).

3.4 Modalities of science classroom

The science classroom is one instance of the real world. Its significance, however, lies in the fact that it is where learners are introduced to the symbolic world. There is a set of topics to be learnt, specified by the science national curriculum, which refer to real world phenomena expressed into symbols. In the science classroom, students should become able to express these descriptions of the real word in 'scientific' or symbolic terms and understand the processes that underlie phenomena. To facilitate learners in achieving these goals, several steps are taken: teaching in the classroom, practical work, applications of information technology.

The modalities employed in science learning are a blend of real and symbolic modalities. In classroom discussions, the communication modality of language is mainly employed. There are also various other representations used either through the textbooks or through the teacher, e.g. gestures, models, graphs. Considering a typical school day, the main activities of students are talking, writing and reading (Tamir 1991). These activities show an emphasis on language as a communication modality. Occasionally, once or maybe twice per week, students will have the chance to use their hands, eyes, smell and other senses to do a task, observe, measure, check the results. Through practical work, students are using their sensory modalities to gain 'hands-on' experiences.

The advantages of practical work could be associated to the use of multiple sensory modalities while learning. The problems of practical work, on the other hand, shows that multiple sensory modalities are not panacea: their usefulness lies on the fact that they can support engagement. Relating practice work to theory and associating the concrete manipulation of substances to specific laws and conclusions, however, depend on more efforts.

Furthermore, practical work within the curriculum has vast differences between the way pupils participate and give meaning to their activity and the way professional physicists do (Lave and Wenger 1991). Lave and Wenger (1991) place the difference in the community of practice (community of physicists vs. the community of schooling adults); here the difference of interest is the type of data which is under investigation. At the school lab, data handling aims to communicate some science content knowledge: to verfy how the world behaves, to understand relationships, to receive explanations of a phenomenon. This, in turn, could mean that the experiments do not have to be 'authentic' or similar to what 'real' science is like. Exploring the unknown is not the same as exploring the known (Millar 2002). Therefore, while the science lab contains real-world objects, it supports artificial (rather than authentic) interactions.

Kress et al. (2001) described a successful demonstration in a science lesson where a combination of real-world modalities with symbolic modalities is employed. In particular, speech, object manipulation, body movement and visual images are in a constant interplay to support meaning making. Since learning in the classroom involves the interaction of modalities not only from the symbolic but also from the real world, the next section explores how technology could support such modalities in situations where the teacher is not available or not as resourceful to relate practical work to theory and object manipulation to specific laws.

3.5 Modalities of the digitally enhanced world

A world that would provide individuals with both sensory and symbolic modalities would be a mixed world. It would aim to strengthen the relations between the real and the symbolic world and facilitate learners in interacting with both of them. Within this world, people would be able to manipulate efficiently symbols and artifacts not only by vision or language but also by the rest of their senses. To do so, this world would be digitally enhanced: not only it would link the real to the symbolic world but also it would incorporate features of digital interactive technology. The DEW is considered as a real world environment with digital features which would support the links between the real and the symbolic world. Using real-world interactions, it would create digital effects of how instances of the symbolic world are affected. It would employ innovative or existing technology coupled with useful activities to facilitate meaning construction.

Manipulation of symbols and artifacts could be related to Laurillard's expression of everyday 'percepts' and learning 'precepts' in education. She argues that learning 'precepts' (symbols) are different from everyday 'percepts' (artifacts and actions) because the means of accessing them are so limited. Percepts are experienced directly and precepts are experienced through representations. A fundamental aim of this DEW would be to strengthen the relations between Laurillard's percepts and precepts; between actions and representations of actions; between the situated and the abstracted; between the real and symbolic world.

To succeed in this aim, DEW should provide learners with resources in the appropriate format for meaning construction. The resources would be multimodal: since actions in real world employs sensory modalities, and actions in the symbolic world employ communicative modalities, the links between the two worlds would need to employ modalities from both worlds. As a result, the multimodal digitally enhanced world would accommodate the range of communicative and sensory modalities that are related to the learning task.

So far natural language aims to provide the bridge between descriptions of the real world and abstract representations of the symbolic world. It structures phenomena and attributes meaning to symbols. Natural language or other linguistic expressions are currently the main medium of transferring pupil's thought from concrete to abstract concepts in schools. However, it is not the only way and not without burdens.

Considering that students have little experience in scientific expressions, either in natural language or symbols, they need to relate abstract representations to something concrete, familiar. Wilensky (1991) argues that to reify abstract ideas, pupils have to go through a concretizing process or 'concretion'. Defining concreteness not as a property of an object but rather as a property of a person's relationship to an object, he regards 'concretion' as a process of the new knowledge coming into relationship with itself and with prior knowledge (Wilensky 1991), which relates to the links that Constructionism advocates. He also argues that "the more connections we make between an object and other objects, the more concrete it becomes for us" (Wilensky 1991). Since concreteness refers to a person's relationship to an object, there is a need to facilitate interactions with different objects, being real or symbolic, in ways that their relationship is augmented.

From such viewpoint, abstraction becomes a process of connection rather than ascension (Noss and Hoyles 1996). The challenge for learners is to construct multi-faced connections between activities and experiences that are somehow similar. Abstraction becomes an issue of how to add new friends and relations instead of ascending to unattainable heights (Noss and Hoyles 1996). For example, learning through physical manipulations of symbols within M-DEW can give learners the opportunity to relate an already known activity (that of manipulation) to something they do not know yet (the symbol). Being able to physically manipulate a symbol, could reify the symbol, since through manipulation it 'becomes a new friend' and learners could construct relations between the physical activity of manipulation and the symbol.

Additionally, learning through physical manipulations of symbols can make symbols personal and give learners a realisation that they are 'doing science' while they are manipulating, as Papert (1980) proposes. Being able to manipulate the symbol with their own actions, makes symbols directly related to them and thus, makes it personal. Learners would have a more direct way to perceive the links between reality and symbolic representations: a way that would trigger their attention, keep them engaged to the task and motivate them to reflect.

Concrete thinking has been considered by Piaget as one stage which should progress to the ability to abstract (Piaget and Inhelder 1958). Later, Turkle and Papert (1990) have argued that concrete and abstract thinking are not stages of development but styles that different learners prefer. In particular, they argue that concrete thinkers (bricoleurs, as they name them) construct theories by arranging and re-arranging, by negotiating and re-negotiating with a set of well known materials. Mistakes are the essence of navigation by mid-course corrections. On the other hand, abstract thinkers are analytic, create plans, follow rules and keep a distant relationship with objects; their mistakes are considered as missteps that should be avoided (Turkle and Papert 1990).

It could be, however, that concrete and formal thinking are neither styles nor developmental stages. Viewing concrete and abstract thinking as two faces of the same coin, they could live together within a learner in a constant interplay to facilitate meaning construction. As Ackermann (1991, cited in Noss and Hoyles, 1996) proposes, concrete and abstract are dialectically interrelated rather than opposed.

One of the ways that scientific thinking is distinguished from everyday thinking is precisely this movement from formal to informal, from analytic to perceptual, from rigorous to intuitive and back (Noss et al. 1997). However, scientific thinking does not simply carry over of meanings derived from 'everyday' referents: on the contrary, scientific and everyday meanings are reshaped in the interplay between 'abstract' and ‘concrete’ activities (Noss and Hoyles 1996). By augmenting this interplay, learners might be facilitated to construct scientific meaning and interpret symbolic entities and their changes.

Multimodal digitally enhanced worlds have an important role to play in the support of this interplay between concrete and abstract. They are related to computational environments where “meanings can be constructed from an intersection of resources mobilised by actions, in which ideas become connected to existing understanding and activities” (Noss and Hoyles 1996). M-DEW would allow learners to construct and negotiate emerging ideas, to create links between concrete understanding and abstract thinking.

3.6 Conclusions

In this chapter, modality was studied as belonging into different ‘worlds’ as an attempt to associate existing uses of the term from research in HCI and ET. Each world is the place where learners interact with symbols and artefacts. Thus, a modality of the real world is a sensory or real world modality and refers to the act of sensing. A modality of the symbolic world is a communicative or symbolic modality and refers to representations, being verbal, visual, aural, kinaesthetic, etc.

The environment of the science classroom was identified as one instance of real-world where learners are introduced to the symbolic world through the employment of multiple sensory and communication modalities. However, pupils’ interactions with objects are not necessarily connected to theory nor to symbolic entities. As a way to support physical with symbols, the introduction of a multimodal digitally enhanced world (M-DEW) has been proposed.

Yet, this categorisation of modalities is only a starting point to describe processes that can support the learning activity. Modality –being sensory or communicative- supports fundamental interactions through which learners construct meaning. Therefore, how the interactions take place in these different worlds needs to be explored. These worlds are seen from a multimodal perspective: it is the contribution of each modality in the learning task that is of interest, and the ways that multiple modalities can be combined and linked through the interventions of digital interactive technology. This exploration leads to a theory-informed framework described in the following chapter: it is the result of analysis and synthesis of a diverse literature of computer aided learning, real world interactions and representations as notational tools.

Chapter 4

A theory-informed framework for multimodal interaction

4.1 Introduction

This chapter presents a framework for multimodal interaction to inform the design of learning environments that support science learning. Towards this aim, it is investigated how people interact with artefacts and symbols within different environments or 'worlds'. The focus is on learners' difficulties with science, which partly occur due to difficulties in interacting with entities of the symbolic world. In this chapter, it is argued that a learning technology should combine elements of real-world and symbolic-world interactions that are useful for the learning task. It would also need to incorporate activities which facilitate engagement and reflection through the employment of multiple real and symbolic modalities.

The previous chapter studied aspects of different modalities as seen into different 'worlds' (see columns of Table 4-1). In this chapter, learners' interactions within these worlds are considered in relation to specific modalities relevant to the task of learning about forces and motion. Three different modalities are considered: moving (and touching), seeing and the linguistic. In particular, a learner that is able to move, to see the effects of his/her movement and to record the actions is considered to be a participant in a multimodal digitally enhanced world (M-DEW). A learner that sees somebody else moving, and records these movements is considered as having restricted access to the proposed world that is very similar to interactions with existing multimedia learning environments. Finally, there is a learner that does not have access to technology at all, but reads what he/she could have done and writes down estimated answers based on these readings. Such a learner has even more restricted access to real-world modalities and thus has to interpret the symbolic world through purely verbal representations (Table 4-1).

Worlds / Modalities	Real World	Symbolic World	Digitally Enhanced World
Full access to real-world modalities (manipulating)	Manipulation of objects and understanding	Thinking of Representations and understanding	Physical manipulation of representations and understanding
Restricted access to real-world modalities (observing)	Watching and understanding		Watching representations being manipulated and understanding
Even more restricted access to real-world modalities (reading)			

Table 4-1: The framework for multimodal interactions: the focus is on learners' interactions within different worlds when they have full access to real-world modalities.

A crucial goal of an M-DEW learning environment would be to enhance the links of the real with the symbolic world. Additionally, regarding a learner-centred approach, multimodal interaction should aim to provide the appropriate interactive means to increase learners' engagement and reflection. The focus of design therefore should not be only on the technology but also on the learners' activity. Issues of main importance for the activity are: manipulation, narration and self-evaluation. Manipulation refers to both objects and symbols' handling, narration refers to oral and written descriptions of the activity and self-evaluation refers to the formation and transformation of ideas through experimentation. These three issues aim to augment rhythmic circles of engagement and reflection that would promote their understanding.

The framework for multimodal interaction, shown in Table 4-1, has been informed by existing literature (see subsequent sections) and three experimental studies described in the next chapters. In particular, learners' interactions with the real world are explored by research in situated interactions with objects/tools in the environment (second column of Table 4-1). It led to an experimental study (case study 1) where students manipulate objects to learn about forces (Chapter 5). The aim was to study how different interactions with objects can facilitate learners' engagement and reflection. It also aimed to verify a proposed categorisation of the employed objects according to their learning potential.

Furthermore, learners' interactions with the symbolic world are studied by research in external representations (third column of Table 4-1). The section studies representations as abstracted forms of action. In particular, Scaife and Rogers (1996) described the underlying processes that occur when learners interact with representations. This thesis extends their view of mental interactions with representations to include also physical interactions with representations in an attempt to enhance the relationships between the processes of acting and abstracting.

Interactions with the real world have been synthesised with interactions with the symbolic world to form a set of multimodal interactions within a Digitally Enhanced World (fourth column of Table 4-1). It is argued that for situations where the representing concept is about changes in the environment, learners that are physically employed with representations will be engaged and able to link concrete actions with the abstract symbolic representations. This argument is explored by two case studies. In the first M-DEW case study, students could physically interact with a distance-time graph to learn how to interpret it (Chapter 6). In the second case study, older students physically interacted with two kinematics graphs to learn about the links between the distance-time graph and the velocity-time graph (Chapter 7).

Interactions within M-DEW are explored through three points. First, the transition between the real-world and the symbolic world is on focus and the use of multiple modalities is stressed as a way to facilitate it. This transition refers to the process of achieving concrete relationships with abstract concepts. It is studied, therefore, how the employment of multiple modalities can facilitate learners in constructing concrete relations among the act of movement and abstract issues of force and motion.

Second, the impact of M-DEW in science learning is explored. The employment of multiple real-world modalities is suggested that augments learners' understanding of scientific concepts. Its main influence derives from supporting learners to enact rhythmic cycles of engagement and reflection. Additionally, M-DEW gives access to Papert's notion of syntonic learning (1980) which provides learners with the opportunity to relate scientific concepts to themselves and allows them to experiment with alternative ideas.

Third, functions of multiple representations are discussed under the multiple modalities perspective. It is discussed how these functions can occur explicitly when the learners' movement causes the changes of the representation, creating a space of multimodal digitally enhanced interactions which can affect the symbolic world. Additionally, it is suggested that multiple (symbolic and sensory) modalities can enrich interactions with representations since they incorporate extra information that support learners' engagement and reflection. To this end, learners' interactions with representations are discussed under the perspective of multiple modalities to explore how the symbolic world can be enriched.

Subsequently, the need of multimodal digitally enhanced interactions is suggested for the successful design of a learning environment. For learners to succeed in their interactions, the focus should not only be on the technology but also on the activity. Therefore, instead of focusing only on the design of a learning technology, in this thesis the focus is on the design of the learning activity that is supported by digital technology. As a result, the characteristics of an M-DEW technology are proposed along with features of M-DEW activities.

Finally, M-DEW is compared to other computational environments where it is proposed that M-DEW is not depended on the type of technology Whichever technology can couple types of sensory action to a symbolic representation and combine activities to support rhythmic cycles of engagement and reflection could be an instance of M-DEW.

To summarise, the diagram below describes the set of issues discussed in this chapter.

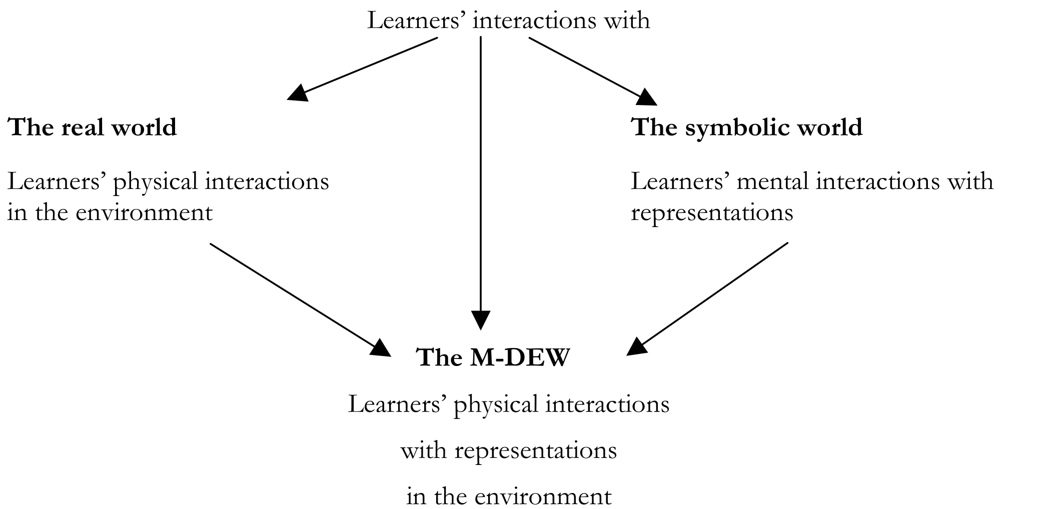


Figure 4-1: The issues of the M-DEW interactions

The next sections explore how interactions with objects and representations can be seen as both physical and mental. In particular, section 4.2 explores interactions with real world objects and how they can enhance learners' engagement and reflection. Section 4.3 explores interactions with representations and their advantages. It also stresses how learners need support in order to benefit from their advantages. Section 4.4 explores M-DEW interactions and their effects on learners in relation to concrete and abstract understanding, science learning and its impact on the symbolic world. It is argued that physical (or real world) interactions with representations can facilitate learners' reification of abstract concepts and their body can provide them with a notation or even a language for understanding graphical representations. Section 4.5 proposes a set of technological and activity-related features that are important for learners to succeed in their efforts. Finally, section 4.6 compares M-DEW to other computational environments including augmented reality, virtual reality and microworlds. The M-DEW related issues are further explored by experimental studies with participants of different age groups discussed in the following chapters.

4.2 Interactions in the real world

In their interaction with the real world, people employ their sensory modalities as they act in their environment. The physical aspects of learning are experienced through the kinaesthetic modality. As mentioned earlier, kinaesthesia refers to movement and position of limbs and it is employed both when the body is moving and when interacting with objects (Sekuler and Blake 1994). Learning through movement could make learning transferable: it can be carried with the learner in other situations (Smith 2002). Additionally, physical artefacts and the ways they are employed by learners are resources for learning and can enhance it in numerous ways. There are several types of objects, and a few categorisations have been proposed by the literature. Baber (2003), for example, considered a general activity of tool-use and suggested that artefacts can act as

- amplifiers to extend humans' perceptual abilities, e.g. the telescope,
- correctors to enhance humans' perceptual disabilities, e.g. hearing aids,
- augmenters which substitute a set of cognitive abilities, e.g. a calculator, or
- representations which represent knowledge or part of a task.

Considering a categorisation that would relate to the learning activity, a different categorisation is proposed in the next section. It is shown how tools as supportive means can be seamless, can facilitate reflection, keep the learners engaged with the activity or sometimes prohibit the activity. Such taxonomy could be useful for the design of the learning activity to advocate which artifacts to have for manipulation, which to make transparent and which to avoid.

4.2.1 Interacting with artefacts: manipulation and understanding

Learning usually involves concern and action by the learner, who sometimes employs surrounding objects for support. This section analyses how interacting with objects can augment understanding. The result is a categorisation of the role of objects in the learning activity. From all the objects that can be used, some are better than others in meaning construction, questioning events or in supporting the task as tools.

To write notes, for example, students have to get a pen or pencil and a piece of paper. These objects become transparent tools and are not perceived as separate from the learning activity. Such objects support learners' continuous engagement, e.g. the pen and notebook when attending a seminar. The pen and paper in such a situation are not perceived as separate entities in the activity but as part of it. The learner is concentrating on the activity of attending or, to use Heidegger's term, is 'thrown' into attending the seminar and they do not attend to the pen's use. Thrownness, as explained by Winograd and Flores (1986), can be evoked by a number of observations, such as that learners cannot stop acting (writing) because they will miss part of the idea they wanted to record; they cannot step back and reflect their actions without losing the information presented by the speaker; they do not have a stable representation of the activity (seminar) at the time, because anything can change as the seminar progresses, but they may have fragmented propositions. At the end of the seminar, the learner will be able to reflect on the situation and interpret it with intentions or outcomes but it was not the understanding they had during the seminar. Learners also have different interpretations of the same learning activity so what one thinks of the seminar can be very different from another. Therefore, the pen and notebook are not the focus of attention and they need to stay transparent if we want the learner to remain engaged in such an activity. If the pen becomes of focus, e.g. if it runs out of ink, the transparency is disturbed and the object becomes apparent as a thing in itself, failing to support the task at hand (Winograd and Flores 1986).

Similarly, Bødker (1989) has talked about activity flow, that is, performing an activity through actions and operations without conscious planning and executing. Automation of effort and direct engagement are apparent when there is coordination among the actions for accomplishing a task, the artifacts and the environment. Unexpected behaviour and interruptions result in breakdowns which are situations wherein planning, acting according to plan and evaluating are necessary. Breakdowns are opportunities to learn but they are exceptions to the daily routine (Bødker 1989).

To put it differently, situations of breakdown or unexpected behaviour are chances for reflection: the learner has the opportunity to focus interactively on the outcomes of the action, the action itself and the intuitive knowing implicit to action (Schön 1991). Depending on the activity, the learner can reflect while in the activity or after the activity is over. Objects have an important role to play in this reflective process. Some objects could pose questions about the activity while in a flow and others could act as anchors to ground the learning activity each time the learner remembers or faces it. While assembling a piece of furniture, for example, a learner could revise the whole activity if a peg is left over. Alternatively, having manipulated a weight in the classroom, learners could reflect on it later when they place it on top of a kitchen scale. Learners that have access to a situation promoting reflection are moving towards a learning activity in which they have total control and freedom to choose for themselves rather than conforming to the influence of others (Boud et al. 1985).

Objects have also been seen as mediating the activity by Vygotsky and his successors: auxiliary means by which interactions between actors and objectives are mediated (Cole and Engeström 1993). Vygotsky also argued that the ways in which tools and signs are used vary depending on the context and the learner's own development (as cited in (Daniels 2001)). Invented tools, turned from history to nature, are invisible, unremarkable aspects of the real world, therefore transparent. These tools literally carry intelligence in them, in that they represent an individual's or a community's decision to reify a set of actions for use by others (Pea 1993). As such, tools become invisible and harder to see them as bearers of intelligence; instead we see intelligence in actor's mind using the tool (Pea 1993).

Manipulation of artifacts, therefore, is not a merely physical activity but involves cognition as well (Baber 2003; Trouche 2003). Each artifact has specific potential and constraints that are closely interrelated. The user is not free to use the artefact at will: its design has pre-structured the user's actions. At the same time artefacts encourage a certain type of utilization: any utility offered to the user promotes one type of action instead of another (Trouche 2003). With the employment of the sensory modalities relevant to manipulation (touch, kinaesthesia and vision) learners could keep themselves engaged not only physically but also cognitively.

Baber (2003) has proposed a categorisation of forms of engagement that could be grouped in physical, cognitive or environmental engagement. Physical engagement is related to the use of morphological, motor and perceptual abilities of humans when they are using an artifact. Cognitive engagement is related to the ability to coordinate actions through psychomotor skills, to relate the use of artifacts to specific goals and to represent the artefact's function with a particular theory of use (that is, the grip and posture the user is supposed to adopt, the type of action assumed to be employed, the materials to be acted upon). Environmental engagement refers to the ability to respond to aspects of the environment. Responses could be innate, learnt through stimulus-respond conditioning, or represent specific perception-action coupling. Environmental engagement includes cultural engagement which refers to the ability to acquire artifact-using skills from others as well as the way in which artifact using reflects traditions of action. These forms of engagement aim to explore the cognitive aspects of tool use (Baber, 2003) which support the idea of the beneficial learning outcome of artifact manipulation. Thus, in a learning situation when learners are involved in questions about how to hold an artifact, what to do with it, what other objects could be used with, etc. they demonstrate their engagement within the activity. Not all questions are difficult to answer, e.g. the decision of how to hold an object is usually straightforward; thus it is also important to encourage learners to seek answers of questions that have varying difficulty.

For learners to keep seeking answers to questions of varying difficulty, there is a need for immediate feedback to facilitate negotiation of meaning. In learning by apprenticeship, for example, learners have access to the tools of the community of practice as well as other elements of a heterogeneous repertoire of resources that the community produced or adapted in the course of its existence and have become part of their practice (Wenger 1998). From this repertoire of resources, learners get immediate feedback either from the experts or from the task itself. They can, for example, plan the activity and perform it; if the use of tool does not confirm the plan then they can revisit the plan. Such practice suggests that there is an interplay of engagement and reflection: being engaged with the activity and reflect on it when revisiting the plan. Therefore, feedback is one fundamental issue for keeping learners engaged and assuring that they seek answers of their practice.

However, some objects may structure the experience more than others. These objects add to the construction of meaning and thus are considered significant for the learning experience. When objects are employed in a learning activity, the learner initially pays attention to its affordances, for example, that a ball affords throwing or squeezing. Apart from the physical properties of the object itself, however, the way that the object fits in the environment and with the learning goal can also influence the activity. As suggested by Pea (1993), when artefacts are used, they usually provide resources for the guidance and augmentation of the learning activity.

To summarise, physical objects may have differing importance in a learning task. Aiming to provide a guideline for designers of learning environments, Table 4-2 has been conducted to clarify the learning potential of different objects. In particular, some objects may seamlessly support the activity and should remain transparent, and others may be obstacles to the activity and thus should be avoided. Focusing on the objects that should be noticeable, some objects support learners' reflection on the activity and should be ready at hand: some objects are opportunities for reflecting while in the activity and others are reminders of a past activity. Furthermore, some objects support continuous engagement in the learning activity: these objects are specific to a domain and should be available to be explored (Table 4-2).

Functions that each object support	Requirement
Seamless support of activity	Objects to be transparent
Support reflection while in the activity Support reflection after the activity Keep learners engaged in the activity	Objects to be ready at hand and capable to be explored
Provide obstacles to the learning activity	Objects to be avoided

Table 4-2: Categorisation of objects according to their learning potential

Interacting within the real world (seen here as manipulation of objects) involves being engaged in three interleaved ways: physically, cognitively and environmentally. This engagement triggers learners' meaning making. However, they also need to realise what learning goals they achieve from object manipulation. It needs to be ensured that learners learn from such interactions with objects and they don't just become caught up with the activity: thus they need to be able to reflect.

4.3 Interactions in the symbolic world

A symbolic modality is an interpretation function which attributes meaning to a specific notation. It is a representation of some kind, so modality has been considered regarding the type of representation, be it a diagram or a graph and not associated to the sensory stimuli.

4.3.1 Interacting with representations

Bearing in mind that the symbolic world is based on communicating through language and other representations, this section focuses on visual representations and what operations take place when people interact with them.

Scaife and Rogers (1996) created a framework for explaining the underlying processes of interacting with representations and proposed 'external cognition' as a perspective for assessing more effectively how technological innovations in graphical representations should be approached. The external cognition perspective focuses on the cognitive processing involved when interacting with external representations, the properties of the internal and the external structures, and the cognitive benefits of different graphical representations. There are three main advantages that people gain while interacting with representations:

- computational offloading that refers to the cognitive benefits from a representation,
- re-representation that relates to their structural properties, and
- graphical constraining that relates to possible processing mechanisms.

In particular, computational offloading expresses the extent to which external representations reduce the amount of cognitive effort required to solve informationally equivalent problems. A diagram, for example, represents only the information that is of interest having abstracted from details. The key issues while interacting with a representation is searching for information, recognising and drawing inferences (Larkin and Simon 1987). The issue that provides the main difference between diagrammatic and sentential representations is the drawing of inferences. Some types of representations afford spatial inferences and some others logical inferences. According to Larkin and Simon (1987), how good a representation is depends on how quickly and easily these inferences can be drawn. Having a title 'a cat and a table', for example, is not the same as a picture of a cat and a table: the picture shows where the cat is in relation to the table which cannot be inferred from the title.

Re-representation refers to how different external representations with the same abstract structure can make problem solving easier or more difficult (Zhang and Norman 1994). For example doing calculations with Arabic number is much easier than using Roman characters. Being able to translate from Roman characters to Arabic provides learners with the luxury of manipulating an easier representation (Arabic numbers) and thus facilitate them in their task.

Additionally to the ability to draw inferences, Stenning and Oberlander (1995) have focused on the weak expressiveness of diagrammatic representations that can facilitate reasoning. Thus, graphical constraining refers to the way graphical elements in a representation are able to constrain the inferences that can be made about the underlying represented world (Stenning and Oberlander 1995).

Whether the user will take these advantages from interacting with representations depends on the level of expertise, the knowledge domain and the type of task (Scaife and Rogers 1996). In the particular case of this thesis, the task is to learn, the knowledge domain is science learning and the level of expertise is novice learners[1]. In such a case, the advantages are under question, mainly because learners are novices. Firstly, learners cannot benefit from computational offloading from their first interactions with a graphical representation because they are in the process of learning to interpret it: they have to put extra effort to understand what the representation stands for. Secondly, while learning to interpret a representation they may also learn about the structural properties of the representations but very few learners are aware of it. Regarding 'graphical constraining', learners can be 'constrained' by graphical representations only when they have understood what the representation represents and they start using it for drawing conclusions.

Another issue is whether learners are willing to manipulate these symbols. The willingness of learners to manipulate symbols could depend on their ability to understand what they are doing and why they need to do it. Diagrams or other abstracted representations are useful for those who understand them and know how to take advantage of them. Bearing in mind the abstracted form of graphical representations, learners often face difficulties in reifying them. Learners who can manipulate velocity-time graphs, for example, may not be able to relate the graph to real world problems and entities.

To be able to benefit from the advantages of using representations, learners need support in interpreting the graphs and be able to use them repetitively in context.

4.4 Multimodal Interactions in the Digitally Enhanced World (DEW)

In this section we focus on learners' interactions with digitally enhanced technology. These interactions would take place within a different world, the M-DEW. M-DEW is an environment where real-world interactions can affect symbols with the aid of digital technology. In particular, the problems that learners face when learning about science can be regarded as being partially due to the problematic transition of understanding between the real world and the symbolic. In this transition, understanding of abstract symbols is the main goal. For the support of both the transition and the understanding of

[1] Even though in some cases the participants of the case studies had a prior understanding of the phenomena under investigation, they had not been involved in the specific activities and thus are considered novices.

abstract symbols, it is argued that a new environment needs to be introduced where learners can employ both real-world and symbolic modalities.

In particular, it is argued that physical manipulation of representations which results through the employment of kinaesthesia and vision (real-world modalities) and representations (symbolic modalities) can support learners in

- understanding the representation and its properties,
- being able to manipulate the symbolic world and interpret its changes,
- drawing inferences in terms of scientific principles.
- relating among representations with similar properties,

With the employment of real-world modalities, learners have the opportunity to exercise activities that are not only related to symbolic representations but also to real world activities. Thus, the process of reification takes place subtly, without the learner having to try explicitly to concentrate on symbol interpretation. The employment of sensory and communicative modalities, additionally, can provide learners with repetitive experiences through unlimited testing of the correspondence of the representation with the real life situation. They have the opportunity to carry out repeated tests in a controlled environment and see the effects in terms of the symbolic representation. Thus, the learners' level of expertise increases rapidly.

It is also argued that the process of combining real-world and symbolic modalities facilitate the linking between the real and the symbolic world. Subsequently, the impact of a multimodal Digital Enhanced World (M-DEW) in learning is studied (Section 4.4.2).

The employment of both symbolic and real-world modalities through interacting within an M-DEW can support learners' engagement and reflection. It also gives them access to syntonic learning, making M-DEW a constructionistic environment of learning by constructing relations among abstract and concrete entities. What is more, an M-DEW environment can enhance the interactions with the symbolic representations: when symbolic and real-world modalities are combined in a learning activity, all of the functions of multiple representations proposed by Ainsworth (1999) are supported as shown in Section 4.4.3.

Thus, providing learners with interactions within M-DEW aims to support learners in a smooth transition betweeb the real and the symbolic world, keep them engaged and trigger them to reflect, and also their interactions with symbolic world are augmented since they can exploit the functions it supports.

4.4.1 Transition between the real and the symbolic world interactions: the role of modalities

Considering learning within school settings, pupils have to understand the world they experience through their senses in a way that is expressed in symbols. Mathematics and science subjects are the most vibrant examples of this symbolisation of knowledge that pupils should understand at school. Symbols are abstracted forms of representing knowledge and pupils have to adjust their understanding through linguistic interpretations of symbols. Such a process has been acknowledged by educationalists as problematic (e.g. (Wilensky 1991; Turkle and Papert 1990; Noss et al. 1997) and many educational technologies aim to make it easier.

Linking the real world to the symbolic, in this thesis, is regarded as a repetitive circular process where learners' understanding is augmented each time they go around. Following this metaphor, 'concretion' (Wilensky 1991) is an iterative process of going from the concrete ideas to abstract thinking and vice versa.

Interactions within a digitally enhanced world can support this process where concrete actions find their abstract counterpart through physical manipulation of representations. With each physical action learners can change the representation, creating causal relations of "actions" and "effects of actions" similar to real-life situations. Furthermore, they can see that their actions cause changes both to a representation and to the real world, which could broaden their understanding to include more symbols as descriptions of reality. At the same time, the representation can influence their action: to generate specific representations, for example, they need to find the corresponding actions. This influence makes learners able to manipulate the symbolic world and interpret its changes. Their actions can also become advocates of abstract understanding which can augment their inferences in terms of scientific principles: their actions can lead to an understanding of the principles that underlie the phenomenon under representation, resulting in more experimentation and creating new relations between the symbolic and the real world.

Therefore, a digitally enhanced world that can support such process would need to be multimodal in order to accommodate interactions from real-world and symbolic modalities.

Additionally, interacting with objects of the real world is something that learners learn early in their lives. By the time they are expected to learn about symbols, learners have already developed an expertise in interacting with objects. This expertise is brought into the classroom by the pupils and teachers try to accommodate it into the lesson: it results in pupils constructing relations among what they already know with the symbols of the content material, which is an example of successful learning (Duffy and Jonassen 1992). Bearing in mind that teachers usually do not have the time to accommodate all learners' experiences into the classroom, some learning technologies aim to facilitate these constructions of relations between real world and symbols. Therefore, even though teachers could do the linking between concrete experience and abstract concepts without the use of digital technology, digital technologies could be the means to augment this linking. M-DEW is a conceptual environment which accommodates technology for this linking and does not rely on the teacher to facilitate learners in constructing relations between concrete and abstract concepts.

The employment of appropriate sensory modalities can provide pupils with the required information to construct relations between the real and the symbolic world. It can provide them with the interactive means to communicate information that reifies abstract concepts. This reified information could not only prohibit them from misunderstandings but also scaffold their understanding by facilitating constructing relations between the symbolic and the real world, the abstract and the concrete.

A crucial question that arises is which modalities to accommodate when. In existing conventional learning technologies, i.e. a book, the visual modality is the main means of communicating the subject to be learnt. However, modalities have a functional specialisation, that is, some modes have been developed to do better than others in specific tasks (Kress et al., 2001). Each modality has a different communicative potential, which is shaped by culture and society as they have provided different opportunities to evolve modalities' affordances and constraints. Graphs, for example, are used to show relationships among two or three variables over a large number of measurements; based on humans' visual pattern recognition abilities, they show trends and spot subtle differences in shape which is not visible in tabular data (Mokros and Tinker 1987). So visualisation of trends and their anomalies are functions for which graphs are specialised. Thus, when learning to interpret graphs, employing the visual modality is important. Depending on what the graph represents, the employment of a second modality may be required. If the graph represents movement or motion, for example, the employment of kinaesthetic modality could help the learner realise the relations between somebody's or something's movement and the changes of the graph. If the graph represents forces, the employment of kinaesthetic along with touch – force-feedback - is crucial so that all three modalities can be accommodated by the interactive technology. Therefore, the learning task denotes which modality to employ: it depends to the connection between the real-world activity and the representations used.

4.4.2 The impact of M-DEW in science learning

In existing interactive learning technologies, there is a correspondence of objects and symbols. So a ball in the real world can appear as an attractive graphic. What appears to be missing is the correspondence of direct manipulation: direct manipulation in the real world is very different from 'direct manipulation' in the virtual environment. The former involves the employment of kinaesthesia, touch and vision to manipulate the actual object. The later, however, involves vision and haptics for striking keys and using the mouse instead of manipulating the actual object. Touching and manipulating materials and objects, however, could lead to a deeper, more effective type of knowing (Jones, M. G. et al. 2004). This lack of correspondence between manipulation in real life and in virtual environments could create a space of assumptions and gaps that may be the cause for learners to fall into continuous misunderstandings.

The aim in a multimodal DEW is that the learner would be able to use the advantages of both the real and the symbolic world without facing their problems. In particular, in an M-DEW, learners will be able to use their modalities, e.g. kinaesthesia, for the same purposes they do in the real world. They could physically interact with objects by moving them and touching them or they could just move themselves about. These interactions, however, would be digitally enhanced: they would be the input to a digital environment to produce related calculations and graphical representations that are of interest. Other types of interactions could involve access to information that was previously hard to access, i.e. manipulating viruses (Jones, M. G. et al. 2004). Thus learners would be able to move or manipulate objects and see the effects of their actions on display expressed as scientific symbols.

It is argued that the use of the relevant modalities, i.e. the use of vision and kinaesthesia when learning about motion, or vision and haptics when learning about forces, triggers the learner's attention and keeps them engaged to the task. The significance of movement to learning has been considered by educationalists but is mainly proposed for primary school children (Smith, 2002, Hadzigeorgiou, 2002). One of the reasons could be that primary school learning does not focus on abstract concepts of science but explores the real-world and how it changes. Secondary school on the other hand, aims to abstract pupils' thinking through mathematics and science. These scientific symbols and concepts not only explore but also explain the environment. As a result of the Piagetian influence that abstraction is a developmental stage, the significance of movement or other real-world modality diminishes to be substituted by mental activities. This thesis argues that information coming from real-world modalities has a great importance, independently of learners' age or subject. If secondary school students employ real-world modalities in the learning activity, thus, they may be able to concentrate for longer periods of time, enjoying the learning activity more.

The main influence of M-DEW in learning is argued to be in learners' engagement and reflection. It needs to be clarified, however, that engagement and reflection are not facilitated at one instance or serially. Through interacting within M-DEW, learners enact cycles of engagement and reflection. Similar patterns have been noted for writing activities: according to Sharples (1994), writing consists of rhythmic movement between engagement and reflection. The act of generating a graph in real time can be considered as a type of writing: instead of writing letters or words, the learner writes other types of symbols on the monitor. The engaged learner devotes her full attention to the task of creating symbols. Reflection consists of 'sitting back' and reviewing all or part of the displayed shapes, forming and transforming ideas, planning what new symbols to create and how to do them.

Engagement and reflection are not mutually exclusive: they are two constituents intrinsic to the process of meaning construction. They are two interactive dimensions which can take different forms and degrees. They are a duality, which describes an interplay. A duality is a single conceptual unit that is formed by two inseparable and mutually constitutive elements whose inherent tension and complementarity give the concept richness and dynamism (Wenger 1998).

What is more, interaction within M-DEW give learners access to what Papert (1980) called syntonic learning. Being a constructionist instance of learning by doing, syntonic learning aims to establish a firm connection between personal activity and the subject to be learnt. The term is used with qualifiers that refer to kinds of syntonicity, i.e. body syntonicity, ego syntonicity, environmental syntonicity (Papert 1980).

In more detail, by having access to the generation of the graph, and being able to change it as they move about, learners can relate the graph to their senses and knowledge about their body (body syntonicity). For example, to move the hand or keep it still would cause a line to be generated on the display: this gives them the chance to realize the difference between the line that represents motion and the line that represents the lack of it. Such an experience can make learners think of the abstract representations not as alien to their understanding but as a source of meaning that is linked to themselves.

Graph generation also gives them a sense of themselves as persons with specific goals and desires (ego-syntonicity) and gives them a sense of excitement and satisfaction when they accomplish it. They have to shape a specific graph: the graph becomes a specific goal that is easily accomplished. The positive feelings arisen from such an accomplishment can greatly enhance learning by keeping the learner on the task and provide stimulus for new learning (Boud et al. 1985).

Being able to plot a graph according to their movements gives learners a realisation that they are 'doing science' and links science to out-of-school activities: it associates science with the idea of being active and on the move (cultural syntonicity). The abstracted form of a graph becomes a meaningful representation of the hand's motion. The graph describes not only school laboratory situations but also real world movement. Learners can be stimulated to relate their activities to scientific concepts and to question whatever is not easily related, they, thus, become scientists themselves.

Furthermore, it could be argued that there is a duality between the movement and its graphical expression that are interchangeable (Noss 1997): the graph is a rigorous description of the learner's movement and the movement is executable as graph via the M-DEW. M-DEW could support this duality, through the constant interplay between the movement and the graph that allows to create dialectic relations between the practical and the theoretical. M-DEW can provide the means to formulate abstract symbols which can be explored by learners in order to be understood. Such a computational environment could offer a 'channel of access to the world of formal systems through the mixture of concrete understanding and abstract thinking' (Noss 1997).

In syntonic learning environments, the pupil's task is not to learn a set of formal rules but to develop sufficient insights into the way she moves in space to allow transposition of this self-understanding into shapes that would look similar to specific 'target' graphs (Papert 1980). The interactions within M-DEW is in accordance to such environments: the pupil would be able to try out different ideas of moving to create an understanding that relates to herself.

Additionally, M-DEW does not aim to provide answers; it aims to encourage learners to find solutions through experimentation. Furthermore, instead of trying to forget their errors, learners are encouraged to study the problem so that the process of correcting is part of the process of understanding.

4.4.3 The impact of M-DEW in interacting with the symbolic world

In this section, functions of virtual learning environments are studied since they describe explicitly the existing learners' interactions with the symbolic world. The functions are discussed regarding what could happen when multiple modalities are employed. The aim is to propose that the use of multiple real and symbolic modalities can provide learners with valuable support throughout their actions in a learning activity.

Ainsworth (1999) proposes that virtual learning environments serve one or more of the following general functions: to complement, to restrict and to construct deeper understanding. These functions can be divided into sub-functions. In particular, a learning environment uses representations to:

- provide complementary information or to support complementary cognitive processes,
- restrict possible misinterpretations,
- construct a deeper understanding of a situation (Ainsworth 1999).

In more detail, complementary information can be different or partially redundant (Ainsworth, 1999). To learn about kinematics graphs, for example, learners need to relate movement with the lines of a distance-time (d-t) graph. During a learning activity, learners could try a specific hand movement repeatedly so that they realise the relationship between the line and the movement. This is redundant information. It aims to make clear what is the effect of movement on the graph. Redundancy is a crucial component in learning but there is a point where redundant information becomes boring. To avoid this, learners should also be able to try different movements to see their effect on the graph. Say for example, a movement to the left generates a line with a different direction than moving to the right. This is different information. It aims to communicate the meaning of directionality of the graph. Thus the coupling of hand movement with the distance-time graph provides learners with different and redundant information, as could two visual representations.

In such interaction, using both vision and kinaesthesia is important. Information processed by a single real world modality might not be enough for the action to occur. Different information, e.g. the movement and the d-t graph, provided by different modalities, e.g. vision and kinaesthesia, is crucial for a learner to understand the abstract representation of speed. If the learner only observes (employs only vision), she might not be able to relate every movement to the lines of the graph. If the learner only moves (employs only kinaesthesia) without seeing the effect of the graph, she might not be able to link the movement to the graph.

In an interactive learning environment, learners may also benefit from complementary cognitive processes supported by different representations. Representations that contain equivalent information can enable salient different inferences (Ainsworth 1999). In the kinematics graphs example, learners move about and watch the d-t graph being generated. The graph shows movement in one dimension but the hand can move in five. Thus when they change the dimension of their movement (e.g. from left-right to forward-backward), the generated graph still shows what happens regarding the initial dimension. This is valuable information: learners can realise that a distance-time graph describes movement in one dimension only; they could also realise that the x-axis of the graph is measuring time and not a different dimension of movement. What is more, they can also realise that 'doing' science means to be consistent with the initial decisions throughout the activity.

To restrict misinterpretations, two representations could be used: one familiar to the user that restricts and one that presents something to be learnt. The restricting representation does not provide new information to the user; it only supports her reasoning about the less familiar one. It aims to restrict the learner's inferences to relevant issues (Ainsworth 1999). The employment of different modalities can also contribute in restricting misinterpretations. It is argued that when employing multiple modalities, a 'real' modality can facilitate inferences for the symbolic one. When a graph is generated by the movement of the hand, learners can be 'graphically constrained': the graph constrains the inferences that can be made about the underlying represented world of motion. When their hand stays still, for example, the graph would show the 'lack of movement' line. Learners, in such a way, can see how 'lack of movement' looks and create associations that they can recognise, instead of recall, every time they see such line or keep their hand still. Thus, possible misconceptions are constrained.

Educational systems that aim to support deeper understanding focus on supporting abstraction, generalisations or showing relations among different representations (Ainsworth 1999). The employment of multiple modalities can also support deeper understanding since it facilitates learners understanding of abstraction: it provides a stable relation to reality that learners can refer to continuously while interacting with the technology.

In particular, in a multimodal learning activity, different symbolic and real modalities could provide links/associations that reify complex abstract concepts. Symbolic and real modalities can provide information and support processes that highlight structural relations between movement and graph, for example, and thus relate abstract graphs to real actions. By combining interactions with representations and real world modalities, learners are also sharing their effort between something they know (how to move) with something they don't know (how the graph would look). Thus, computational offloading is achieved since learners do not have to memorise rules of what a specific line represents. With their ability to test the effect of movement on the graph repetitively, the linking between movement and its graphical representation becomes explicit, personal and easier to handle.

By employing multiple modalities, learners can also link among multiple representations of motion. When employing their own movement, the learner is able to realise that the same movement (of their hand) can be represented by more than one graph; each one looking different. The continuous update of the graphs can enhance the linking among different representations and movement (see chapter 6). With such conditions they can realise that there are different ways of representing the same event, and thus be introduced to the concept of re-representation. Two representations can share the same structural properties but look different: each one is useful for a different task. Then the learners have the chance to question which representation is better when.

In summary, when symbolic and real-world modalities are combined in a learning activity, any of the functions of multiple representations are supported, providing learners with a fruitful activity.

4.5 M-DEW: special features

In the previous section it was argued that allowing learners to interact within an M-DEW supports them in linking between the real and the symbolic world, keeps them engaged, makes them reflect. Additionally, learners' interactions within an M-DEW supports further functions that are provided by the symbolic world. It was also mentioned that an M-DEW would be an environment where technology and learners' activities have an important role. The employment of multiple symbolic and real-world modalities is maximised not only by the use of specific technologies but also by the use of specific activities. While studying multimodal interaction, it became apparent that learners' interactions took place not only with the technology but also with the researcher, the task they had to do and the objects that were part of the particular environment. When studying interactions within M-DEW, therefore, the focus is both on features of the technology and the activity.

The next section therefore discusses technological and activity-related features that are significant in M-DEW interactions for the support of science learning. These features form a set of requirements for designing a learning environment, which aims to capture the needs of learners for specific science learning tasks. These requirements are not exclusive but aim to extend technology-based approaches to requirement elicitation to include a broader context of use. The M-DEW case-studies described in chapters 6 and 7 have taken into consideration these requirements and explored their usefulness in specific science learning tasks.

4.5.1 Technological features

When technology can generate symbolic representations from real-world movement, the link between movement and its representations is reinforced and meaning construction can be fostered. In such a highly interactive environment, the integration of symbolic with real-world modalities gives the opportunity to associate real life actions with scientific symbols. However, for the coupling between the movement and the representation to be strong, the technology should have specific features which are mainly related to its feedback to the learner. A set of these features is provided below.

4.5.1.1 Automaticity

The system's generation of the symbolic representation should be automatic. The symbol generation from the system speeds up the process of representing since it omits the difficulties of creating the symbol, e.g. a graph and frees pupils to focus on its interpretation. Researchers have argued for the importance of immediacy both in pupil's developing understanding of the conventions of graphing, and in their ability to interpret complex graphical representations (Ainley et al. 2000; Hennessy 2000).

Automated symbol generation in combination to real time feedback offers to pupils the maximum of immediacy. If minor changes in real-world movement cause changes on the representation then learners gain advanced understanding not only regarding symbol interpretation but also regarding the accuracy of their movement. They can realise, for example, that the concept of constant speed is difficult to implement by hand.

4.5.1.2 Synchronicity

The system's generation of the symbolic representation should be accurate and in real time with the movement. Having accurate and real time generation of the movement's symbolic representation can help learners believe the symbol and rely on it. Minor delays in symbol generation can make learners doubt the correspondence between their movement and the representation. According to Brasell (1987), delays of 20-30 seconds in the generation of a kinematics graph appeared to influence negatively student's motivation, engagement and their eagerness to experiment; in essence such delays made them passive. If the symbol is not in real time, learners may not 'remember' that they did movements that were inappropriate and they ignore or doubt the symbol. A few seconds delayed or inaccurate feedback from the system could also impose learners to challenge the correspondence between the symbol and the movement hindering any learning potential. If the symbol is in real time but not accurate, learners miss out the representation of their movement's details and cannot understand in full the correspondence between real-world movement and symbolic representation.

4.5.1.3 Sensitivity

Accuracy is related to system's ability to track physical action. An accurate system can guide learners to attend to salient points of the representation. A very sensitive system, however, could hinder opportunities for learning. Such system would be the one that presents involuntary actions such as a hand tremble. This extra information can confuse learners instead of give them the opportunity to learn. Thus, the system should be sensitive enough to show the movement that the learner is able to interpret, but not too sensitive to represent any involuntary movement which the learner does not control.

4.5.1.4 Continuity

Another feature of the interactive technology is that symbol should be continuously produced by the learner. Continuous graphing, for example, would highlight emerging patterns and anomalies and give access to the complete graph which gives a holistic view in graph interpretation rather than focussing on separate components (Ainley et al. 2000).

4.5.1.5 Ease of presentation

The symbolic representation should be easily produced by the learner. Easy generation of symbolic representations would keep learners trying different configurations in a game-like manner rather than effortful considerations. When new configurations can be tested, the learner is able not only to construct but also to negotiate meaning with the aid of the system's feedback. Negotiation can be seen as an active process through which learners dynamically adjust their expectations as new information arrive. It can facilitate meaning construction since learners can challenge their understanding.

4.5.1.6 Interpretability

The symbolic representation should be presented in a form that can be easily interpreted by the learner. The presentation style of the symbol is also important, for example, having numbers instead of graphs might not be useful to understand patterns. Having appropriate scales is also required as well as having a 'freeze' function at hand. Being able to freeze the symbolic representation could give learners an instant overview of the physical action in the form of a static symbol without having to repeat the action. It would even be useful to include Gestalt principles as a means to organise interpretation: objects that are grouped together, for example, they are perceived as "travelling" together, especially if they are moving towards the same direction or along some common path (Baron 2001). Therefore, presenting two symbolic representations at the same time it would be more interpretable if they are all moving in the same direction.

To summarise, a table of the specific technological features is given.

Technological features	Effects on learners
Automaticity: automated generation of the symbolic representation	speeds up the process of representation generation, omits the difficulties of creating a representation and allows pupils to focus on symbol's interpretation.
Synchronicity the generation of representation should be accurate and in real time with the movement.	helps learners believe the representation and rely on it.
Sensitivity the presentation of representation should balance between accuracy and efficiency	guides learners to attend to salient points of the representation.
Continuity representations should be continuously produced by the learner.	highlights emerging patterns and anomalies and gives access to the whole representation rather than focussing on separate components.
Ease of presentation representations should be easily produced by the learner.	keeps learners trying different configurations in a game-like manner rather than effortful considerations.
Interpretability representations should be presented in a form that can be easily interpreted, with appropriate scales and a 'freeze' function	supports learners' willingness to understand the symbolic representation. provides an instant overview of the action in a form of a static symbol.

Table 4-3: The proposed technological features and their effects on learners.

4.5.2 Activity-related features

When technology supports the features above, the coupling between movement and its representation is reinforced. For a successful interaction within M-DEW, however, the de-coupling of movement and symbol should also be supported. The de-coupling of movement and symbol would be demonstrated if the movement is reminded by the symbol without the presence of technology to provide a direct link. It would also be demonstrated if the symbol is reminded when moving without the presence of technology. Such de-coupling would also ensure that the learner abstracts from the real-world situation the relevant scientific concepts. To support such de-coupling, the emphasis is on the activity. The aim of the activity would be to create supportive scientifically-rich activities in which representations become meaningful. The activity therefore, should support physical manipulation, narration and self-evaluation.

4.5.2.1 Physical manipulation of symbols

By manipulating objects and symbols, learning is enriched by being not only a cognitive activity (which would be that of mentally manipulating symbols) but also a physical one (that of manipulating objects). By reinforcing their own physical manipulations, learners have the ability to personalise symbols and give them a feeling of 'doing' science which could have a key role in providing them with an engaging activity.

4.5.2.2 Narration

Creating narratives would be a way to emphasise the links between the movement and the symbol. In narration, there are two elements: spoken and written descriptions. When learning to *tell* a story, learners re-create a static representation in terms of the dynamics by which it was created. From their movement they get the narrative drive; having already a language to describe their movement, they use it to do so. This is everyday language. From the static representation they get a picture of the whole story; they can relate visual appearances of the symbolic representation to specific activities described in their story, e.g. the hand was steady and then it moved to the right. Therefore, through the spoken narrative learners verbalise their actions: their movement gives them access to body syntonic learning which is verbalised in natural language and thus becomes personal before it relates to scientific language.

By describing their actions in *writing*, learners would be in a rhythmic cycle of engagement and reflection (Sharples 1994). Learners would have to stop their interaction with technology and be able to reflect on what they did. They would also take a distance from their interactions with technology and reflect on their movements. This rhythmic cycle of engagement and reflection pushes understanding forward since engagement provides new material for consideration and reflection offers re-interpretation of the material and new plans to be enacted (Sharples 1994). Additionally, learner's written descriptions would be characterised from manipulation-specific vocabulary, i.e. the directionality and speed of movement. Thus, it is not only that they learn to match each movement to a symbol's component but is also that they learn to describe what they do in a learning task-specific way.

Learners' written descriptions could also be associated with the descriptions of their science textbooks, providing an anchoring backdrop to the schooling procedures. Generating representations that can be found in textbooks could associate these representations to their current activity.

Additionally, introducing scientific terminology (used in the classroom) during the activity could relate specific vocabulary in the context of manipulation and visualisation. Learners' spoken narratives could have words that are related to the symbolic representation but are not necessarily scientific: it would be the intervention of the teacher or the researcher that would hint to the appropriate vocabulary, i.e. in constant speed. Writing about such activities aims to facilitate learners in articulating their manipulations in a 'scientific' way, thus augmenting their understanding and providing them with the language to describe representations. It also aims to create a terminology link: writing down narratives of 'real-world' manipulations could couple real-world language with scientific one. In such a way, the transition from real-world to symbolic is further augmented and the vocabulary itself could be one more influence to the symbolic world.

4.5.2.3 Self-evaluation

Apart from writing narratives, M-DEW should also be characterised by activities where learners evaluate their performance and they could form and transform ideas through experimentation. To transform ideas about the relation between representation and manipulation, the activity would need to support breakdowns. Breakdowns are opportunities to learn (Bødker, 1989), so learners that have access to such activities can enhance their understanding of a scientific phenomenon. Breakdowns give learners the opportunity to reflect while they are doing the activity (Schön, 1991). They can be physical, related to their manipulations, or conceptual, related to their ideas about the manipulation outcome. When learners experience breakdowns while in the activity, they might look for guidance from the teacher or the technology. The aim is however to find the answer by themselves, by challenging their manipulations or ideas about what the symbolic representation shows. Through breakdowns from the physical activity or their thoughts, they have the chance to reflect-in-action, explore new configurations and adjust their movement and their understanding. Thus, the activity should prompt learners to evaluate their performance and overcome breakdowns by themselves through experimentation. Such activity would support the coupling between manipulation and its symbolic representation.

Rhythmic cycles of engagement and reflection

Cycles of engagement and reflection are not only noted during writing activities. According to Ackermann (1996), to reach deeper understanding, both 'diving in' and 'stepping out' are equally needed. Cognitive growth emerges as a result of people's attempts to solve irresolvable tensions between getting embedded and emerging from embeddedness (Kegan 1982 as cited in Ackermann, 1996). Learners need to get immersed in situations but also to step out (Ackermann 1996). They need to detach themselves by projecting their experience: to 'objectify' it and address it as if it was not theirs, to become their own observers, narrators, and critics. Then again they can reengage their previously objectified experience. They dive into it and try once more to gain intimacy (Ackermann 1996). Thus, through physical manipulation, narration and self-evaluation learners are involved in a rhythmic process with two interleaved entities: engagement and reflection.

4.5.2.4 Open-ended investigations

The activity should also involve open-ended investigations in which symbol generation and interpretation skills are developed through exploring different kinds of manipulations. Open-ended investigations can facilitate processes like problem solving where there is no single 'right' solution and learners can discover the underlying assumptions of the symbolic representation (Watts 1991). Through such questions, learners can identify causes for changes and make inferences, in other words, they can think critically.

The activity would also need to incorporate different but similar representations to allow pupils to focus on differences and common features, encouraging discrimination in a friendly way. Additionally, it could provide opportunities to explore relationships between representations.

4.5.2.5 Clear learning objectives

There are also educational related features that the activity should support, such as having an explicit purpose to the activity with clear learning objectives so that contextual questions can be set (Rogers, L. 2002) and a variety of scientific entities like newly minded objects (atoms), relations (Hooke's law), formal structures (graphs), etc. become entities not only to 'think about' but also to 'think with'.

Additionally, having a structured activity with introduction, development and conclusion is also important (Wellington 2003).

To summarise, the proposed activity related features are shown below

<table>
<tr><th>Activity-related features</th><th colspan="2">Effects on learner</th></tr>
<tr><td>physical manipulation of symbols</td><td>match each movement to a symbolic element
explore relationships between representations
learners are ‘doing’ science which provides them with an engaging activity.</td><td rowspan="3">provide rhythmic cycles of engagement and reflection</td></tr>
<tr><td>narration</td><td>learn how to describe what they do in a learning task specific way and thus provide them a language to describe representations
provide an anchoring backdrop to the schooling procedures
use of scientific terminology which facilitates vocabulary understanding and use
create a terminology link between scientific and everyday language</td></tr>
<tr><td>self-evaluation</td><td>form and transform ideas through experimentation
support breakdowns
support reflection-in-action</td></tr>
<tr><td>open-ended investigations</td><td>facilitate experimentation and problem solving</td><td></td></tr>
<tr><td>include different but similar representations</td><td>allow learners to focus on differences and common features of representation
allow learners to explore relationships between representations</td><td></td></tr>
<tr><td>clear learning objectives</td><td>allow to set contextual questions
scientific entities become not only entities to ‘think about’ but also to ‘think with’</td><td></td></tr>
</table>

Table 4-4: The proposed activity-related features and their effects on learners.

4.6 Comparing M-DEW to other computational environments

M-DEW is a conceptual environment where the real world is augmented by technology and specific activities in order to facilitate meaning construction. M-DEW’s technology does not have to be advanced or complex. As a matter of fact, simple technologies like data-loggers or oscilloscopes could be instances of M-DEW if they support the coupling and de-coupling between actions and types of symbolic representation. For instance, learners could explore concepts like wavelength and frequency through the ‘Sound &

Waves console and speaker set'[2] that measures the frequencies of sounds they hear (or do not hear) and shows the waves in graphical form. If such equipment supports the technological features and could be combined with activities that facilitate rhythmic cycles of engagement and reflection, it would have been an instance of M-DEW. Therefore, M-DEW could employ simple or advanced interactive technologies.

Likewise, instances of M-DEW could be introduced by existing technologies used for different tasks. Instead of using the mouse, for example, as a selection device, it could be used as a device to create kinematics graphs. Additionally, instances of M-DEW could be found in advanced technologies that provide learners with unique interactive experiences. Such technologies are reviewed briefly in the next section under the umbrella title of mixed reality environments.

4.6.1 M-DEW and mixed reality environments

Milgram and Kishino (1994) have proposed that computer environments can be placed in a continuum according to the degree of computer generated world (Figure 4-2). Starting from the left with the real environment, where there is no computer generated environment, connection to reality weakens as we move to the right and virtual components increase (Milgram and Kishino 1994). M-DEW sits in between real world and augmented reality: it is a real world in which some physical actions have a digital effect which can be seen on the monitor. It does not superimpose images on the real world as does augmented reality nor replaces the real world to a virtual equivalent as do immersive virtual environments.

Figure 4-2: The M-DEW in relation to Milgram & Kishino's (1994) Reality-Virtuality Continuum

Furthermore, Rogers Y. et al. (2002) have proposed a conceptual framework for interactions within mixed reality environments based on the changes that take place in

[2] http://www.cpo.com/CPOCatalog/SW/sw_home.htm. *Copyright 2003 CPO Science (*Formerly Cambridge Physics Outlet*)*

the state of the world as a result of the interaction between real, virtual and digital enhanced substances. These ‘tranforms’ could be:

- Physical action with a physical effect,
- Digital action with a digital effect and
- Physical action with a digital effect,
- Digital action with a physical effect

Each transform type has a different level of familiarity starting from the first which is highly familiar, the second type of transform being unfamiliar, the third familiar and the last highly unfamiliar (Rogers, Y. et al. 2002). M-DEW interactions lie on the first and third transform, where physical actions can have not only a physical abut also a digital effect.

The next sections discuss technological systems that belong to Milgram’s and Kishino’s (1994) reality-virtuality continuum and have focused on educational settings. In particular, it discusses augmented reality and tangible applications as well as some general issues of virtual reality. The review is not extensive since the technological details are not of interest for this thesis. It describes the available interactions that can be supported. Unless otherwise stated, the systems under description have not been tested in learning tasks.

In the majority of these environments, a starting point seems to be that physical manipulation of objects or any 3D structure would facilitate learning. It has not been studied why physical manipulations are beneficial for learning nor how such interactions can augment learners’ engagement. M-DEW however explores exactly such arguments: using an existing technology that supports physical manipulations, it studies what is the influence of such interactions to learners’ attempts to understand scientific concepts.

4.6.1.1 Augmented Reality systems

Augmented reality (AR) aims to enhance the real world by superimposing computer generated digital images onto video frames. An AR application presents a view composed of the real-world and digital information managed by computers (Klinker et al. 1998). AR can enhance users’ perception of and interaction with the real world. The virtual objects display information that users cannot directly detect with their own senses. The information conveyed by the virtual objects helps a user perform real-world tasks (Azuma 1997).

Most AR systems focus on blending real and virtual images and graphics. However, AR systems are sometimes extended to include sound. The user could wear headphones equipped with microphones: the headphones would add synthetic, directional 3–D sound, and the external microphones would detect incoming sounds from the environment (Azuma 1997). Recent technological advances allow also tangible interactions with objects e.g. (Fjeld and Voegtli 2002; Ikeda et al. 2003; Rajagopal et al. 2003).

An example of visual AR system is the MagicBook, which uses a book as the main interface object (Billinghurst et al. 2001). People can turn the pages of the book, look at the pictures, and read the text without any additional technology. However, if they look at the pages through a handheld Augmented Reality display, they see three-dimensional virtual models appearing out of the pages. The models appear attached to the real page, so users can see the AR scene from any perspective simply by moving themselves or the book. The models can be any size and are also animated, so the AR view is an enhanced version of a traditional three-dimensional "pop-up" book. Users can change the virtual models simply by turning the book pages. They can also fly into the page and experience the story as an immersive virtual environment. In the VR view, they are free to move about the scene at will and interact with the characters in the story. Thus, users can experience the full Reality-Virtuality continuum.

An example of visual, aural and haptic interaction is Augmented Chemistry: a workbench consisting of a table and a rear-projection screen (Fjeld and Voegtli 2002). Users interact with models in this virtual environment using a booklet, a cube, a platform, and a Gripper. Each page in the booklet is used to identify an element of the periodic table. A 3D model augments the mirror image of a booklet page, a platform, a cube, and a Gripper. Hence, users can select, position, rotate, compose, and deselect 3D models, thereby affecting the virtual environment with physical manipulations. They have differentiated the visual representation of atoms from that of the molecules and atoms are shown with a clearly visible nucleus and the outermost valence shell. Augmented Chemistry provides an audio feedback suited to each molecule construction, which is triggered by the different states of the molecule.

AR can provide a powerful tool that allows students to view and interact with sophisticated phenomena while providing flexibility to allow exploration of component parts of this system such as time, position, angles, rotation, and revolution (Shelton and

Hedley 2002). Exploring the potential of AR to advance visualization tools in astronomy education, Shelton and Hedley (2002) developed a tool to support geography students as part of an undergraduate curriculum class. In a pre- and post assessment, they studied how students' understandings of spatial content change through their physical interactions with virtual objects and they found a significant change. However, they did not compare these results to learning situations without using technology or with a different type of technology.

Tangible interactions

Focusing on systems that provide tangible interactions with objects, it has been argued that they can provide innovative ways of interaction: everyday objects can become devices with computational capabilities and thus provide extra opportunities for learning (Dourish 2001). In particular, tangible systems distribute computation across a variety of devices, which are spread throughout the physical environment and are sensitive to the location and their proximity to other devices. They augment the everyday physical world with computational power so that pieces of paper, ornament, toys etc. can be made active entities that respond to their environment and people's activities (Dourish 2001).

Several tangible systems have been implemented for educational purposes as an attempt to enhance educational experiences without technology being the focus of attention. Instead, they focus on the interactions with the artifacts, the effects of their actions in the digital environments and the novel ways of receiving feedback from the artifacts (Price and Rogers 2004). The artifacts used are called tangibles as they are embedded with computational power or closely coupled with digital responses (Rogers, Y. et al. 2002). Providing learners with these artefacts gives them opportunities for physical manipulation; therefore, from the augmented reality systems aiming at learning, there is a brief review of those that allow tangible interactions.

Monitoring systems

Tangible learning interfaces have been designed mainly for young children's learning as an attempt to trigger their imagination and accomplish the learning task through discovery. For example, TICLE (Scarlatos 2002) tracks the positioning of the pieces of a Tangram puzzle that a group of children try to solve and gives them hints about the correct positioning of the pieces. It is an experience where the children can just ignore the computer's suggestions and act as they would want or they could make use of its hints. The hints have the form of questions so that the children could think about the specific sub-problem before they get the answer. It has been used in the environment of a museum where groups of children (forth or fifth US grade) are invited to play with puzzles but such a task is not close to curriculum requirements.

Another example of tangible interface for learning purposes is proposed by Today's Stories (ESPRIT-i3-ESE Project No. 29312) which develops an experimental school environment for young children (4 to 8 years old) aiming that, firstly, children will learn from reflecting on their own or other children's activities and, secondly, that children will learn from other children's perspectives on their own activities. The project developed wearable technology to document such different perspectives, as well as tangible interfaces to review and to manipulate these episodes. In particular, there is a 'wearable' device (Kidscam) that audio-visually captures events in the child's daily life, and sends them to a collective memory of interrelated episodes. There is also a multi-media editing environment that allows children to build their own ongoing collective memory or portfolio out of the events captured with the KidsCam. The story authoring is achieved in collaboration with educators (teachers and parents) who stimulate processes of reflection and understanding. The aim is to aid the achievement of educational goals set in a curriculum for broad social development (Panayi et al. 1999).

The 'Lab of tomorrow' project resulted in developing wearable computers and intelligent sensors which use students movements to gather data, which can then be used to graph trends and patterns and investigate the laws of engineering and physics. This would provide students with the ability to apply science more widely, not only in specially designed experiments in controlled laboratory conditions.

Explorative environments

Snark (one of the products of the Equator project) is a digital creature that lives in a tangible environment where it expresses cues of behaviour depending on the children's interaction. The tangible objects of the environment provided unexpected responses in which the children had to reflect and find out ways to achieve their goals, that is, to trigger Snark's reactions. As children explored the tangible environment, they discussed their actions and their effects with the other children and there could also collaborate in acting to find out more reactions from Snark. Thus, children reflected on their behaviour and tried creative ways to interact with the environment. The children's reflection also heightened their awareness and stimulated them to speculate about their experiences (Price and Rogers 2004).

The 'magic carpet' (another product of the Equator project) is another example of a tangible interface to support storytelling activities within the classroom, involving large groups of children, and allowing young children to enact stories to audiences. They incorporated a number of technologies, i.e. arrays of pressure mats under the 'carpet' and the use of physical propos that are associated with either barcode or video tracking technologies (Stanton et al. 2001; O'Malley and Stanton 2002).

Digital Manipulatives

More examples of tangible interaction are the toys that have been developed by the MIT Media Lab as part of the initiative 'New Toys to Think With'. Digital Manipulatives (Resnick et al. 1998), such as Programmable Bricks (Resnick et al. 1996), Beads and Balls (Resnick et al. 1998) as well as environments where learners can think about the actions and interactions of individual objects (StarLogo, MOOSE Crossing). Later systems involve System Blocks, a physical interactive system for children to explore dynamic systems (Zuckerman and Resnick 2003), 'Curlybot', a vehicle that records its prior movement and repeats continuously which could support young children's learning of advanced geometry (Frei et al. 2000) and PegBlocks, a set of five wooden blocks that each supports nine protruding pegs to illustrate the 'conservation of energy' principle and allow children to discover the relationship between kinetic and electric energy (Piper and Ishii 2002). Such technologies aim to create 'spaces' of possible activities and experiences where educational designers cannot control what learners can learn (Resnick et al. 1999). Therefore they have not studied in depth how learners' interactions with the technologies have changed learners' abilities.

4.6.1.2 Virtual Reality systems

Virtual Reality (VR) proposed a new paradigm in interactive computer technologies in which all human senses would be exploited to create a substitute of the real world. It replaced the desktop metaphor with a world metaphor: a very useful shift in human-computer interaction. In some occasions, it also replaced interactivity with immersion.

Learning via VR environments can offer important benefits since it provides alternatives for training in hazardous environments, for manipulating very expensive real-life variables (regarding logistics, finance, personnel or national security), for experiencing entities in micro or macroscopic level, for enhancing, degrading or altering some aspect of reality, for simulating locations where physical interaction is impossible or difficult (e.g. under the sea, outer space) (Stedmon and Stone 2001).

Mantovani (2003) argues that VR can offer the following potential benefits:

- VR provides experience with new technologies through actual use: learning in virtual environments (VEs) requires interaction, thus encouraging active participation rather than passive observation.
- VEs can be an alternate method for presentation of material, new forms and methods of visualization.
- Interacting with a VR model can be as motivating or more motivating than interacting with the real thing, for example, using a game format.
- Shared VR can encourage collaboration and foster the learning of skills that can be better developed through shared experiences of a group in a common environment.
- VR learning offers the possibility to be tailored to learner's characteristics and needs
- VR itself offer a great potential as a tool for evaluation, since every session in the virtual environment can be easily monitored and recorded by teachers, thus facilitating assessment tasks (Mantovani 2003).

However, there are technological limitations regarding delivery of high performance and visual fidelity on low-cost personal computer workstations, assuring the longetivity and re-usability of training applications and standardising techniques for 3D computer modelling (Stedmon and Stone 2001). Additionally, other technological limitations demonstrated that is easier to use the world metaphor and interact with a digitally improved physical environment rather than simulating the physical environment convincingly (Psotka 1995). Furthermore, there is a great discrepancy among VR systems, which could differ according to many technological components, such as hardware and software configurations (obviously with different costs and usability issues), interaction modes, the use of the Internet, support of single/multi-user interaction, multimedia components embedded in the 3D worlds. These components influence many VR features such as the levels of immersion, graphic fidelity and interactivity, multisensory cues, possibility of collaboration, number and complexity of tasks supported (Mantovani 2003).

VR is distinguished since it focuses on the immediacy and control created by immersion (the feeling, which results from changing the visual display depending on the head and eye movements). The primary effect of immersion is to place a person into a simulated environment, which should look and feel like the real world. VR uses head mounted displays, tracking mechanisms, gesture and force feedback technologies to create a compelling experience. Stereo sound also can add to the sense of presence and immersion. However, technological limitations of burdensome equipment, lack of detail and slow computers limit the user's experience who are usually subjected to physical side-effects like nausea. The benefits of immersion focus on motivation and mindful engagement, which would result from the novelty, as well as from the challenge, interactivity, and realism of the experience (Psotka 1995).

VR systems have been used in training settings where learners could practice in difficult situations which rarely occur, or it is too expensive to do a mistake. These situations refer to warfare or astronautics. The main issue of concern was the ability of learners to transfer the skills learned in the virtual reality environment to the real world. Bearing in mind the sensitive information used, however, such training systems have extra needs for secure, remote network connectivity that are not directly relevant to schooling settings.

Construct3D is a construction tool in an immersive virtual environment which addresses specific needs of mathematics and geometry education (Kaufmann 2003; Kaufmann et al. 2000). The main advantage of Construct3D is that students actually see three dimensional objects which until now they had to calculate and construct with traditional methods. VR provides them with a nearly tangible picture of complex three dimensional objects and scenes. They argue that working directly in 3D space can facilitate comprehension of complex spatial problems and relationships better and faster than with traditional methods. However, there were inaccuracies in measuring positions of the virtual world (Studierstube) caused by tracker hardware, and user studies revealed a light form of cyber-sickness.

Additionally, Dede et al. (2000) developed ScienceSpace worlds, namely "NewtonWorld", "MaxwellWorld" and "PaulingWorld" which rely on 3D representations, multiple perspectives and frames of reference multimodal interaction and simultaneous visual, auditory, and haptic feedback, afforded by VR. These systems provide immersive learning environment in which students may explore the kinematics and dynamics of motion, electrostatic forces, and quantum-mechanical bonding (Dede et al. 2000). Exploring students' interactions with these worlds they argued that multimodal interaction (voice, virtual and physical controls) facilitate usability since individuals can adapt interaction to their own style. Additionally, they suggested that multisensory cues can engage learners direct their attention to important behaviour and relations, help them understand new sensory perspectives, and prevent errors through feedback use. Regarding the learners' experience they suggested that the display and virtual controls should be calibrated for each individual, sessions should be 45 minutes or less, to minimise simulation sickness and verbal communication should be used instead of written because of head mounted display restrictions (Dede et al. 2000).

4.6.2 M-DEW interactions and microworlds

Considering a microworld as a place where learners, though playing, may stumble over and then ponder important inspirations and concepts (Hoyles et al. 2002), we may find commonalities and differences to the proposed M-DEW interactions.

M-DEW, like microworlds, is a constructionism-based environment: it allows syntonic learning; it establishes a firm connection between personal action and the subject to be learnt. It offers a channel of access to the symbolic world through a mixture of concrete understanding and abstract thinking. It focuses on the construction of understanding through public entities which are 'windows' for investigation by both the learners and the researchers. The public entities in M-DEW are the symbolic representations that are presented on the monitor and the learners' writings.

The idea of a microworld involves an intention to develop an open and investigative stance to mathematical and scientific enquiry. It involves the designer's predictions of where breakdowns might occur: at the core of the microworld there is a model of a knowledge domain to be investigated by interaction with the software (Noss and Hoyles 1996). In M-DEW such predictions take place during the design of learners' activities: they result from studying the problems that learners face when learning specific subjects. Learners' activities are specific, but the ways that these activities can be done are open for learners to find out. Therefore learners have to develop an investigative stance to scientific enquiry.

In microworlds, exploration is necessarily constrained but in ways to promote learning; knowledge is not simplified, it is recognised as a complex, interrelated and evolving in action (Noss and Hoyles 1996). M-DEW has the same approach for exploration: manipulation of symbols occurs within the constraints of their symbolic reference; their meaning is recognised as complex which evolves through physical action.

In microworlds, as in M-DEW, meaning is expressed in action (Noss and Hoyles 1996). However, in M-DEW there is no need for what Papert (1980) has termed transitional objects, standing between the concrete/manipulative and the formal/abstract: this transition comes from their physical manipulations which correspond to their situated experience from the real world.

A main difference between M-DEW interactions with microworlds is that the former does not include text-based programming. Text based programming has been seen as a way for learners to be builders and thinkers while they build their own physical, virtual and mental structures (Hoyles et al. 2002). It is seen as a way for learners to express their ideas symbolically and as a glue that bound the different representations together (Hoyles et al. 2002). In M-DEW text-based programming is not supported but the same functions are aimed to be supported through physical movement: physically manipulating the symbols helps them construct their own physical, virtual and mental structures. Therefore, it is based on a new type of expressive 'language' that of direct physical manipulation instead of LOGO. Microworlds are based on linking among different symbolic representations; M-DEW supports linking between physical actions and symbolic representations.

Additionally, microworlds have their own tools and operations which are open for inspection and change: learners are both users and designers (Hoyles et al. 2002). The ability of learners to build their own tools has been restricted in M-DEW since the interaction with the technology does not change according to learner's conceptual change. Therefore learners are not designers. However, in M-DEW the operations provided by technology are open for inspection because this is a way to understand the links between the physical manipulation and the corresponding changes of the symbolic representation. Therefore learners can become critics of the conventions that underlie the symbolic representation.

Furthermore, regarding the structural features that characterise microworlds suggested by Edwards (1998), microworlds have a set of computational objects to aid reflection; links more than one representation of concept and includes a set of activities through which the learner is challenged to use entities and operations for a goal. M-DEW could be in accordance to the structural features of microworlds but computational objects do not need to be many, representations do not need to be visual (they can be aural or kinaesthetic) and learners are not challenged to use operations, just symbols. Regarding the functional approach of microworlds, suggested by Edwards (1998), in M-DEW, learners can manipulate objects and explore, interpret feedback and self-correct and use objects to solve specific problems. They cannot however use the objects to create new ones, as they could in microworlds.

As Noss et al. (1997) put it, the aim of supportive technologies is to find ways to help learners build links among seeing, doing and expressing, to study how meaning is structured, and to trace if the proposed process is helpful (Noss et al. 1997). The aim of the M-DEW is also to support such links: learners' physical manipulations are linked to changes of symbols to result to physical manipulation of symbols. It studies meaning construction through moving and seeing the effects of the movement, and through activities where learners are prompted to interpret these manipulations both in natural language and symbolically. The trace of the process occurs through programming in microworlds; in M-DEW the trace is provided through writing activities and generation of symbols on display. They are traces of how meaning construction is evolved throughout the activity. These traces are the means of studying meaning construction.

4.7 Conclusions

In this chapter, a theory-informed framework was suggested for multimodal interaction. This framework elaborated interactions within real world and how people engage in objects manipulation. Additionally, through research in interacting with representations, the interactions with the symbolic world were explored.

Furthermore, the interactions within a multimodal digitally enhanced world were studied. Initially, the transition between the real and the symbolic world was studied to suggest that the real world modalities can facilitate learners to reify abstract representations and other symbols. The impact of a multimodal DEW in learning was also studied to suggest that such an environment (M-DEW) can support learners' engagement and reflection and gives them access to syntonic learning. Additionally, the impact of M-DEW in the symbolic world was explored. Elaborating how the functions of multiple representations are augmented by a multimodal digitally enhanced environment, it was suggested that an M-DEW also gives learners better access to the symbolic world providing valuable support for complementarity, deeper understanding and restricting misinterpretations.

Subsequently, specific features that M-DEW should support were proposed. These features will act as requirements for the design of M-DEW case-studies that are described in subsequent chapters. In particular, technology-related features were proposed that would support the coupling of real-world actions with symbols. The features related to

- automaticity,
- synchronicity,
- sensitivity,
- continuity,
- ease of presentation and
- interpretability.

Furthermore, for learners to be able to de-couple the real with the symbolic world interactions, so that one reminds the other without the use of technology, activity-related features were also proposed. These features included:

- physical manipulation of symbols
- narration
- self-evaluation of learner's performance
- provision of open-ended investigations
- inclusion different but similar symbolic representation
- clear learning objectives

The last section compared M-DEW interactions with those suggested by other computational environments. In particular, it was argued that M-DEW technology do not have to be advanced to cover the technological requirements. Simple technologies combined with appropriate activities could be instances of M-DEW. Nonetheless, augmented reality and virtual reality systems with learning purposes are studied as a way to illustrate the lack of the benefits of physical manipulations in learners' meaning construction. However, meaning construction has been studied through interacting with microworlds. Therefore, a comparison between M-DEW and microworlds is conducted as a way to illustrate their commonalities and differences.

The next chapters investigate the framework for multimodal interactions in relation to different levels of employment of multiple modalities. In particular, it studies whether full access to multiple modalities, restricted access to multiple modalities or even more restricted access to real-world modalities has an effect on learners' meaning construction. Chapter 5 reports an experimental study that took place without the aid of interactive technologies that explored learners' real-world interactions with objects. Chapter 6 and 7 report two experimental studies, where students interact within an instance of M-DEW to learn about kinematics graphs.

The studies occurred in parallel to the theoretical investigations. In particular, research in real-world interactions led to the design and implementation of the experimental study described in Chapter 5. The experimental study informed the issues explored in the framework of multimodal interactions. Furthermore, the informed research of real-world interactions along with research in symbolic world interactions led to the first M-DEW study, after which the proposed framework was updated. Finally, the second M-DEW study arose from the informed framework and influenced it further. The timeline of the studies in relation to the rest of the research project appears in Figure 4-3.

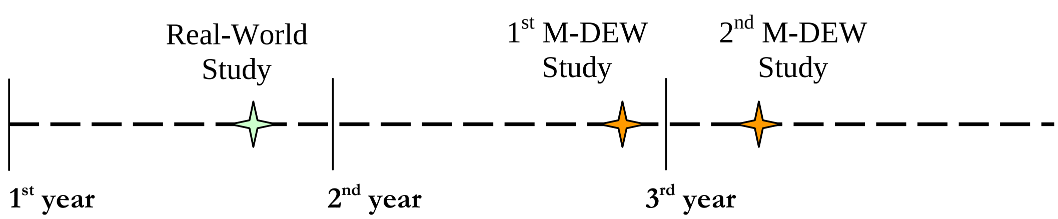


Figure 4-3: The timeline of the experimental studies in relation to the rest of the research

Chapter 5

Real-World Interactions: a case study

5.1 Introduction

As part of the framework for multimodal interactions that was elaborated in the previous chapter, a categorisation of real-world objects was given aiming to study the effects of real-world interactions in learner's meaning making. It was argued that physical objects may have differing importance in a learning task (Table 5-1). Some objects may support reflection during the activity and other objects may support seamlessly the continuous engagement in the learning activity. Objects may also influence the way learners reflect on the activity: some objects could be reminders of a past activity and others could be opportunities for reflecting while in the activity.

Functions that each object support	Requirement
Seamless support of activity	Objects to be transparent
Support reflection while in the activity Support reflection after the activity Keep learners engaged in the activity	Objects to be ready at hand and capable to be explored
Provide obstacles to the learning activity	Objects to be avoided

Table 5-1: Categorisation of objects according to their learning potential

In this chapter, this categorisation will be corroborated through an experimental study that provided learners with real-world objects for interaction. The question under investigation is how interactions with different objects structure the learning activity and facilitate meaning construction. In particular, real-world interactions are studied whereby students manipulate objects to revise the concept of force. The manipulation of objects is not supported by digital technology.

Additionally, the employment of multiple modalities is studied as to whether they can augment learners in constructing relations among manipulation and scientific issues of force. In particular, in the previous chapter, it was argued that the employment of real-world modalities can support learners in relating real-world actions to abstract concepts, and in drawing inferences in terms of scientific principles. In this chapter we investigate those arguments in the particular case of learning about force.

Furthermore, it has been argued that acting on real objects necessitates no push towards generality, no need for symbolic expression. The means of expressing actions is separate from the activity itself (Noss et al. 1997). This study takes into consideration this argument: the employment of real-world modalities is combined with other activities supporting learners in reifying the abstract concept of force subtly, without having to try explicitly to concentrate on symbol interpretation.

5.2 A pilot study

Prior to the main study about forces, a pilot study took place to become familiar with the process of designing and constructing an experiment and analysing the results. Additionally it was a chance to study multimodal interactions in relation to multimedia software use: would virtual objects have the same effect as real-world objects and which is going to better affect learners? If there is no difference in the communication of scientific principles between the different objects, what other factors influence learning apart from the employment of different modalities?

The comparison was among the participants using real equipment (Hands-on), 2D software, and 3D software. Both virtual equipments were the same as the real one. The aim was to see if there was a difference in learner's understanding between a real and a virtual learning environment, since different modalities would have been employed.

The 2D software simulating Hooke's law was created by the Open University, Knowledge Management Institute (Eisenstadt and Vincent 1998). The 3D software simulating Hooke's law, was created by B. Chong as part of his MSc project (Chong 2001).

Participants of the pilot study were 12 postgraduate students of the University of Birmingham. The learning task of the study was Hooke's law. Hooke's law states that the extension of a spring is directly proportional to the force acting on it. The objective was to have a concept related to forces but with an optimal level of challenge, so that participants would not be employed with too easy or impossibly difficult activities. Activities that provide an intermediate level of difficulty and challenge will motivate students the greatest (Malone and Lepper 1987)

The study was divided into three parts: a set of introductory questions, which students answered about the possible behaviour of the spring; a training session where the students experiment with real or virtual springs and weights; and a final test. The purpose of the introductory questions was to introduce the participants to the learning task and to verify that they did not know Hooke's law. The participants, subsequently, did the main task which was to interact with the software or the equipment, fill in a table with data and plot a graph. At the end, the participants answered the test.

5.2.1 Implications

There were problems regarding performing the experiment and assessing the learning outcome. In particular, in the Hands-on condition, there were problems with the equipment: the students' measurements were not accurate and the differences in the springs' diameter were not easily noticed. In the 3D-version condition, participants had problems with the interface regarding navigation as well as recognising the differences among the different springs.

Regarding the learning outcome, it became apparent that there should be an introductory session that would put students in context. The introductory questions were not enough and as a result students paid attention only to the issues required to answer the questions. Additionally, the learning activity did not have a particular structure: learners were left free to explore the equipment and find out what they need to do. In contrast, the 2D software had focused on the procedural aspects of collecting data and transforming it into a symbolic representation which can be easily interpreted (Eisenstadt and Vincent 1998). As a result, it had a clear structure which facilitated learners in meaning construction. Moreover, the 2D software had omitted details that were not of interest, e.g. the oscillation of the spring, helping students to get accurate results.

To summarise, the main benefit of the study was the experience of designing and constructing an experimental study. Additionally, manipulating objects per se is not enough to make learners construct meaning as Noss (1997) has argued. It was noticed therefore that there could not be a comparison between virtual and real objects. There should also be a teaching session to structure the activity and put it into context. The 'how' aspect of the learning experience needs to be combined with the 'what' aspect, which is the content of the learning task (Marton and Booth 1997). Thus, for multimodal interactions to be beneficial, it needs to regard both aspects of the learning experience.

5.3 The main study

For this study, the learning task concerned the concept of force for children aged 10, so the learning content had to be adjusted to the age group. In particular, they needed to show proficiency in four scientific aims:

- A force is a pull or a push,
- When a force is applied to an object, the object will move or it will change its shape,
- The greater the force applied to a spring, the greater its extension will be,
- The extension will be constant for the same amount of weight.

A force cannot be seen or heard. A force can be felt. The effects of a force, however, can be seen because it produces a change in shape or position at an object. By involving multiple modalities when learning about force, it might be that the abstract concept of force becomes reified.

In relation to the framework for multimodal interaction that was explored in the previous chapters, this study lies on the column of real world interactions as shown on Table 5-2. In particular, the study compares students that had access to full multimodal interactions, those that had access to restricted multimodal interactions and those that had no access to multimodal interactions. The full multimodal interactions consisted of manipulating objects, looking at the affects of their actions and reading and answering questions on the subject. A partial multimodal interactions consisted of looking at somebody else manipulating objects, watching the effects of the action and reading questions and writing answers. Finally, the students that did not have access to multimodal interactions had to read and answer questions based on a written introduction to the topic.

Modalities \ Worlds	Real World	Symbolic World	Digitally Enhanced World
Full access to real-world modalities (manipulating)	Manipulation of objects and understanding		Physical manipulation of representations and understanding
Restricted access to real-world modalities (observing)	Watching and understanding		Watching representations being manipulated and understanding
Even more restricted access to real-world modalities (thinking)	Thinking and understanding		

Table 5-2: The framework for multimodal interactions: the focus is on real-world interactions.

The study's hypothesis was: "when children manipulate objects by themselves, they will gain a better understanding of forces and produce better justified answers". The null hypothesis was that there will be no difference in children's understanding among the three conditions.

5.3.1 Method

The study was undertaken by three researchers in an adventure camp over a period of two days. Participants were 18 children with a median age of 10 years (Year 6). The pupils were from two primary schools. They were randomly assigned to one of the three conditions. The study took place in a laboratory room where there were three sets of equipment.

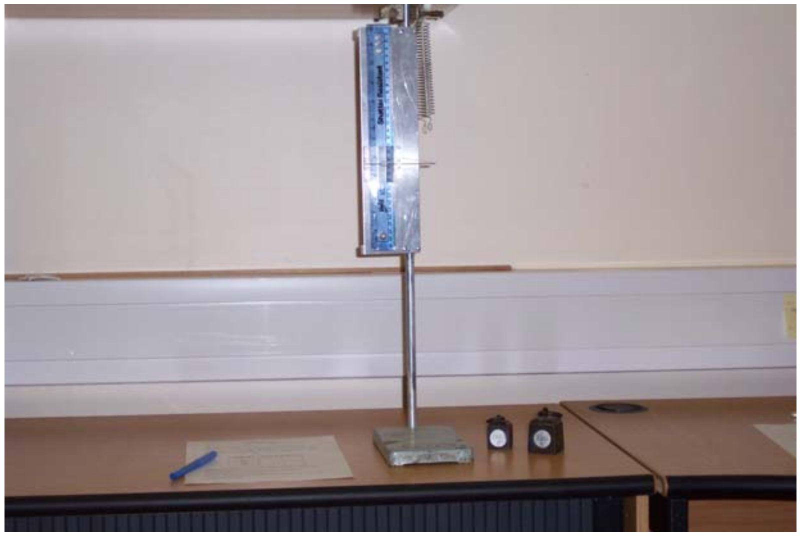


Figure 5-1: The equipment

5.3.1.1 Equipment

Based on lessons learnt from the pilot study, the students had special-purposed equipment that is used when studying Hooke's law at school. Each set comprised:

- a stand with a pointer and a ruler attached,
- a spring,
- two objects with a ring on top and their weight written on them and
- a piece of paper where the children recorded the experiment (Figure 5-1).

There were standard positions for the equipment.

5.3.1.2 Conditions

The study investigated the differences in children's understanding

- when they manipulated the equipment – the Hands-on condition,
- when they saw the equipment – the See-only condition, and
- when they had no access to equipment – the Imagine condition.

The first two conditions were the experimental conditions and they were compared with the third one, which was the control.

In the experimental groups, there were three children in the laboratory room in each session. Each child sat next to one of the researchers and both of them faced one set of equipment (Figure 5-2).

Figure 5-2: The researcher measures the length of the spring for the See-only condition

5.3.1.3 Procedures

Four tasks were assigned to all of the conditions (see Table 5-3): a set of questions, which asked the children about the possible behaviour of the spring; a training session, which introduced the educational task explicitly, and concluded by the children filling in a recording sheet; a test, which had eight questions of varying difficulty, and an interview, in which the children were asked to justify their answers in the test. The different sheets could be seen in Appendix A.

The children were introduced to the researchers and asked to answer a set of questions whilst trying to imagine what could be happening to the spring. Then, the author introduced the tasks they would have to do and explained the role of the researchers sitting next to the children. Throughout the study, a set of verbal protocols was used, to ensure that all children are given exactly the same instructions. Children could ask questions but nobody did so.

The training session for each condition involved the children being divided in the different conditions where they did the tasks of Table 5-3.

	Hands-on	**See-only**	**Imagine**
Set of questions	Appendix A		
Training session	The researcher gave a short introduction about forces, and prompted them to feel how a spring reacts to a force applied by them or by objects. The researcher spoke to all three children. The children were able to see and hold the spring and objects. Subsequently, the children were shown the equipment as a means of validating their understanding of forces in springs. They had to find out which object to hang on the spring and measure springs' length in order to fill in the Table of Results on the Recording Sheet. Children were then asked to complete the rest of the Recording Sheet.	The children attended the researcher's short introduction about forces, and how forces can be felt in springs and objects. The researcher spoke to all three children. The children could see the researcher handling the spring and objects. Subsequently, the children were shown to the equipment as a means of validating their understanding of forces in springs. Each child pointed at the objects they wanted to hand and each of the researchers hung the objects on the spring and measured its length. The children filled in the Table of Results on the Recording Sheet. They were then asked to complete the rest of the Recording Sheet.	The children read the teaching session, which explained what would happen if they experimented with springs and objects (see Appendix A). Subsequently, children were asked to complete the Recording Sheet by imagining an experiment where different objects were suspended on a spring.
Test	Appendix A		
Interview	Children were asked why they gave such answers in the final sheet.		

Table 5-3: The tasks of the participants of different conditions

The third part of the experiment for all conditions involved the children answering a test. They could go back to the Recording Sheet and look at the measurements; this was necessary for answering the last two quantitative questions.

Figure 5-3: A child plays with a spring in the Hands-on condition

Finally, each researcher asked a child to justify their answers to understand the children's reasoning. At the end of the experiment the children were thanked and given a certificate of completion (Appendix A).

5.3.1.4 Design

The students were assigned four tasks: initial questions, a teaching session, a final test and an interview. The initial questions asked them what they already knew about the subject. It was expected that the pupils will know about forces since they had already been taught the subject at school.

The teaching session aimed to remind participants about forces in the particular occasion of interacting with a spring and objects of different weights. One of the main aims of the case study was that when hanging an object to a spring, the spring is not only pushed but it also pulls back. For the Hands-on condition, children pulled a spring with the researcher, and then hanged on it two objects with different weights. They were prompted to feel the spring's tendency to pull back. Then, they used the stand to hang the spring and measure its length and its changes when they hang different objects on it. At the end they were asked to fill in the blanks in the Recording Sheets so that they can summarise what they did.

The third part of the case-study involved each participant answering a final test. They could look back to the previous sheets which was necessary in order to answer the last two questions. The final test aimed at checking if the children understood the scientific aims of their activity. In particular, the first question asked them if weight is a kind of force to locate the interest on the object's weight. The second and third questions checked if the children had understood that the object applied a force to the spring but also that the spring applied a force to the object –therefore that a force can be a push *or* a pull which was the first scientific aim. The fourth question was tricky: it had two correct answers. It wanted to check if they had understood that the spring will stretch *and* shrink when there is a force applied to it –therefore when a force is applied to a spring, it will change its shape which was the second scientific aim. The next question asked them in simple words, if the extension of the spring was proportional to the object's weight: if they could answer it they would have succeed in the third scientific aim. The sixth question asked them to name what is the cause of spring's oscillation: it aimed to double check that children understood that a force can be a push or a pull. The seventh and eighth questions were numerical questions related to the amount of the spring's extension. They were extensions of the 'table of results' of the Recording Sheet and required them to calculate what would have been the next two rows of it. To answer them correctly would show that they fulfilled the forth scientific aim of the case-study.

Finally, the fourth part of the case-study involved participants justifying their answers: for each answer they had given, the researcher asked them why they gave such answer in an attempt to make them reflect on their responses and open a 'window' in their thinking. The researcher wrote on the same answer sheet their responses.

5.3.2 Results

The results discussed below are based on the sheets completed.

From the initial set of questions, it was apparent that the children knew about forces and expected heavier objects to stretch the spring more. The students' ability was distributed between the conditions: there were two children in the Imagine condition that connected spring's behaviour to gravity, three children in See-only and one child in the Hands-on condition.

From the Recording Sheet, it was apparent that, in all conditions, the children realised the general concepts of force mentioned in Section 5.3, and they did not have problems in understanding what they did.

To understand the results of the test, the children's answers were scored according to the following criteria:

3 = correct answer and correct justification of the answer.

2 =half correct answer or answer with a calculation error but correct justification.

Half correct answer is considered to be when the children were supposed to mention two different behaviours of the spring and they mentioned only one, e.g. in question 4, twelve children answered 'the spring stretches because of the pull' instead of 'the spring stretches in case of pull, and shrinks in case of push'.

1 = correct answer but wrong justification

0 = wrong answer and wrong justification

For each child, the total score was calculated which was the sum of all the scores. The scores for each child can be seen in Table 5-4.

Final Test Scores per condition							
Hands-on							
Question	**Child1**	**Child2**	**Child3**	**Child4**	**Child5**	**Child6**	**Median**
1	1	0	1	3	3	3	2
2	1	3	3	3	3	3	3
3	0	0	3	3	3	3	3
4	2	2	2	2	3	2	2
5	3	3	1	1	1	3	2
6	2	2	2	0	0	3	2
7	0	1	0	3	3	3	2
8	0	0	1	0	2	3	0,5
Total	**9**	**11**	**13**	**15**	**18**	**23**	**14**
See-Only							
Question	**Child1**	**Child2**	**Child3**	**Child4**	**Child5**	**Child6**	**Median**
1	3	1	0	0	0	0	0
2	0	1	3	3	3	3	3
3	1	1	0	1	3	3	1
4	1	2	2	2	3	3	2
5	1	1	3	3	1	3	2
6	0	2	1	1	3	2	1,5
7	0	0	0	0	2	3	0
8	0	0	0	0	3	2	0
Total	**6**	**8**	**9**	**10**	**18**	**19**	**9.5**
Imagine							
Question	**Child1**	**Child2**	**Child3**	**Child4**	**Child5**	**Child6**	**Median**
1	2	3	3	0	0	3	2,5
2	0	3	0	3	3	3	3
3	0	1	1	0	3	3	1
4	2	1	2	3	2	3	2
5	1	1	1	3	3	1	1
6	2	1	1	2	1	2	1,5
7	0	0	2	0	0	0	0
8	0	0	0	0	0	0	0
Total	**7**	**10**	**10**	**11**	**12**	**15**	**10.5**

Table 5-4: The scores and median values of the final test for each condition (max score=24).

Additionally, the median scores were calculated for each question of the final test (Figure 5-4).

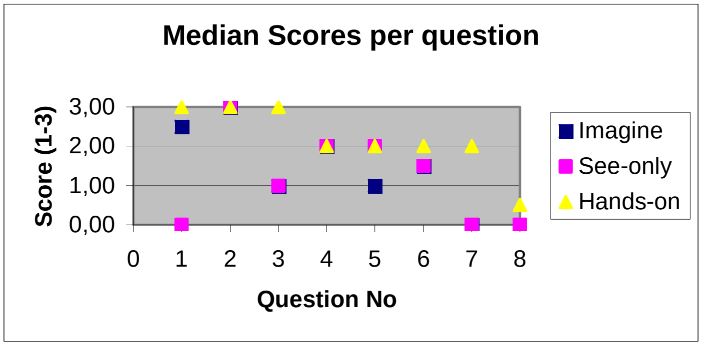


Figure 5-4: Performance per question based on median scores

A statistical test of significance was also performed. The experiment had one factor of analysis: the condition of the training session. It was a between subjects design and the data available was ordinal. The analysis of the results was based on the comparison between each of the experimental groups and the control one, thus two Mann-Whitney tests were run (Kinnear and Gray 2000). Significance was set at $p<0.05$.

In comparing the overall results of Hands-on with the Imagine condition, manipulating objects and springs did not have better results than reading about forces. In comparing the See-only condition with the Imagine condition, demonstrating forces to children did not produce any significant differences from reading about the forces. Therefore, the null hypothesis cannot be rejected.

Additionally, comparing the results of each individual question of the final test there was no significant difference between hands-on and Imagine, nor between See-only and imagine.

Furthermore, the ability of children to justify correctly their answers was measured based on their responses during the interview (Figure 5-5).

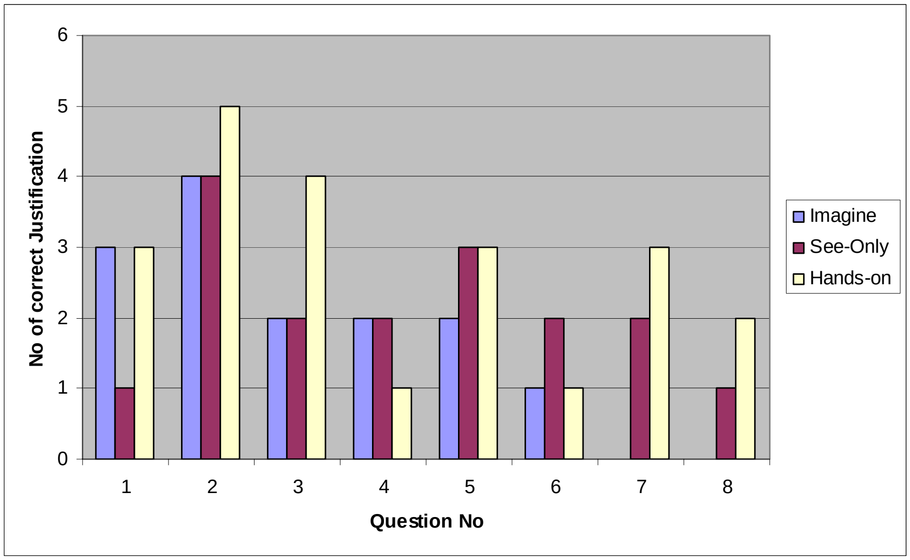


Figure 5-5: Number of correct justifications per question

5.3.3 Discussion

Even though the results did not show significant differences, children in Hands-on condition had better median scores than the children in the other conditions (Table 5-4). They produced answers showing that they understood the abstract concept of force but it cannot be for certain that manipulation of springs and hanging objects while learning about forces may be beneficial to learners.

5.3.3.1 The employment of multiple modalities

The use of modalities in different conditions is shown in Table 5-5.

	Linguistic cues	Visual cues	Tactile cues
Imagine	x		
See-only	x	x	
Hands-on	x	x	x

Table 5-5: The use of different modalities per condition

The children in the Imagine condition could only read and write, which made the learning task difficult. It is worth noting that children in the Imagine condition needed double the time to do the task than the rest of the children. It appears that reading a text needed more effort from children and thus, they needed more time. If they were given the same time as the other two conditions, the children would not be able to complete the tasks. The See-only condition, on the other hand, which employed the visual modality, produced similar overall results to the Imagine condition. It was the employment of touch that could have made a difference in this study. Children in the Hands-on condition tended to create less mistakes than children in the other conditions.

Additionally, a spring's affordance is to stretch. However, for the children, stretching had not been necessarily related to the application of force that is in contact to the spring. Thus, all the children stated that the spring would stretch. However, when children were asked about 'what makes the spring travel up and down' (question 6), three children in the See-only and 3 children in the Imagine condition reasoned that this behaviour is due to gravity that pulls the object and not due to the object's weight and the springs' pulling back.

In the Hands-on condition where children had contact with the objects and felt their weight, this confusion did not occur. Thus, manipulation of objects may have provided children with a clear view of the weight as a contact force that is applied to the spring. Being able to feel the weight of the object may have provided them with a strong link between weight and force. The transfer of the object from the table to the spring via their hand could have supported them in transfer their thinking from the object's weight to force. Children in See-only condition did not have access to haptic information and therefore, did not do this connection.

Furthermore, the employment of real-world modalities through the manipulation of real-world objects supported children in their attempts to draw inferences in terms of scientific principles. In particular, Hands-on children could infer that the extension of the spring would be proportional to the objects' weight, applying, in other words, Hooke's law. In the 'See-only' condition, children were not as successful even though they could see the weight of the objects and the extension of spring on the 'Table of Results'. Children in the 'Imagine' condition did not have access to a correct 'Table of Results' and so they did not know how much the spring would stretch.

5.3.3.2 Meaning construction

When considering differences regarding each question of the test, the following could be noted. Children in the Hands-on condition performed the same or better in all questions (Figure 5-4).

Question 1: Is weight a kind of force?

In question 1, being able to manipulate objects and spring may have helped children realise that weight is a force: only one child of the hands-on condition did not answer correctly. On the contrary, in the See-only condition, four children did not recognise weight as a force. Being able to see the equipment and listen to the researcher may have not been enough to disambiguate the abstract meaning of weight as a force. In the Imagine condition, on the other hand, 4 children answered correctly. Reading about forces had better results than watching a demonstration.

Question 7: Estimate what would be the length of the spring when we apply a weight of 1000grams to it.

In question 7, regarding the constant extension of the spring, four children in the Hands-on condition answered correctly implying that they could draw inferences in terms of scientific principles. Nobody from the Imagine condition was able to give a correct answer.

Question 8: Estimate how many grams do we need to hang in order to have a spring length of 30cm

Similarly, question 8, was even harder for the children: they had to estimate the weight of the object that would extend the spring to a certain length. It required not only understanding of the relation between the weight and the extension of the spring but also arithmetic skills. In the Hands-on condition, four children understood what they needed to calculate but one did an arithmetic error. In the Imagine condition, nobody answered correctly.

5.3.3.3 Engagement and reflection

Another issue under investigation was the effect of the employment of multiple modalities in children's engagement and their abilities to reflect on the learning activity.

When learning about the effects of force while manipulating objects, the forms of engagement suggested by Baber (2003) are met. In particular, physical engagement is achieved when learners manipulate the spring, hang the object and use their psychomotor skills to coordinate their actions. Cognitive engagement arises when learners relate their actions to specific goals, and represent their actions with a theory of use which is related to the posture the learners adopt, the type of movement they employ and the material that changes due to their actions (Table 5-6).

Physical engagement
▪ Hang the object to the string ▪ Measure changes on the spring's length ▪ Write down the measurements ▪ Coordinate their actions in order to do the action
Cognitive engagement
▪ Relate their actions to specific vocabulary. ▪ Relate changes of objects' weight to specific changes in spring length. ▪ Represent a set of actions to a specific table of data.
Environmental engagement
Responding to the whole activity by doing the actions, reading the material and filling in the Recording Sheet. All done with the cultural requirements for cooperation that comes with the initial decision of participating in the activity.

Table 5-6: The 3 forms of engagement revisited: the impact of multiple modalities in learners' engagement when learning about force

Children's ability to reflect was investigated by their ability to give correct justifications of their answers (Figure 5-5). Children in the Hands-on condition were slightly better in giving correct justifications with the exception of question 4 and question 6. Additionally, their ability to reflect on the tabular data they collected was measured by the last two questions of the test. As mentioned previously, the majority of the Hands-on children answered both questions correctly while the Imagine children could not generate correct answers. Regarding the See-only children, the majority of the participants could not answer correctly but there were two children who did give a correct justification in question 7 and one child that gave correct justification in question 8.

Therefore, it could be suggested that the manipulation of objects kept the children engaged in the learning activity and supported them in their ability to reflect on their actions.

5.3.3.4 The categorisation of objects

A question under investigation was how interactions with different objects structure the learning activity and facilitate meaning construction. It was argued that the categorisation of objects according to their learning potential proposed in Chapter 4 can describe these interactions. Indeed, in this study, there were transparent objects, i.e. papers and pens that aimed to support seamlessly the activity. The results were not encouraging when these objects became of the main interest: in the Imagine condition, children did not have haptic information from objects but only from the papers and pen available. These children had difficulties in completing the learning task and they did not produce as good answers as the children that had access to springs and hanging objects. Having therefore only transparent objects ready to hand may not have an effect in facilitate meaning construction.

There were also objects that were related to the study, such as springs and hanging objects and children in the Hands-on condition had them ready at hand. As shown in Table 5-7, manipulation of these objects gave Hands-on children the ability to answer each question better than any other condition, with one exception in the fifth place.

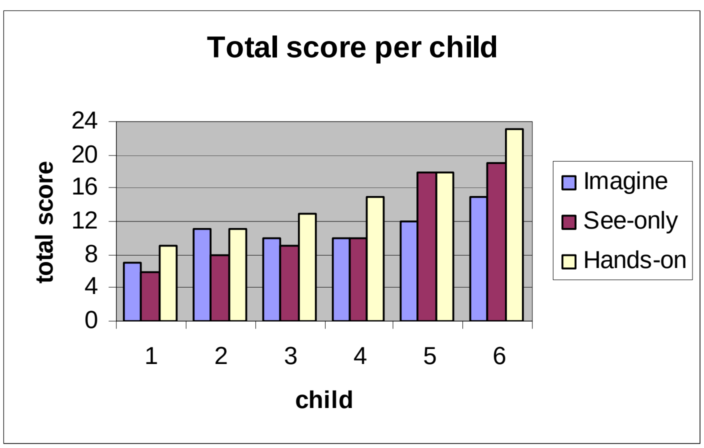


Table 5-7: The score of each child is compared to his/her equivalent in each condition. They are compared based on performance: no1 is the poorest total score in each condition and no6 is the best total score.

There was also a symbolic object on the 'Recording Sheet': the table where the children recorded the measurements of the spring extension. Being able to manipulate physical objects, may have given additional interest to the Hands-on children to interact with the symbolic object. Hands-on children extended the tabular representation since they answered the last two questions of the test, unlike the children in the other two conditions.

As it appeared from the pilot study, the use of a ruler unattached to the stand for measuring the extension of the spring was not giving consistent measurements and thus such object needed to be avoided. In the main study, the ruler was attached to the stand so that children could not move it, limiting the possibility to take wrong measurements.

5.4 Conclusion

Regarding the validity of the proposed categorisation of objects, the current case study was not conclusive. The categorisation proposed a structure for the study of learners' interactions with real-world objects. The selection of objects is usually left on the intuition of the designer of the learning activity; in this case the activity was structured according to the learning potential of objects. Therefore, to realise which objects can provide a fruitful and stimulating experience for the learner, which ought to be transparent and, of course, which not to have at all, for this study was not a intuitive decision but a result of structured considerations.

Furthermore, children in the Hands-on condition appeared able to translate the abstract phenomenon of force from the weight of the objects they interacted. Therefore, objects' manipulation may have facilitated children's meaning construction for the abstract phenomenon of force. Additionally, the employment of real-world modalities through the manipulation of real-world objects could have supported children in their attempts to draw inferences in terms of scientific principles since they could infer the proportionality between the object's weight and the extension of the spring.

Chapter 6 M-DEW interactions: first case study

6.1 Introduction

This chapter explores the arguments suggested in chapter 4 through an experimental study. In particular, the study investigates how the employment of multiple modalities can facilitate learners in constructing concrete relations between movement and the abstract symbols of motion. In relation to the framework for multimodal interaction that was explored in the previous chapters, this case-study lies on the column of Digitally Enhanced World interactions as shown on Table 6-1.

Worlds / Modalities	Real World	Symbolic World	Digitally Enhanced World
Full access to real-world modalities (moving)	Manipulation of objects and understanding		Physical manipulation of representations and understanding
Restricted access to real-world modalities (observing)	Watching and understanding		Watching representations being manipulated and understanding
Even more restricted access to real-world modalities (thinking)			Thinking of Representations and understanding

Table 6-1: The framework for multimodal interactions: the focus is on Digitally Enhanced World interactions.

It has been argued in Chapter 4 that physical interactions with symbols can facilitate learners' meaning making. This study explores the coupling between learners' own movement and graph generation with the aid of M-DEW and whether reification of kinematics graphs takes place. It also explores the de-coupling of the real-world activity and the symbolic representation from M-DEW through activities that encourage rhythmic cycles of engagement and reflection designed to support the skills of interpreting graphs.

It was also argued that the combination of engaging and reflective activities provide better access to the symbolic world for learners since the links between the real world and the symbolic world would be strengthened. This case-study explores this argument in the particular case of learning about kinematics graphs.

Additionally, the study aims to validate the argument of chapter 4 that physical manipulation can support learners in

- understanding the representation and its properties,
- being able to manipulate the symbolic world and interpret its changes,
- drawing inferences in terms of scientific principles.

The next section relates data-logging experiences to M-DEW activities. In section 6.2, a pilot study is summarised which led to the main study with 14 years old students. The case study in section 6.3 investigates the use of movement as a means to record data, which is displayed as graphs. Students' generation and correction of movement provides a multimodal learning experience. For the students to learn how to interpret a graph, the relation between the movement and the line of the graph is important. Seeing how the graph is plotted by their hand movement and being able to change it as they move about, gives them the ability to test their ideas and discard the problematic ones.

6.1.1 Relating data-logging experiences to M-DEW

In section 2.4.2.1, data-logging and microcomputer-based laboratory (MBL) experiences were studied as a way of introducing real-time data-logging technologies in the classroom. Such tools give students the opportunity to do real science in the physics course since students can build a model and test it explaining the world around them (Thornton and Sokoloff 1990). MBL has many common features with the technology suggested by M-DEW such as

- it allows frequent repetition and plenty of opportunities for graphing
- reinforces students' concepts of different graph shapes to be represented by different classes of motion events,
- the high quality of data displayed make the task of interpreting and evaluating the graph relatively simple and unambiguous (Brasell 1987)
- the graph is a central means of communication with students (Mokros and Tinker 1987)
- students predict results in terms of graphs and if there is a discrepancy between the observed and predicted graph students must recognise this and make the necessary corrections (Mokros and Tinker 1987).

Therefore, regarding the technological features proposed in Chapter 4, data-logging technology supports automaticity and synchronicity since it allows automated and in real time generation of graphs. Additionally graphs were easily produced and interpreted by learners which refer to the last two technological features of m-DEW. Sensitivity seems to be rather low (ranging from 0.5m to 6m) but it could be efficient enough if different types of movement were employed, i.e. walking instead of moving only the hand.

However, the technology should not be seen separately from the activities that take place. In particular, most of the studies that used MBL have been tried in collaborative learning situations where a group of students collect data together (Adams and Shrum 1990; Brasell 1987; Mokros and Tinker 1987; Thornton and Sokoloff 1990). For example, Mokros & Tinker (1987) describe the students' actions in roles: one being the 'dancer', one being the 'choreographer' giving instructions of how the 'dancer' should move to create a graph, and a person on the sidelines being in charge of the computer. However, they do not compare if there was a difference between 'dancers' 'choreographers' and 'computer experts'. They analyse their experiences collectively as a group. There might have been a difference with activities that are done by the single learner since she cannot avoid thinking about the effect of movement on the graph and she cannot get guidance from classmates.

The data-logging studies were also longitudinal and the session could be a school lab session with the cooperation of the teacher (Mokros and Tinker 1987; Brasell 1987) or a university physics course (Thornton and Sokoloff 1990; McDermott et al. 1987). The activities proposed within M-DEW refer to sessions where students collaborate with the resources available but which may not include the presence of peers and a teacher.

Additionally, Thornton & Sokoloff (1990) suggested that MBL tools are not a panacea in facilitating learners' understanding. They focused on the curriculum materials that influence the student's learning. In more detail, they suggested that students should focus on the real world, gain immediate feedback through collaborating with peers, have access to tools that reduce unnecessary drudgery associated with data collection and graph construction, and understand first the specific and familiar before moving to more general and abstract (Thornton and Sokoloff 1990). This thesis extends their view and suggests that it is the broader activity features that can support learners' understanding.

Regarding the activity-related features proposed in Chapter 4 for M-DEW, the data-logging activites described in the literature support physical manipulation of graphs and self –evaluation but narration is not always described as part of learners' experience. Exceptions include (Rogers, L. 2002) and (Nemirovski et al. 1998). Additionally, open-ended investigations and clear learning objectives were supported but there are not always detailed descriptions regarding the inclusion of similar but different graphs. Therefore, data-logging could be an instance of M-DEW depending on the activities accommodated while interacting with the technology.

This case-study focuses on single learner activities that employ a motion-tracking technology for interpreting symbolic representations. It is considered a way to combine real actions that are coupled with symbolic representations facilitating meaning construction of abstract concepts.

6.2 The pilot study

Prior to the case study, a pilot study took place that indicated to difficulties that can arise from the initiation of such an innovative learning experience. In particular, the pilot study aimed to test ideas related to content, activity and presentation of information by the technology (Anastopoulou et al. 2003). The learning aim was to introduce the concept of acceleration and its graphs. Acceleration was recorded by the SensVest, a device developed at the University of Birmingham as part of the lab of Tomorrow project. It is a vest with an accelerometer attached to it that records the force generated by the hand of the person who wears it when the hand moves. The data are transmitted to special-purpose software, which calculates the acceleration and plots the relevant graph at 10 seconds intervals.

The study started with a teaching session where 12 pairs of students, aged 14-16, were introduced to the concept of acceleration, its relation to velocity and their graphical representations. Afterwards, they threw a ball and watched the acceleration graph of their hand on the visual display of a laptop. They talked about the graph's characteristics and compared it to a velocity graph that was generated from a spreadsheet. It was expected that the students who saw their graphs after their throwing would perform better than those who saw ready-made graphs on paper.

The problems that arose were related to the technology, the activity and the educational content. The technological problems were related to the time delay (approximately 10 seconds) after which the graph was presented to the participants. Additionally, the presentation of the graphs was not helpful: initially the graph was very condensed and the researcher had to zoom into the graph after the activity was finished. Such delay, however, caused participants to loose the connection between the graph and their movement, as it was also argued by Brassel (1987). Therefore, the second and third technological features of M-DEW were not taken into consideration.

A simple activity such as throwing a ball was not very successful. It was thought, originally, that it would relate to game-like situations but the participants found it rather simplistic. The ball itself did not trigger their attention since they repeated the movement without the ball to see the effects of the graph. Additionally, the movement was very specific and it did not allowed open-ended investigations.

Additionally, the educational benefit did not prove to be very high. The link between the activity and the graphical representations was rather weak: throwing a ball was a rapid activity and didn't give enough time to participants to realise how their movement affected the graph. Additionally, the concept of a graphical representation of acceleration was rather difficult for the participants to grasp. Students are not expected to understand acceleration-time graphs at school and thus they were not keen to learn the concept.

6.3 A case study for M-DEW interactions

The issues above informed the design of the main study. Several steps were taken towards augmenting the learning experience: the educational content was simplified, the technology improved, the usability of the activity enhanced.

The learning content was about distance-time graphs, which is an important issue in the science classroom for Key Stage 3 in UK and elsewhere. The students needed to learn five scientific aims through relating the graph to their hand movement:

- to realize that a horizontal line on a graph means no movement,
- to realise that a line that goes up or down shows movement,
- for the line to go up, there should be movement in one direction,
- for the line to go down, there should be movement in the opposite direction,

- the slope of the graph shows how fast the movement is done, that is the speed of the movement.

The mathematical aims of the activity were:

- to reinforce understanding of a graph as a relationship between two variables,
- to introduce negative numbers in the context of distance,
- to practice reading, choosing and changing axis and axis scaling.

The technology used provided learners with graphs without delay, in an understandable scale which could be easily altered according to their range of movement. Additionally, the activity involved simple movements of the hand and distance-time graphs similar to those found in textbooks, demonstrating that such graphs refer to really simple movements.

The study focused on the differences in understanding about distance-time graphs between students who manipulated graphs as they moved their hand (doers), those that watched somebody else manipulating graphs (watchers), and those who did not see any graph been manipulated (thinkers). The second condition removes any advantage of using their own body for data collection. It does not employ the learners' kinaesthetic modality and so it does not give access to body-syntonic or ego-syntonic learning. The hand of the other person could be just another object in the world: all that is needed is for this object to send input to the visual display. The participants of the third condition had to imagine the graphs as expressions of their own movements. Their experience, however, was limited: they had no access to the technology and thus they could not correct themselves as a result of a visual graphical feedback.

There were five null hypotheses in this study which were:

1. by being able to manipulate graphs physically, 'Doers' will not gain better scores than those who do not physically manipulate graphs ('Thinkers');
2. 'Doers' will not get better scores than 'Watchers';
3. 'Watchers' will not get better scores than 'Thinkers';
4. 'Doers' will not score more favourably the activity in the Likert scale than 'Thinkers';
5. 'Watchers will not score more favourably the activity in the Likert scale than 'Thinkers'.

6.3.1 Relating M-DEW features to the case-study for M-DEW interactions

In Section 4.5 specific features was suggested as requirements for designing M-DEW case studies. These features informed this case-study for the particular learning task. In particular, the employed technology allowed automated generations of the graph and it was generated on the display in real time to the hand movement. The generated graph had a balance between accuracy and efficiency since learners had to try to create straight lines –therefore realising that steady speed it not easily maintained by hand- but it would not show involuntary movements such as hand tremble. Additionally, the graph was continuously and easily produced by the learner: they only had to move their hand. The graphical representation was also presentable in ways that would be interpretable by learners: it would be scaled according to the details to their movement and it would show a continuous line instead of a dot without a trace. Finally the graph generation would freeze as soon as the stop button was pressed giving an instant overview of the movement in the form of a static picture.

Furthermore, as it will be described in detail in the next section, the activities of learners involved iterations among physical manipulation of the graph, narrations and self-evaluations, allowing rhythmic cycles of engagement and reflection to take place. In particular, learners had to create specific graphs based on their hand movement which allowed them to see the effects of their movements on the graph: they therefore manipulated the graph. They would keep trying to generate the graphs until they felt satisfied with their likeness: they therefore were evaluators of their actions. At the end of each sub-task, they were asked to describe their movement that generated the graph on display and on paper: they therefore became narrators.

Additionally, each of the learners' tasks had clear learning objectives and it included comparisons between similar graphs, i.e. the graphs that represented the same movement occurring in different speeds. The initial activities of the learners that had full access to multiple modalities were also characterised by open-ended investigations at the beginning when they tried to familiarise with the technology.

6.3.2 Method

The study was conducted with 33 students in year 9 (14 years old) of a secondary school in Birmingham, UK. It was expected that the students would know little or nothing about the subject because they had not then been taught distance-time graphs. There were 11 students in each condition. Students were randomly assigned to the conditions on presentation to the researcher[3]. Each session lasted about half an hour and took place in an empty classroom where there was one student with the researcher.

6.3.2.1 Equipment

The technology used consisted of a motion tracker to capture data and a PC. The motion tracker (Fastrak Polhemus), a ready-made product, computed accurately the position and orientation of a tiny receiver as it moved through space. This receiver was attached to the top of participants' wrist with the aid of a sweatband (Figure 6-1).

Figure 6-1: The student generated a graph and is writing down how he did it –a 'doer'

The tracker had an update rate of 120 Hz and 4ms latency which indicates its high accuracy and literally no delay. The data are then transmitted over a high speed RS-232 interface to a PC with special-purpose software. The software was developed in LabView 6.0 by the researcher and translated the data in distance–time graphs on the visual display (Figure 6-2). The system did not produce noise, except in cases where the receiver was twisted: for this reason the receiver was placed on top of the participants' wrist so that the participants were not likely to twist it.

[3] There was an arrangement with the Head of Science teacher to send a child every 30 minutes. All children were of medium ability.

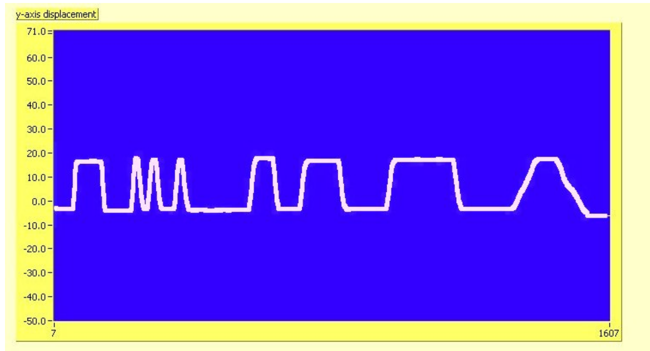


Figure 6-2: Screenshot of the display

6.3.2.2 Conditions

There were three conditions: students who formed graphs as they moved their hand ('Doers'), students that watched somebody else generating graphs with their movements ('Watchers'), and students that thought about their hand movements in order to explain the graphs ('Thinkers'). 'Thinkers' were also allowed to move their hands, but their movement did not generate a graph.

6.3.2.3 Procedures

Initially, students were given a set of initial questions. The second task was the teaching session where participants divided into 'Doers', 'Thinkers' and 'Watchers' alternatively. The teaching session's procedures for each condition is shown in Table 6-2. During the study, a set of verbal protocols was used, to ensure that all students were given exactly the same instructions. The third task of the case-study involved the students answering questions in the form of a written test. They could not look back to the previous sheets. Finally, the fourth task included a short attitude survey, based on a 5 point Likert scale which participants completed. The different sheets could be seen in Appendix B.

The feedback from the researcher was kept to a minimum: the learners received feedback at the beginning of the teaching session where two very simple graphs were explained to them. In particular, they were told that the horizontal line showed no movement and a diagonal line showed movement which was necessary for 'Thinkers' to proceed with the study.

	Doers	Watchers	Thinkers
Initial questions	Appendix B		
Teaching session	'Doers' had the tracker's receiver attached to top of the top of their wrist with the aid of a sweatband (Figure 6-1). They moved their hand about freely to get familiar with the movement and the generation of the graph for approximately 3 minutes. While they were moving, the researcher posed the following oral questions: ▪ what is the name of the x-axis, ▪ what is the name of the y-axis, ▪ could we get negative values on the y-axis, ▪ if yes, what they would mean; if no, why not ▪ could we get negative values on the x-axis, ▪ if yes, what they would mean; if no, why not. If they were not able to answer these questions, they were told the answers. Subsequently, participants were shown graphs on paper which they were asked to generate. Next to the graphs on paper, there was space for participants to write. Once they had generated one graph, they described their movements orally and in writing. When finished, they proceeded to the next graph.	'Watchers' were shown the same graphs on paper (Appendix B) and they watched the researcher generating them on the display. At the beginning of the first movement, the researcher asked them the same oral questions as she did with the 'Doers'. If they were not able to answer these questions, they were given the answers. After the graph was generated on the visual display, students described the researcher's movements orally and in writing. The same procedure was kept for the rest of the graphs that were on the paper.	"Thinkers" were shown the same graphs on paper (Appendix B) and the researcher asked them the same oral questions as she did with the 'Doers'. If they were not able to answer these questions, they were given the answers. Afterwards, they could either say what they would have to do to generate the graphs shown on paper or move their hand accordingly. They were asked to write down what they said or did.
Final test	Appendix B		
Attitude survey	Appendix B		

Table 6-2: The experimental design with the procedures of the teaching session for each condition

6.3.2.4 Design

The students were assigned four tasks: initial questions, a teaching session, a final test and an attitude survey. The initial questions asked them what they already knew about the subject. It was expected that the pupils will not know about distance-time graph since they had not been taught the subject at school yet. The researcher explained the last two graphs explicitly to all conditions by saying: "if I told you that this graph shows no movement and this graph shows movement, could you tell me why?" aiming to trigger their attention and support them while reading the graph on the paper. If they could not say why, they were asked to describe what happened in every time unit so that they could conclude that the graph shows the change of distance over time. This explanation took place because Thinkers could not continue to the teaching session unless they understood what the last two graphs showed.

The teaching session aimed to support the participants' ability to translate between the graphical representation of motion and their own movement. For 'Doers', the movement of the teaching session were initially open-ended: the learner could move their hand in any way they wanted. Then, they are asked to generate specific graphs so they had to find out how they should move their hand, aiming at strengthening the link between the activity and the graph. They could move their hand towards two directions (forwards-backwards and left-right) but it had to be the same throughout the study. They had to relate the hand movement to three different graphs and write down the description of the movement.

Additionally, the teaching session aimed to relate the graphs to scientific principles: the last two tasks stressed the differences between two graphs with different slopes aiming to relate the slope of the graph to the speed of the movement. It needs to be noticed, however, that 'Thinkers' could not do this relation and were asking the researcher for the answer. It was therefore decided that all participants will be told the answers of the last two questions.

The third part of the case-study involved each participant answering a final test without look back to the previous sheets (Appendix B). The final test aimed at summarising the teaching session giving them the chance to reflect the whole experience. For this reason, the first two questions were the same as the last two of the initial questions. They were two very simple graphs, aiming to check the first two scientific aims of the case-study. The third question was a graph combining movement and lack of it to be interpreted as hand movements. It was considered as the most important one since it required understanding of the first four scientific aims of the case-study. The fourth question aimed to demonstrate their understanding in relation to numerical values of the graph. It requested not only to describe the specific hand movement but also to mention the values of distance and time where there was a change, e.g. the hand stayed still for 20 seconds then moved to the right for 30 seconds and stayed still for 30 seconds. The fifth and sixth question tested the fourth aim of the study that the slope of the graph shows the speed of the movement. The fifth question assessed whether they realised that graphs of different slopes differ on how fast the movement is done and the sixth question assessed whether they knew about the meaning of the slope.

Finally, in the fourth part of the case-study participants could express their opinion about the study by completing a short attitude survey, based on a 5 point Likert scale (Appendix B). In particular, the attitude survey asked students whether they found the session interesting, if they liked it, if they liked watching their own data, how difficult were the questions and whether they felt that they understood the distance-time graphs. They aimed to investigate if learners' experience was enjoyable and to check the usability regarding the learning task.

6.3.3 Results

The results discussed below are based on the sheets completed. Each sheet was scored and the findings are based on the overall performance in each sheet. The scores were given as:

- For each question they answered correctly, they would take 1 mark,
- if they mention the corresponding direction, they would take 1 mark,
- if they mention the amount of time each movement lasted, e.g. twice as much, they would take 1 mark.
- If they mentioned distance or time values, they would get 0.5 mark,
- If they mentioned the words 'faster' or 'slower' in question 5, they would get 3 marks,
- If they mentioned more or less hand movement in question 5, they would get 1 mark,
- In question 6, if they mentioned speed, they would get 3 marks, if they mentioned 'how fast or how slow it goes, they would get 2 marks, if they mentioned 'how steep is the graph, they would get 1 mark, if they mentioned that there is a difference in time and distance, they would get 1.5 marks.

Since pupils could not interpret the two simple graphs of the initial questions, it could be inferred that the students did not know about the distance-time graphs. There was no difference in what the pupils knew between conditions (Table 6-3).

Initial Questions			
	Doers	**Watchers**	**Thinkers**
Pupil1	1	1	2
Pupil2	2	1.5	2
Pupil3	2	2	2
Pupil4	2	2	2
Pupil5	2	2	2
Pupil6	2.5	2	3
Pupil7	3	2	3
Pupil8	3	2.5	3
Pupil9	3.5	3	3.5
Pupil10	3.5	3	4
Pupil11	5	3	4
Median	2.5	2	3

Table 6-3: The scores of participants for the initial questions (max score=6)

From the writings of the teaching session, it appears that the 'Doers' were more able to describe correctly the graphs in terms of their hand movements. 'Watchers' were not precise enough to write down every single movement and 'Thinkers' could not correct themselves (Table 6-4).

Teaching session			
	Doers	**Watchers**	**Thinkers**
Pupil 1	9	12	5
Pupil 2	20	15	8
Pupil 3	21	16	8
Pupil 4	22	16	12
Pupil 5	22	18	13.5
Pupil 6	25	19.5	16
Pupil 7	28	21	25.5
Pupil 8	29	21	26
Pupil 9	29.5	27	30
Pupil 10	31	31	31
Pupil 11	33	31	32
Median	**25**	**19.5**	**16**

Table 6-4: The scores of participants for the teaching session (max score=35)

The comparison for the final test results was done in pairs. 'Doers' gained better scores than 'Thinkers' (Mann-Whitney test $z = -2.275$, $p<0.05$). Comparison of individual questions shows that 'Doers' were more able to describe the distance-time graph in terms of hand movements and they understood better the meaning of each line on the graph (question 3). Thus, the first null hypothesis can be rejected. It seems that when relating graphs to hand movements and getting immediate corrective feedback from the display, learners were more able to understand distance-time graphs.

The final test scores between 'Doers' and 'Watchers' were not significantly different, therefore, the second null hypothesis cannot be rejected. However, in question 3, where pupils demonstrated the ability to 'describe the distance-time graph in terms of hand movements, there was a significant difference (Mann-Whitney test, $z=-1.968$, $p<0.05$) which means that the results are encouraging (Table 6-5).

Final Test

Doers

	Pupil1	*Pupil2*	*Pupil3*	*Pupil4*	*Pupil5*	*Pupil6*	*Pupil7*	*Pupil8*	*Pupil9*	*Pupil10*	*Pupil11*	***Median***
Q1	0	1	0.5	1	1	0.5	0	1	1	1	1	**1**
Q2	0	0	0.5	1	1	0.5	0	1	1	1	1	**1**
Q3	9	5.5	9	9	6	8	9	9	9	9	10	**9**
Q4	1	2	1	1	1	2	1	1	1	1	2	**1**
Q5	0	0	2	1	3	3	3	3	3	3	3	**3**
Q6	0	2	0	1	2	1	2	1.5	2	2	3	**2**
Sum	**10**	**10.5**	**13**	**14**	**14**	**15**	**15**	**16.5**	**17**	**17**	**20**	**15**

Watchers

	Pupil1	*Pupil2*	*Pupil3*	*Pupil4*	*Pupil5*	*Pupil6*	*Pupil7*	*Pupil8*	*Pupil9*	*Pupil10*	*Pupil11*	***Median***
Q1	0	1	1	1	1	0	1.0	1	1	1	1	**1**
Q2	0	1	1	0.	1	1	1.0	1	1	1	0.5	**1**
Q3	0	0	0	3	2	9	5.0	8	9.5	9	9	**5**
Q4	0.5	1.5	2	0.	1	0	1.0	1	2	1	2	**1**
Q5	2.5	3	3	3	3	0	3.0	3	1	3	3	**3**
Q6	2	1	2	1,5	3	2	3.0	2	2	2	3	**2**
Sum	**5**	**7.5**	**9**	**9.**	**11**	**12**	**14**	**16**	**16.5**	**17**	**18.5**	**12**

Thinkers

	Pupil1	*Pupil2*	*Pupil3*	*Pupil4*	*Pupil5*	*Pupil6*	*Pupil7*	*Pupil8*	*Pupil9*	*Pupil10*	*Pupil11*	***Median***
Q1	1	0	1	0	1	1	1	1	1	1	1	**1**
Q2	1	0	1	0	1	0.5	1	1	1	1	1	**1**
Q3	0	0	0	5	7	3	3	8	5	8	8.5	**5**
Q4	1.5	0	1	1	1	0	1	1.25	1	0.5	0.5	**1**
Q5	0	3	3	3	0	3	3	0	3	3	3	**3**
Q6	0	2	3	0	0	3	2	0	3	2	3	**2**
Sum	**3.5**	**5**	**9**	**9**	**10**	**10.5**	**11**	**11.25**	**14**	**15.5**	**17**	**10.5**

Table 6-5: The scores of participants for each question of the final test and the median values (max score = 20). The median values were calculated because data were not interval and the questions did not have the same weight. Additionally, the final results were not standardised.

Additionally, 'Watchers' were not different than 'Thinkers' in the scores of the final test (Figure 6-3), therefore the third null hypothesis cannot be rejected.

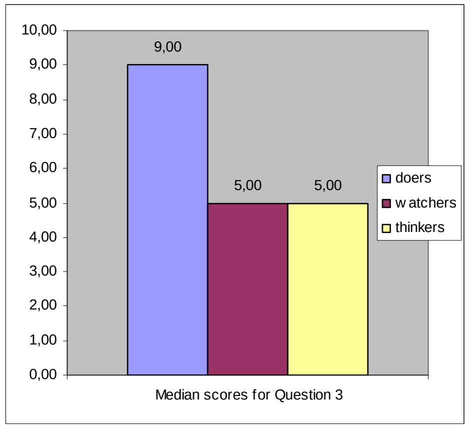


Figure 6-3: Median scores per condition for question 3 (max score=10). The specific scores are shown in grey in Table 6-5.

When asked for their opinion about the study, 'Doers' liked it more than 'Thinkers' (Mann-Whitney test, $z=-2.181$, $p<0.05$) and found it more interesting (Mann-Whitney test, $z=-2.355$, $p<0.05$). Thus, the fourth null hypothesis can be rejected. Furthermore, there was no significant difference between 'Doers' and 'Watchers', therefore, the fifth null hypothesis cannot be rejected.

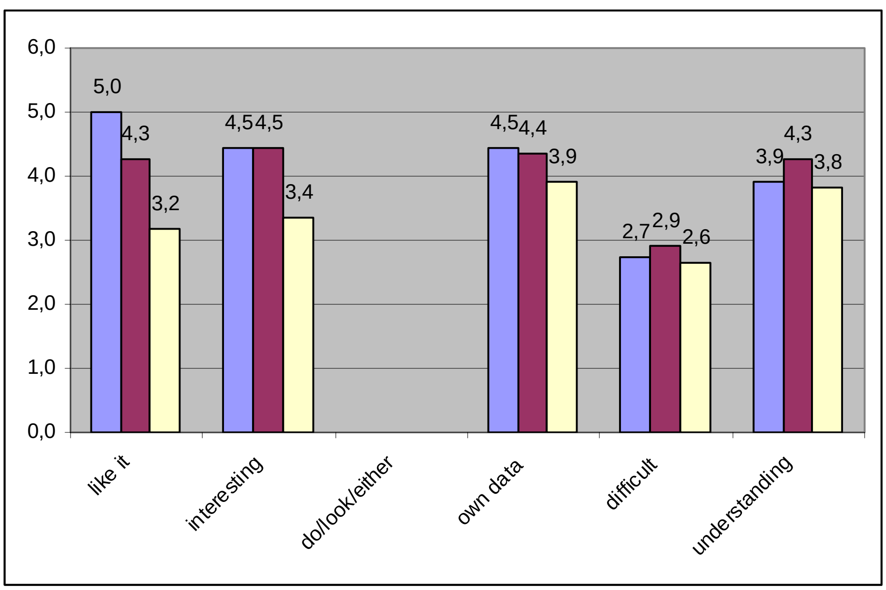


Figure 6-4: Attitude survey results per condition in mean scores because data was interval

6.3.4 Discussion

The results demonstrate that learners who were able to physically manipulate the graph ('Doers') were better from those who could not manipulate the graph physically.

Learners who could see the graph being manipulated ('Watchers') were not different from 'Thinkers'. Additionally, 'Doers' performed better than 'Watchers' in question 3, where they had to demonstrate their ability to interpret the graph in terms of hand movement.

'Doers' were also engaged in the activity: moving their hand about and seeing its distance-time graph on the visual display was a novel activity. The feedback came from the visual display as soon as they moved their hand, meaning that their initial ideas were challenged as soon as they started moving. Most of the times, they needed to stop and reflect how they had to move in order to generate the specific graphs. Therefore, it could be argued that physical interactions with the graph strengthened the link between the concrete movement and its symbolic representation.

'Watchers', on the other hand, did not need to think in advance how the hand would have to move. They saw the movement happening from the researcher, so their original ideas were not challenged: they accepted that the hand has to be moved like the researcher did. As a result, they were not fully engaged with the task, their attention drifted and nine of them did not fill in the sheets properly because they gave summarised responses during the teaching session.

'Thinkers', finally, had to reflect on their movements but the lack of feedback did not challenge their initial conceptions. As a result, their understanding did not progress as rapidly as 'Doers' throughout the activity.

Performance, therefore, seems to be affected by the use of multiple modalities which is demonstrated by physical manipulation of graphs and which along with narration and self-evaluation augmented learners to be employed in rhythmic cycles of engagement and reflection.

6.3.4.1 The employment of multiple modalities

The employment of multiple modalities provided learners with repetitive experiences through unlimited testing of the correspondence of graph with the real life situation. Thus, the process of reification took place subtly, without the learner having to try explicitly to concentrate on symbol interpretation.

The use of modalities in different conditions is shown in Table 6-6. 'Doers' had access to physical interactions with the graph and a better ability to express themselves when interpreting the graph. In particular, 'Doers' were required to use their kinaesthetic modality to complete the learning task. 'Watchers' could only see the effect of the movements that a person next to them was doing. 'Thinkers' could move (or use the kinaesthetic modality) but they could not see how the graph would be updated to correct possible misunderstandings.

	Writing	Seeing		Moving
		Paper Visual cues	Online visual cues	
'Thinkers'	x	x		
Watchers	x	x	x	
'Doers'	x	x	x	x

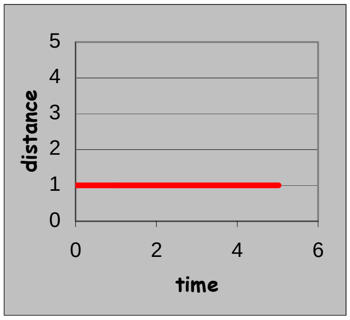
Table 6-6: The use of different modalities per condition

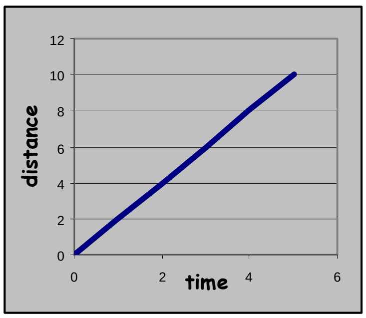
'Doers' performed better overall than 'Thinkers'. In particular, 'Doers' were more able translate correctly graphs into hand movements. All 'Doers' responses in the final test also mentioned that the hand would move towards a direction. This is in contrast to the 'Thinkers' who did not relate movement to a direction. Five pupils mentioned that a straight line expresses movement across and a sloped line expresses a movement diagonally (picture-like effect). At the beginning of each session, most of participants in all conditions thought that they had to move their hand diagonally in order to draw a diagonal line on the graph. 'Doers', however, would neglect this idea because they could see that the effect on the graph was not the expected. They had to correct themselves via the visual feedback and thus, discover the correct movement. Therefore, using their movements to generate the graph resulted in solving common misunderstandings: the activity constrained their inferences about the represented symbols.

6.3.4.2 Meaning construction

The structure of the final test made the students re-think the whole case-study from the beginning.

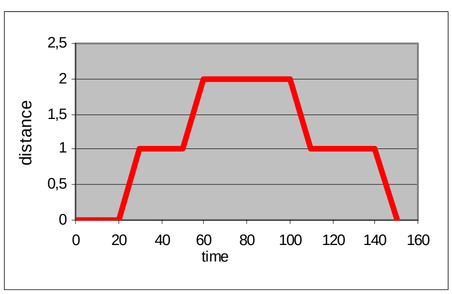
Question 1&2: Please write down what each graph illustrates:





Most of the students in all conditions were able to answer correctly the first two questions of the final test. That means that the study was successful in reaching the first two scientific aims in all conditions: to realise that a straight line on a distance-time graph shows no movement and the diagonal line shows movement.

Question 3: Describe how the hand moves during the 150 seconds



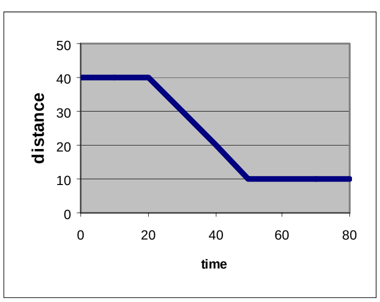
To answer the third question, pupils needed to demonstrate understanding of the first four scientific aims. 'Doers' performed significantly better than the 'Watchers' (Figure 6-3). In particular, 'Doers' were precise to the number of times the hand moved or stayed still. This can be contrasted with the 'Watchers' who did not always pay attention to the number of times the movements happened. They described the movements in overview (i.e. you moved your hand backwards and forwards), which could be an indication that they might have been bored of the repetitive movements. Additionally, they omitted details regarding time, such as long horizontal lines showed that the hand stayed still longer than short horizontal lines. From their responses in the teaching session, it could be inferred that 'Watchers' had a summarised idea of what movements were required without linking each line to a particular movement. As a result, at the final test there were four incidents describing more or less movements than lines. This is an indication that they were responding without understanding, showing evidence of learning by rote. This behaviour was not apparent with 'Doers' at all.

The answers in the final test showed that there was also a strong link for all 'Doers' between movement and the direction with which the hand would move. This was not straightforward for 'Watchers': five watchers mentioned a wrong direction for the movement and there were four students who described movements that would result in a completely different graph. In particular, a pupil describing the graph of question 3 wrote:

"The hand goes straight[4] and moves to the left, and then moves to the right and stays still and then moves to the left and then stays still then moves to the right and then stays still and then moves to the left".

Five 'Thinkers', on the other hand, interpreted the graph as an exact picture of the movement: having no visual feedback of the movement did not challenge the picture-like effect which is a common misunderstanding of the subject (Beichner 1994).

Question 4: Describe how the hand moves during the 80 seconds

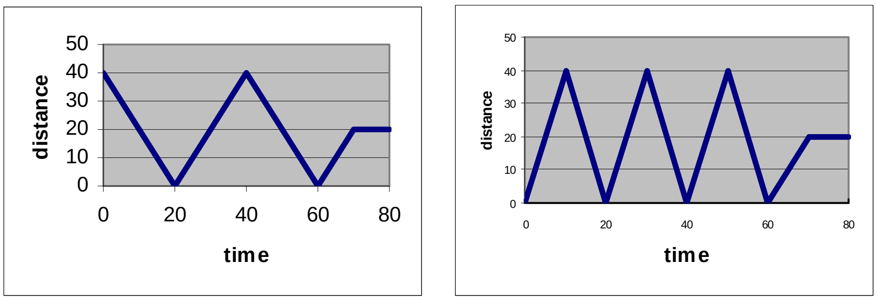


In the fourth question, almost everybody was able to describe the movement but very few students from all conditions mentioned the distance or time values. A reflection on the case-study reveals that during the teaching session pupils were not asked to pay

[4] This is an incident of picture-like effect.

attention to the values obtained, it should not be expected, therefore, to write down the distance and time values.

Question 5: Can you tell which are the differences between the two graphs?



Question 6: What does the slope of the graph tell us?

Most of the students in all conditions were able to answer the fifth and the sixth question correctly (Table 6-5). This could be related to the fact that the researcher had told them the answers during the teaching session.

6.3.4.3 Engagement and reflection

When learning about kinematics graphs with the support from kinaesthesia and vision, the forms of engagement of tool use suggested by Baber (2003) are extended to situations where learners manipulate symbols instead of objects. In particular, physical engagement is achieved when learners are using their perceptual abilities while moving and their psychomotor skills to coordinate their movements. Cognitive engagement is achieved when learners relate their movements to specific goals, and represent their movement with a theory of use which is related to the posture the learners adopt, the type of movement they employ and the symbol that changes due to their movement (Table 6-7).

Physical engagement
▪ move about and see changes in the graph ▪ coordinate their movements in order to draw specific graphs.
Cognitive engagement
▪ Relate a type of movement to a specific line. ▪ Relate changes of movement to specific changes in the line. ▪ Represent a set of actions to a specific graph shape. ▪ Experiment with different movements to create different graphs
Environmental engagement
Responding to the whole activity by doing the movements, reading the material and writing answers. All done with the cultural requirements for cooperation that comes with the initial decision of participating in the activity.

Table 6-7: The 3 forms of engagement revisited: the impact of multiple modalities in learners' engagement when learning about kinematics graphs

Additionally, to compose information that would result in learning, learners also need to reflect. Towards this end, the learner would also need to challenge the provided information based on prior ideas and feelings (Boud et al., 1988). While interacting within the M-DEW, 'Doers' can use their body to challenge the information provided. By using their own movements, 'Doers' would not need to look around in the environment to see the effects of objects on the representations. Instead they can relate the given information directly to themselves and challenge a twofold link in which movement corresponds to a given graph and vice versa. This state of introspection could scaffold a personal synthesis and integrate the learning material in a personalised way that is self-validated.

To translate the case study to Ackermann's words, by asking learners to become their own observers, narrators, and critics, cycles of engagement and reflection were greatly facilitated. To become observers, learners needed to be immersed in an event and notice its changes. To become narrators, they needed to describe their event to a third party. To become critics they needed to evaluate their actions regarding specific goals. Since 'Doers' had access to all three roles, their answers demonstrated reflective abilities and engagement with the task. 'Watchers' were observers and narrators but not critics: they could not challenge the physical manipulation of the graph. Their answers demonstrated lack of engagement and their meaning construction was not as rich as 'Doers'. 'Thinkers' were neither observers nor critics; they were only narrators and thus their answers showed difficulties in correcting themselves which had an effect in engaging to the learning activity and reflecting on their movements.

6.3.4.4 Learners' preferences

When learners stated their opinion, 'Doers' liked the activity more than 'Thinkers' and found it more interesting. This implies that physically manipulating symbolic graphs captivates learners and keeps them engaged to the learning task.

On the other hand, there was no significant difference between 'Doers' and 'Watchers' but when calculating the median value of their scores, 'Doers' gave a greater score than 'Watchers' (Figure 6-4). Additionally, the rest of the scores indicated that students in all conditions would like to watch their own data; they found the questions of medium difficulty and they understood 'distance-time' graphs. Therefore, there were good remarks regarding the usability of the study.

6.3.5 Conclusion

The case-study suggested that the employment of real-world modalities supported 'Doers' in understanding the symbolic representation of motion and its properties as well as in drawing inferences in terms of the scientific principle of speed.

The case study gave access to learners to body-syntonic learning providing an example of constructionism-based interactions. Physical manipulation of the graph seemed to provide learners with a fruitful resource that enhanced their ability to build relations among seeing, moving and expressing. Graph writing appears to be a powerful type of expressing since it is a visible path of the progress of the symbolic representation of movement in relation to time. Being able to describe what they did orally and in writing gave them another way of expressing since they verbalised their movements. Their movements gave them access to body syntonic learning which was verbalised in natural language and thus became personal before it was related to scientific language.

Doers' understanding was facilitated by strengthening links between real-world movements and symbolic-world adaptation: they were able to couple their movements with the changes in the graph. Through this coupling, they were able to interpret the special features of the graph and overcome misunderstandings demonstrating that links were indeed built while interacting within M-DEW.

Moving their hand about and watching the generated graph in real time facilitated students' meaning construction and kept them engaged to manipulate the graph through their own movements. Having access to this M-DEW gave them the chance to reify the abstract graph and view it as part of their moving hand. Through the narrative activities, they could also reflect on how the abstract graph described the reality of their hand.

However, the coupling between the movement and the graph would not be successful unless learners were able to de-couple their movements from the graph and explain what a graph symbolises without the presence of technology. The de-coupling was aimed to happen through the different activities. Doers' greater ability to describe the graphs during the final test without any help from the provided technology (or any other available resources), demonstrate that this de-coupling was more successful for them.

Finally, pupils' ability to respond correctly to the final test provided support to the argument that such activities offer the opportunity to learners to understand distance-time graphs.

The findings from this study may have implications for the teacher who wish to use data-logging activities in the classroom. Even though these results were taken from a clinical setting, the aim was that they should be applicable to normal laboratory situations. The students performed structured experiments which took a short time to do (less than 10 minutes). As it was suggested by the head of science teacher of the school where the study was conducted, it should be very easy for the teacher to modify the existing laboratory exercises to allow collection and display of data from moving activities. However, there should be a clear distinction between graph construction and graph interpretation. The experimental study showed evidence for facilitating graph interpretation; constructing a graph was not an issue. Thus, teachers should not rely on such a technique to instruct students in graph construction (Adams and Shrum 1990).

To conclude, this case study verified that providing learners with strong links between the real and the symbolic world could augment their attempts to interpret and manipulate symbols that are taught in the science classroom. Within an M-DEW where real-world and symbolic modalities interact, learners can construct meaning and overcome misunderstandings. A question arises however regarding the complexity of the task: how would different – older - learners relate to a similar activity? Would physical interaction with abstract symbols be a 'childish' activity to them? Would it extend their understanding of the symbols? How would they link among different symbols and their own movement? These questions were addressed in a subsequent study that was conducted with older learners trying a more advanced learning task.

Chapter 7 M-DEW interactions: second case study

7.1 Introduction

The previous chapter explored the arguments suggested in chapter 4 through an M-DEW case-study. In this chapter a different case-study is described, aiming to investigate these arguments in a different age group, in a more difficult task. In particular, the study investigates how the employment of multiple modalities can facilitate learners in constructing relations among movement and multiple representations of motion. In relation to the framework for multimodal interaction that was explored in the previous chapters, this case-study lies on the column of Digitally Enhanced World interactions as shown on Table 7-1.

Worlds / Modalities	Real World	Symbolic World	Digitally Enhanced World
Full access to real-world modalities (moving)	Manipulation of objects and understanding		Physical manipulation of representations and understanding
Restricted access to real-world modalities (observing)	Watching and understanding		Watching representations being manipulated and understanding
Even more restricted access to real-world modalities (thinking)		Thinking of Representations and understanding	

Table 7-1: The framework for multimodal interactions: the focus is on interactions within Digitally Enhanced World.

It has been argued previously that physical interactions with symbols can facilitate learners' meaning making. The preceding study explored the coupling between learners' own movement and graphs and the de-coupling of the movement and the symbolic representation through activities that encourage rhythmic cycles of engagement and reflection. In the current study, the same coupling and de-coupling is studied. However, the focus this time is only on the differences between those that can manipulate symbols physically and those that watch symbols being manipulated.

In the previous study, there were some differences in their performance between 'doers' and 'watchers'; therefore the current study investigates whether there would still be a difference in performance for a more advanced task. In particular, during the current study, the students had to interact with several entities: two representations on the visual display, their own movements and the representations shown on paper. Each interaction had a learning potential from which students could benefit. From these interactions, the ability to physically interact with symbols is considered as crucial when learning to link among multiple representations of motion.

Additionally, it was suggested in Chapter 4 that physical manipulation of representations can support learners in

- understanding the representations and their properties,
- being able manipulate the symbolic world and interpret its changes,
- drawing inferences in terms of scientific principles, and
- relating among representations with similar properties.

The first three claims were supported by the results of the previous M-DEW case study. In this study, the same claims are investigated as well as the fourth one: could physical manipulation of representations support learners in relating among representations with similar properties? With physical manipulation of symbols, learners have the opportunity to exercise activities that are not only related to symbolic representations but also to real world activities. This subtle process of reification aims to augment learners' abstract symbol interpretation.

An important question under investigation is the number of the available different modalities. Considering that the representations of motion (the symbolic-world modalities) would be more than those of the previous study, there is the question as to whether real-world modalities need also to be increased. In more detail, there would be two kinematics graphs on display: a distance-time graph and the equivalent velocity-time graph. It might be beneficial to add one more real-world modality, e.g. the pitch of sound to indicate changes in speed and thus in the slope of the graph. It needs to be emphasized, however, that even though the pitch of the sound is a real-world modality, the relation between the pitch and speed or the pitch and the slope of the graph is abstract. This relation is not necessarily straightforward, so it could be that learners have to make just another translation. The pitch of the sound could be just another abstract representation of speed which is not necessarily easier. It was decided that the extra real-world modality would not be added unless the students showed difficulty in doing the tasks.

Furthermore, there were considerations regarding the learners' age. The employment of multiple modalities can provide learners with repetitive experiences through unlimited testing of the correspondence of graph with the real-life movement. The effect of this testing, however, may not necessarily be welcomed by older students. An issue to be explored, therefore, is how older learners would relate to physical interactions with the graphical representations.

7.2 Pilot study

To investigate the above issues, a pilot study was conducted to explore the interactions with a different age group and the advanced learning task. The pilot study was conducted with eight pairs of undergraduates that did not have prior knowledge in physics.

Interactions with pairs gave completely different input which was not the main interest of this research. Each pair developed a unique dynamic which could not be compared with another and could not be easily quantified. Bearing in mind that the aim was to draw conclusions about the differences between the 'doer' and the 'watcher', the two participants could not be easily separated in the analysis since they were interacting. Additionally, the results could not be compared with the prior studies. There were discrepancies in the time that the two participants would answer the questions and, most of the times, the quicker participant would dominate the session. The other participant just followed instructions or tried to understand on their own pace. On the occasions where the second participant would ask for help explicitly, the first participant would explain the issues, resulting in different experiences among pairs of participants.

Furthermore, there were some difficulties with the learning task: the participants did not have prior knowledge in kinematics graphs, which made the session too difficult to complete. In addition, due to the complexity of the task, the activities of the training session were not in accordance to the questions of the final test.

7.3 Main Study 3

For the main study, the above issues were addressed. Participants completed the study individually and the activities of the session were re-designed. Participants should also have prior knowledge in kinematics graphs. The investigation focused on the importance of physical manipulation of symbols when relating among different representations of motion.

The learning content

The students had to compare the dynamic distance-time graph of the display with the equivalent static graph of the paper, the dynamic velocity–time graph of the display with the equivalent static graph of the paper, and all of them with the actual movement of their hand (Table 7-2).

The study aimed to investigate

- how would learners interact with velocity-time graphs,
- how would they relate distance-time graphs to velocity-time ones,
- how would they relate velocity-time graphs to distance-time graphs,
- how would they relate both graphs to linguistic descriptions of movement

The first three comparisons could be augmented by enhancing the links among the meaning of the line of each graph and the corresponding movement. Additionally, the fourth comparison would be augmented by participants' activities: they would have not only to write down descriptions of their movements but also to translate narratives to distance-time and velocity-time graphs.

Learning aim	Dynamic			Static
	Kinesthetic	**Visual**		
	Hand	d-t graph	v-t graph	Graphs on paper
Meaning of line features	keeping the hand still	a horizontal line	horizontal line at zero	
	hand moves steadily forward	straight line goes up[5]	A horizontal line above zero[6]	
	the hand moves steadily backwards	straight line goes down	A horizontal line below zero at the same absolute number as above	
	the hand accelerates steadily forward	A curved line goes up	a straight line goes up	

Table 7-2: The matrix of learner's movements and its associations to each graph.

As with the first M-DEW study, participants would have to be narrators and critics or self-evaluators. After the generation of the dynamic graph, they would have to describe the movements in writing, becoming thus narrators of the movements. Through the comparison between static and dynamic graph, they would be critics or self-evaluators: if they are generating graphs themselves they would be self-evaluators, otherwise they would be critics.

The null hypothesis was that students who are able to manipulate symbols physically will not get better scores in the test than the students who see someone else manipulating symbols. Additionally, a second null hypothesis was that 'doers' will not score more favourably the activity in the Likert scale than 'watchers'.

7.3.1 Relating M-DEW features to the case-study for M-DEW interactions

Relating the current case study to the requirements suggested for M-DEW interactions, it could be noted the following:

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[5] The line could go down depending which is defined as a positive direction.
[6] the line could be below zero if moving to forward is defined as negative direction.

- as with the previous M-DEW case-study, the employed technology allowed automated generations of the graph
- the graph generation was in real time to the hand movement.
- the generated graph had also in efficient accuracy for learners to be able to create straight lines without showing involuntary movements such as hand tremble.
- the graph was continuously produced by the learner
- the graph was easily produced by the learner
- the graph was interpretable in terms of drawing a continuous line and it would freeze easily providing an instant overview of the movement in a static visual form.

Furthermore, relating the current case-study to the activity features of M-DEW interactions, it could be noted that as with the previous case-study, the activities of learners involved iterations among physical manipulation of the graph, narrations and self-evaluations, allowing rhythmic cycles of engagement and reflection to take place.

- Learners were able to manipulate the graphs with their hand movements and try out different movements.
- They were their own evaluators which meant that they defined when they had created the appropriate graphs.
- They were writing down narratives of the movement which described the graphs.
- Their hand movement generated two symbolic representations which aimed to facilitate the links not only between the movement and each of the graphs but also the links between the two graphs: the distance-time and the velocity-time graph.

Additionally, each of the learners' tasks had clear learning objectives and it included comparisons not only between similar graphs but also between equivalent graphs, i.e. the distance-time graph and how it corresponds to the velocity-time graph. The initial activities of the learners that had full access to multiple modalities were also characterised by open-ended investigations at the beginning when they tried to familiarise with the technology.

7.3.2 Method

The participants were 18 Electronics Electrical and Computing Engineering undergraduate students (first and second year), 20 years old in average. There were 9 students in each condition. Students were alternatively assigned to the conditions on presentation to the researcher. The sessions lasted in average 50 minutes even though watchers spent less time on the tasks since they would not spent time to explore which movement corresponds to which static graph.

7.3.2.1 Equipment

The technology used was the same as in the previous study but the software had been updated to show the two graphs in real time with movement. Hand movement was the input to the software.

7.3.2.2 Procedures

At the beginning participants were asked to answer a set of initial questions about kinematics graphs to check their prior knowledge (Appendix C). Afterwards, they tried to generate the distance-time graph of the initial questions and validate the velocity-time graph they drew. If it was wrong they were asked to draw the correct one on paper. Then, the researcher asked them oral questions, such as

- what is the name of each axis,
- could both axis get positive and negative values and
- what was the meaning of negative values.

The teaching session had three parts. In part A, the students tried to generate the second distance-time graph shown on paper (Appendix C) while attending to the v-t that was produced simultaneously. Next to the graph on the paper, there was space for writing: as soon as they generated the graphs, they were asked to write down their movements and draw the corresponding v-t graph without looking at the display.

In part B, participants were given a narrative, asked to draw the corresponding d-t graph and check if it was correct with the aid of the system. Subsequently, they were given another narrative, asked to draw the corresponding v-t graph and check if it was correct.

In part C of the teaching session, there were questions that focused on special features of each of the two graphs. They were asked to generate the third d-t graph and answer d-t related sub-questions, such as:

- when the hand did not move,
- when did it change direction,
- when it travelled the fastest or slowest,

- when did it accelerate and
- when did it have the greatest acceleration.

They wrote down their responses and they drew the equivalent v-t graph.

Subsequently, they were asked to generate the velocity-time graph shown on paper (Appendix C) and answer sub-questions such as

- When the hand was moving with positive acceleration,
- when was it moving with negative acceleration,
- when did it have negative velocity,
- when did it move fastest
- when did it move slowest,
- was there a time where the hand was not moving, was changing direction, or was moving with constant velocity and acceleration.

At the end of this part they had to draw the equivalent d-t graph.

Figure 7-1: The system and a student using it.

7.3.2.3 Design

The students were assigned four tasks: initial questions, a teaching session, a final test and an attitude survey. The initial questions asked participants to interpret simple graphs aiming to check what they already knew about the subject (Table 7-3). It was expected that students would know about each of the graphs but their ability to translate between the two graphs would be limited.

	Doers	Watchers
Initial questions	They were asked to write down ▪ what simple theoretical graphs on paper showed, ▪ what did each graph show, they were asked to describe orally how they would have to move their hand to generate a d-t graph, and to draw a velocity-time graph that would correspond to the distance-time graph shown on paper (Appendix C).	
Teaching session	'Doers' had the tracker's receiver attached to their wrist with the aid of a sweatband (Figure 1). At the beginning of the session, they moved their hand about freely to get familiar with the system. Then they did the tasks described above.	Watchers' watched the researcher generating the graphs shown on paper.
Final test	Answer the questions shown in Appendix C	
Attitude survey	Complete a Likert survey (Appendix C)	

Table 7-3: The experimental design of the case-study.

For the last question of the initial questions participants were alternatively assigned as 'Doers' or 'Watchers'. During part A of the teaching session, participants had to find the corresponding movement from a d-t graph, write down a description of the movement and draw the equivalent v-t graph. These activities of part A aimed to strengthen their ability to translate among multiple representations of motion (two graphical and one verbal).

In part B of the teaching session, participants had to draw a d-t graph and a v-t graph from a narrative and then check if it was correct. The aim of these activities was to change the order of the activities so that the link between the narrative and the actual graph would become sounder.

The aim of the questions of part C was to give students the chance to think of the same information regardless of the type of the graph. Bearing in mind that the curriculum proposes different questions for each graph, the questions of this teaching session stressed that the same information can be extracted from both graphs.

Furthermore during the teaching session, 'Doers' were asked to draw the corresponding d-t graph from the velocity-time graph of the previous task. It was investigated if there was a relation between the type of drawing and their performance. There could be two types of drawing: one with curves and another with angles. Curved lines on the graph show gradual changes in movement and it is how the representation of the moving hand looks on the visual display. Angles show rapid changes: it is related to theoretical representation of movement and is difficult to do by hand. The difference between the different types of drawing could be an indication of what type of information students were using: did they rely on their prior knowledge of the subject or they were influenced by the study? The tendency to draw a d-t graph with curved lines was expected because the v-t graph on paper had curved lines.

In the third part of the case study, each of the students was administered a final test (Appendix C). The final test aimed at summarising the important aspects of the teaching session. They could not look back to the previous sheets.

Finally, the students were asked to express their opinion about the study. They completed a short attitude survey, based on a 5 point Likert scale (Appendix C).

7.3.3 Results

The results discussed below are based on the sheets completed. Each sheet was scored and the findings are based on the overall performance in each sheet. The scores were given as:

- For each question they answered correctly, they would take 1 mark,
- for each line they would draw correctly, they would take 1 mark (with the exception of the last graph of the final test which consisted of one line but they would get 2 marks),
- for each line they would interpret correctly, they would get one mark,
- if they mentioned the corresponding direction, they would get 1 mark,
- if they mentioned information about the speed of movement, they would get 1 mark,
- if they mention the amount of time each movement lasted, e.g. twice as much, they would get 1 mark.

Since students were able to answer the initial set of questions, it could be inferred that the students knew about the distance-time and the velocity-time graphs. They had problems, however, in translating to v-t graph from d-t graph: 7 'doers' and 4 'watchers' drew a v-t graph that did not correspond to the d-t graph.

Initial Questions		
	Doers	**Watchers**
Pupil1	9	5
Pupil2	12.5	8
Pupil3	13	9
Pupil4	15	17
Pupil5	15.5	17
Pupil6	18	17.5
Pupil7	19	19
Pupil8	19	20
Pupil9	19	20
Median	15.5	17

Table 7-4: The scores for the initial questions (max score=21)

From the writings of the teaching session, it appears that after training both conditions were able to describe each graph in terms of their hand movements, to draw graphs from narratives and draw v-t graph from d-t ones.

Teaching session		
	Doers	**Watchers**
Pupil1	28.5	22.5
Pupil2	29	27.2
Pupil3	30.5	28.7
Pupil4	32	33.5
Pupil5	32	35
Pupil6	32.5	35
Pupil7	33	36.5
Pupil8	35	39.5
Pupil9	38	42.5
Median	32	37.5

Table 7-5: The scores of participants for the teaching session (max score = 44)

In the final test, 'doers' scores were better than 'Watchers' (Mann-Whitney test $z = -2.166$, $p<0.05$)[7], which means that the first null hypothesis for this study can be rejected. The scores for each student in each question are shown on Table 7-6.

[7] The Mann-Whitney test was used since the level of data was ordinal, the type of design unrelated and the data were not interval.

Final test										
	Doers									
	Student 1	*Student 2*	*Student 3*	*Student 4*	*Student 5*	*Student 6*	*Student 7*	*Student 8*	*Student 9*	***Median***
graph 1	0.5	1	1	1	1	1	1	0.5	1	**1**
graph 2	1	0.5	1	1	1	1	1	1	1	**1**
question 1	1	0	1	1	1	1	1	1	1	**1**
question 2	1	0	1	1	1	1	1	1	1	**1**
narrative	6	7	8	7	7	7	7	8	7	**7**
v-t graph 3	4	6	6	6	7	6	7	7	7	**6**
v-t graph 4	4.2	4	0.8	3.30	2.5	4.8	4	4.5	4.3	**4**
draw 1	2	0	2	2	2	2	2	1	2	**2**
draw2	0	2	1	0	0	2	2	2	2	**2**
Sum	**19.7**	**20.5**	**21.8**	**22.3**	**22.5**	**25.8**	**26**	**26**	**26.3**	**22.5**
	Watchers									
	Student 1	*Student 2*	*Student 3*	*Student 4*	*Student 5*	*Student 6*	*Student 7*	*Student 8*	*Student 9*	
graph 1	0.5	0	0	1	1	0.5	1	0	1	**0.5**
graph 2	0.5	0	0	1	1	0	1	1	1	**1**
question 1	0	1	0	1	0	1	1	1	1	**1**
question 2	0	1	0	1	1	1	1	1	1	**1**
narrative	4	7	7	6	6	7	8	7	7	**7**
v-t graph 3	7	4	7	4	4	7	6	7	6	**6**
v-t graph 4	0.5	1.5	2.4	2	4.5	1.5	1	4	6	**2**
draw 1	0	2	1	1.5	0	0	2	2	2	**1.5**
draw2	0	0	0	0	0	2	2	1	0	**0**
Sum	**12.5**	**16.5**	**17.4**	**17.5**	**17.5**	**20**	**23**	**24**	**25**	**17.5**

Table 7-6: The scores of participants for the final test (max score = 29).

In particular, the seventh question of the final test ('v-t graph 4') had six sub-questions the actual scores for each of the sub-question are given below.

Seventh Question of final test (v-t graph 4)										
	Doers									
	st 1	*st 2*	*st 3*	*St 4*	*st5*	*st 6*	*st 7*	*st 8*	*st 9*	**Median**
accelerating	0.3	0	0.3	1	*0*	1	0.8	0.5	0.8	**0.50**
not moving	0	1	0	1	*1*	1	1	1	1	**1.00**
change direction	0	1	0	0	*0*	1	0	0	1	**0.00**
fastest	0	0	1	1	*1*	1	0.5	1	0.5	**1.00**
slowest	0	0	1	0	*1*	0	1	1	1	**1.00**
greatest acceleration	0.5	0.5	1	1	*1*	0.2	1	1	0.5	**1.00**
Total	**0.8**	**2.5**	**3.3**	**4**	***4***	**4.2**	**4.3**	**4.5**	**4.8**	**4.00**
	Watchers									
v-t graph 4	*st 1*	*st 2*	*st 3*	*st 4*	*st 5*	*st 6*	*st 7*	*st 8*	*st 9*	**Median**
accelerating	0.3	0.8	0.3	0.3	0.3	0.2	0.3	0	1	**0.30**
not moving	0	0	0	1	1	1	1	1	1	**1.00**
change direction	0	0	0	0	0	0	1	1	1	**0.00**
fastest	0	0	1	0	0	1	0.5	0.5	1	**0.50**
slowest	0	0	0	0	0	0	1	1	1	**0.00**
greatest acceleration	0.2	0.2	0.2	0.2	0.7	0.2	0.2	1	1	**0.20**
Total	**0.5**	**1**	**1.5**	**1.5**	**2**	**2.4**	**4**	**4.5**	**6**	**2.00**

Table 7-7: The actual scores for each participant of the seventh question (v-t graph 4)(max score=6)

Looking into detail of the individual median scores in each question (Table 7-6), there could be noted specific differences (the median scores are used because the scores are not interval, each score does not have equal units in it, and each question does not have the same weight). In particular, doers were more able than watchers to describe what a curved d-t graph showed for the first question (graph 1) (Figure 7-2) and to describe special features of the velocity-time graph than 'watchers' (Figure 7-3). Additionally, 'Doers' were more able to translate from a narrative to distance-time graph (Figure 7-4) and from narrative to velocity-time graph (Figure 7-5).

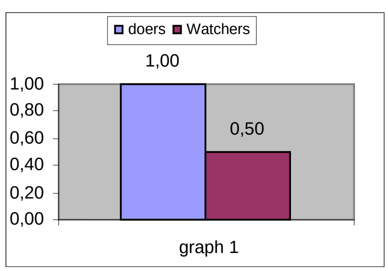


Figure 7-2: Performance in the first question (graph 1), in median scores

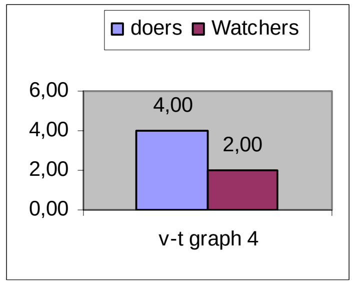


Figure 7-3: Performance in describing special features of v-t graph in median scores

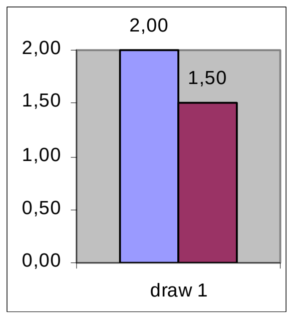


Figure 7-4: Performance in drawing a d-t graph from a narrative, based on median scores

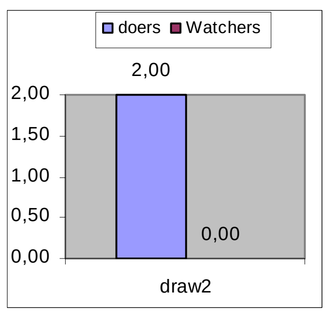


Figure 7-5: Performance in drawing a v-t graph from a narrative, based on median scores

Analysing the attitude survey, it was shown that ‘doers’ liked the activity as much as ‘watchers’ (Figure 7-6). Therefore the second null hypothesis cannot be rejected.

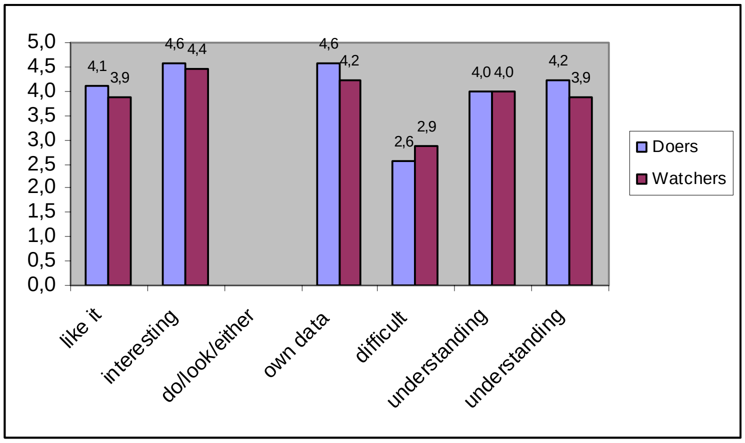


Figure 7-6: Attitude survey results per condition

7.3.4 Discussion

The above results show that physical manipulation of symbols has a positive effect on students' ability to relate among different graphs, narratives and movement. In particular, physical manipulation of abstract symbols extended students' understanding since 'doers' could gain better scores in the final test.

Looking into the initial questions that participants answered, it was verified that participants had prior knowledge of kinematics graphs' interpretation. Regarding the ability to translate from the d-t graph to the corresponding v-t graph, most of 'doers' did not have this ability -only two doers could draw the corresponding graph. However, 'watchers' were more able: five out of nine could draw a correct corresponding velocity-time graph from the beginning.

When, during the teaching session, students were asked to draw the corresponding d-t graph from a velocity time graph, all doers drew it correctly and in curved lines as was shown on the display. It could be inferred therefore that doers were influenced by the study and performed well. From the six watchers that answered correctly, five drew it with curved lines. It is interesting, however, that the three watchers who answered wrong drew lines in angles. It could be inferred therefore that 'watchers' that used prior knowledge were prone to mistakes. Even though it would have been interesting to check if there is a relation between the type of drawing and performance, these results are not conclusive.

7.3.4.1 The employment of multiple modalities

The use of modalities in different conditions is shown in Table 7-8. 'Doers' had to move their hand to complete the learning task. Thus, they had access to physical interactions with the graphs which augmented their ability to link descriptions of movement to graph shapes. 'Watchers' could only see the effect of the movements that a person next to them was doing and they could not take advantage of physical interactions with the graphs. As a result, their performance did not improve during the study and their understanding did not extend to include translations from narratives to v-t graphs.

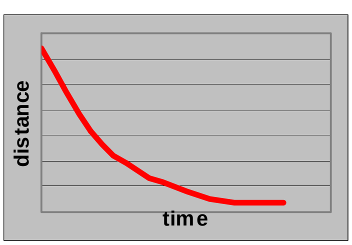
	Writing		Seeing		Moving
	Graphical representations	Verbal representations	Graphical representations	Verbal representations	
Doers	x	x	x	x	x
Watchers	x	x	x	x	

Table 7-8: The use of different modalities per condition

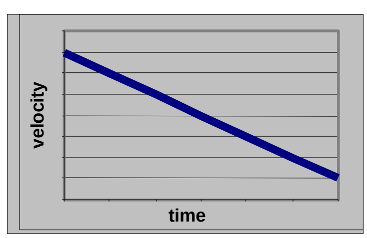
Additionally, when students were answering the final questions, it was observed that they often used gestures as a means to find the answer. It could be stressed, therefore, that interacting within M-DEW gave them not only a verbal language to describe a graph but also a gestural way to express themselves. The issue, however, could not be explored further since there were no video recordings of the session.

7.3.4.2 Meaning construction

As it was showed by the comparison of the scores in the final test statistically, 'Doers' performed better than 'Watchers'. Being able to physically manipulate the graphs and seeing how the graph changed seems to be more effective than just seeing the graph changing.



the graph above shows:



the graph above shows:

In particular, doers were more able than watchers to describe what a curved d-t graph showed for the first question (graph 1). Eight 'doers' answered correctly but only 5 'watchers' did so (Figure 7-2).

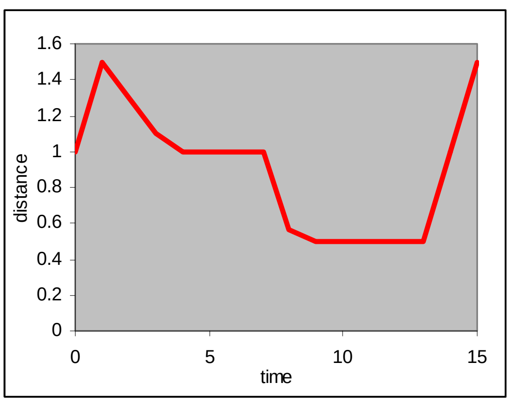
For the second question (labelled 'graph 2'), both groups were able to infer that the v-t graph showed accelerated movement. Thus, both groups were able to understand the representations and their properties.

Q3: The slope of the distance-time graph shows the ________ of the movement.

Q4: The slope of the velocity-time graph shows the ________ of the movement.

For the third and fourth question of the final test (question1 and question2) almost everybody answered these questions correctly, apart from one 'doer' and two 'watchers'. Therefore, both groups were able to draw inferences in terms of scientific principles.

Q5: Describe the hand movements the graph below shows:

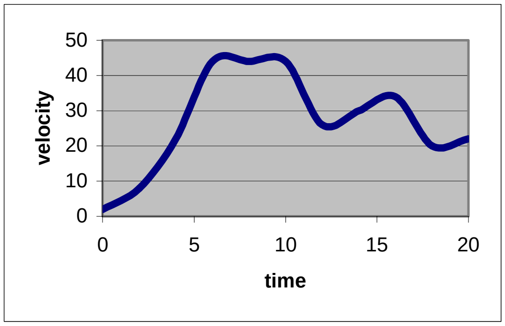


The fifth question (narrative) required students to write down the description of the movement that the distance-time graph showed. Most of students in both conditions were able to answer this question correctly which means that they could understand what the distance-time graph represents.

Q6: How would the velocity-time graph look like?

For the sixth question (v-t graph 3), students were asked to draw the corresponding velocity-time graph from the distance-time graph. No differences in median scores between the two groups were found.

Q7: For the velocity-time graph below:



When is the hand accelerating?

When is the hand not moving?

When does the hand change its direction?

When is the hand travelling fastest?

When is the hand travelling slowest?

When does it have the greatest acceleration?

The seventh question (v-t graph 4) referred to the ability to interpret special features from the velocity-time graph. 'Doers' were more able to answer these questions than 'watchers' in median scores as shown in Figure 7-3. Looking into the sub-questions of question 6, it could be seen that 'doers' were better in answering the question regarding velocity and acceleration (Figure 7-7). The wrong answers from 'Watchers' often assumed that the graph was a d-t one which could be an indication that they were not fully engaged to the task. Regarding direction, however, 'doers' were equally bad as watchers. Additionally, doers and watchers were equally good in detecting that the graph always showed movement.

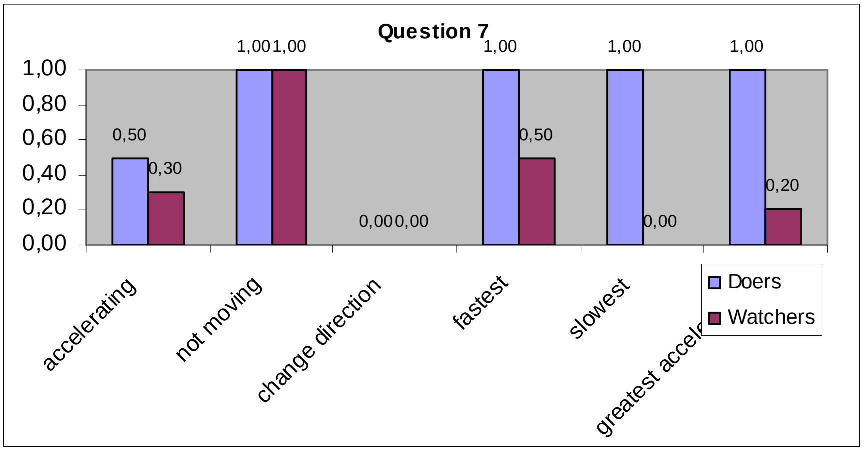


Figure 7-7: Students' responses on sub-questions of question 6 in median scores.

Q8: Sketch a distance-time graph for a hand moving to the left and accelerating from a high velocity to a low velocity.

Q9: How would the velocity–time graph look like?

The last two questions regarded translating from a narrative to a graph, which is an innovative and difficult task since students rarely exercise it at school. Seven 'doers' could translate from the narrative to the d-t graph but only four 'watchers' could do so. 'Watchers' that drew an incorrect d-t graph, had drawn the equivalent v-t graph, which could be an indication that either they did not pay enough attention to understand the question or they did not gain as much knowledge from the learning session as 'Doers'. Additionally, five doers could translate from the narrative to the v-t but only two 'watchers' could do this translation. Thus, it could be inferred that interactions within M-DEW augmented their ability to manipulate the symbolic world because 'doers' could translate from narrative to both symbolic representations.

7.3.4.3 Engagement and reflection

When learning to link among graphical, linguistic and kinaesthetic representations of motion, the forms of engagement suggested by Baber (2003) are extended to situations were learners manipulate symbols instead of objects. In particular, physical engagement is achieved when learners use their movement to visualise changes in the graphs. Cognitive engagement is achieved when learners use their psychomotor skills to coordinate their movements; relate their movements to specific static graphs, and create a theory of use, which is related to the posture they adopt, the type of movement they employ to generate specific graphs and the changes that occur on the display due to their movement (Table 7-9).

Physical engagement
▪ Move about ▪ See changes on the distance-time graph ▪ See real-time updates on velocity-time graph ▪ Write down the movements ▪ Draw static graphs from descriptions of movement
Cognitive engagement
▪ Coordinate actions to draw specific graphs. ▪ Relate a certain movement to a specific line. ▪ Relate changes of movement to specific changes in the line. ▪ Employ a set of actions to a specific graph shape. ▪ Relate the lines of one graph to points of the other ▪ Relate the shape of one graph to the other ▪ Relate descriptions of movement to the distance-time graph ▪ Relate descriptions of movement to the velocity-time graph
Environmental engagement
▪ Responding to the whole activity by doing the movements, reading the papers and writing answers. ▪ All activities done with the cultural requirements for cooperation that comes with the initial decision of students to participate in the activity.

Table 7-9: The forms of engagement revisited: the impact of multiple modalities in learners' engagement when linking among multiple representations of motion.

Furthermore, to relate information about motion to graphical and linguistic representations, participants mainly need to reflect. Therefore, reflection was required by participants at all times during the teaching session. In particular, participants had to reflect-on-action to relate the dynamic generated graphs to the static graphs on paper and all of them to specific movements. Doers, however, could also reflect-in-action since they had to decide which movement would generate the desired graph. Reflecting-in-action and generating graphs provided doers with the rhythmic cycles of engagement and reflection: similar to writing linguistic symbols, doers were able to 'write' graphical symbols, engaging into generating graphs and reflecting on them by relating them to the static graphs on paper. They could relate their movement to the distance-time graph and see how the velocity-time graph was formed. The real-time visual feedback from both graphs scaffold their understanding and supported them in discovering the appropriate associations. These rhythmic cycles did not exist for 'watchers': they did not have to 'write' graphical symbols thus they lacked the engagement part of the cycle and the interplay between engagement and reflection.

Additionally, to reflect the learner would also need to challenge the provided information based on prior ideas and feelings (Boud et al., 1988). Being able to physically manipulate the graphs during the teaching session gave the chance to doers to challenge their prior ideas about representation of movements and compare it to the provided information. For watchers this challenge did not happen: they were given the correct movement without challenging their prior conceptions of kinematics graphs. This could lead to awkward situations: one watcher for instance stated during the teaching session that he did not believe the software when explaining the reason for drawing a wrong graph. He did not draw the d-t graph as it appeared on the display but as he thought it was correct.

The final test was a summary of the teaching session. The fact that they could answer the final test could be an indication that all participants reflected on the teaching session. The fact that doers were able to gain more scores, thus, to give more correct answers, than watchers could be an indication that doers reflected more successfully than watchers. Furthermore, doers were able to gain better median scores for the last two questions of the final test which required them to relate a narrative to a graph. This demonstrated ability to relate could be another indication that doers were more engaged and more able to reflect than watchers.

7.3.4.4 Learners' preferences

When learners stated their opinion, there were not significant differences between the two groups. However, students in all conditions would like to watch their own data. This could be an indication that physical manipulation is an interesting and engaging activity. Additionally, the rest of the responses in the Likert questionnaire indicated that they found the questions of medium difficulty and they understood 'distance-time' and 'velocity-time' graphs, giving evidence for the usefulness of their activities.

7.4 Conclusion

The second M-DEW study described in this chapter explored how multiple real-world and symbolic-world modalities facilitated undergraduate students in constructing relations among movement and multiple symbolic representations of motion. Studying the differences between students that could physically manipulate graphs and students that could not, there was a difference in the overall scores of two groups. Therefore, physical manipulation seems to strengthen the links among graphical, linguistic and kinaesthetic representations of motion.

Part of the experimental design was to support the coupling between learners' own movement and the two dynamic graphs for 'doers' but not for 'watchers'. Additionally, the de-coupling between the narratives and the two graphs was decided to be supported for doers but not for watchers. As a result, rhythmic cycles of engagement and reflection was expected to be strong for 'doers' but not for 'watchers'. The ability of doers to answer the questions better than watchers is an indication that 'this expectation was met.

Finally, the study supported the argument that real-world modalities can extend learners' understanding when relating among representations with similar properties. By being able to move their hand and watch the graphs to be informed, doers could structure their ideas of representations of motion in an enjoyable learning experience. Students who did not have access to kinaesthetic information did not have so strong links among the movement, the narrative and the graphs.

As with the previous M-DEW case study, this case study provided doers with body syntonic learning experiences providing another instance of constructionism-based interactions: simultaneous physical manipulation of two graphs seemed to support learners in constructing relations among real-world movement, its symbolic representations and ways of expressing them. They had two types of expression at hand: graph 'writing' on display through hand movement and writing narratives about their movements on paper. Their movements gave them access to body syntonic learning; their expressions made it personal and the written one related it to scientific language.

Furthermore, a question under investigation was the number of the available different modalities. Each modality covers different aspects of the phenomena and challenges prior conceptions of the world of the learner. The integration of kinaesthetic and visual modalities in a learning activity gives the opportunity to test real-life actions and receive feedback from the system. Visual representations, that are effectively coupled with movements, in real time, facilitated comprehension of kinematics graphs and related science to their body. Since participants of both groups were able to perform all the activities of the study, there was no need to add another real-world modality.

Another finding of this study is that physical manipulation is not age-oriented. Undergraduate students were as willing to see the effects of their movements on the visual display as 14-year-old pupils. This finding could be a starting point for more investigations of the effects of movement and physical manipulation of abstract concepts at the university level or workplace learning.

Additionally, a question might arise regarding the age of the participants. Even though it is A-level pupils that learn about kinematics graphs, they were not the participants. Bearing in mind that the links under investigation are not required by the national curriculum, it was decided to ask undergraduate students to do the task and not stress a-level pupils with extra-curriculum activities.

Chapter 8 Conclusion

8.1 Overview

This thesis focused on multimodal interactions for the design of learning environments. It studied the benefits of multimodal interactions in learning and analysed the interactive space between the learner and the learning task when technology is used. It introduced and tested a framework for multimodal interactions and proposed how multimodal interactions can benefit learners in their efforts to understand science concepts, such as 'forces and motion'.

A literature review was conducted with the theoretical framework of constructionism as a starting point. It examined how specific educational technologies (microworlds) have been designed to support learners' engagement and abstraction. In addition, the review addressed what learners have to do in the science classroom, the lab and through interacting with information technologies. Learning with multimedia was the next consideration which supports learners mainly through visual and verbal means. Comparing educational technologies to classroom learning, the richness of the latter appears to be due in part to the employment of multiple sensory and communication modalities. Thus, multimodal technologies may be able to enrich the learning environment in ways that existing technologies could not. However, what researchers mean by the term multimodality and multimedia in HCI and ET was explored in an attempt to clarify the term 'modality'.

Subsequently, a categorisation for the term 'modality' was proposed to describe the task of science learning and to build a bridge between the different usages of the term. The categorisation puts modality into two different 'worlds': the real world and the symbolic world, in each of which learners have to act and construct meaning. From all real-world learning situations, the focus is on the science classroom: it is where pupils should link descriptions of the real world to symbolic terms and shift from concrete to abstract understanding. It was argued that interactions with the symbolic world could be enriched if they are augmented by real-world manipulations. A multimodal Digitally Enhanced World (M-DEW) was therefore proposed as a model of an environment where learners can physically interact with symbolic entities.

Furthermore, a framework was proposed to structure learners' interactions within each world and to inform the design of learning environments. The framework focuses on the links between real world and symbolic world interactions. Coupling the physical activity with the relevant symbols and linking physical changes to symbolic variables is identified as a way to facilitate the smooth interplay between the real to the symbolic world. Bearing in mind that this coupling is achieved by the mediation of technology, there should be an equivalent de-coupling so that the activities are also related to the symbols without the presence of the technology. Additionally, the effects of such coupling and de-coupling are studied in relation to learners' engagement and reflection.

The framework was the outcome of an iterative process of analysis and synthesis between existing theories and three studies with learners of different ages. Through these theory-informed studies, the significance of physical manipulation of objects and symbols through the employment of multiple modalities was emphasised as a way to facilitate learners' meaning construction, engagement and reflection.

8.2 The research questions re-visited

This thesis investigates how multimodal interactions with technology can facilitate learners in understanding the science concepts of forces and motion. Through multimodal interactions within a digitally enhanced world environment, learners employed a combination of real-world and symbolic modalities that were related to the subject to be learnt. This multimodal digitally enhanced world (M-DEW) coupled elements of the real and symbolic world interaction aiming to facilitate learners' meaning construction, engagement and reflection. The M-DEW is a generic real-world environment with digital features and a set of technological and activity-related requirements that characterise it. In the Introduction chapter, a set of research questions was mentioned; below are the answers to these research questions based on the findings expressed in the previous chapters.

Q1: How do people learn science in the classroom and where do they face difficulties?

To answer this question, several steps were taken. Initially, a literature survey was undertaken exploring how science is delivered to students in practice through teaching in the classroom, practical work, and through information and communication technologies (see section 2.3). The survey also considered the different problems that students encounter, and what approaches were considered to overcome them (Section 2.3.1.1).

From this survey it was noticed that classroom interactions are based on verbal and visual communication and interactions in the laboratory are based on employing multiple sensory and communicative modalities. Additionally, data used in the classroom originate from everyday life but are abstractedly related to the representational forms of symbols. Laboratory data on the other hand are collected in situ but they are not always connected to symbolic entities showing an overemphasis to manipulation without relating actions to theory.

As a result, the employment of multiple sensory and communicative modalities was proposed for learning in the classroom and the laboratory. The employment of multiple sensory and communicative modalities stresses the interplay between real and symbolic world: as an example of illustration data-logging activities were reviewed to show how physical activities were combined with technology to present symbolic representations of data.

Q2: How can multiple modalities be organised so that the task of science learning could be described?

The task of science learning was partially considered as the transition between 'real world' and 'symbolic world'. Within these two different 'worlds' the employment of multiple modalities occurs. A categorisation of 'worlds' and the modalities employed in each one aimed to highlight the significance of sensory modalities in science learning. When modality is considered in relation to the 'real world', it is regarded as one of our sensory channels to perceive the world. There, the different modalities are regarded as being vision, audition, touch, smell and taste. Instead of focusing on the sensory organs, the focus is on the act of sensing, that is, seeing, hearing, feeling, etc. Modality in relation to the 'symbolic world' can be seen as a representation which gives structure to information and makes it meaningful. Modalities of the symbolic world relate to communication, thus verbal language and other representations are communicative modalities and they differ from the sensory modalities of the real world. Apart from verbal and visual representations, there are aural representations which refer to sounds of something not visually present. Additionally, there are kinaesthetic representations which lead to specific movement or action. They are associated with the employment of specific artifacts or tools and the movements related to such employment.

It was argued that when designing learners' interactions with technology all of the above representations need to be considered: each one can facilitate understanding differently and, depending on the learning content, each has a different contribution in supporting engagement and reflection.

The science classroom is one instance of the real world. Its significance, however, lies in the fact that it is where learners are introduced to the symbolic world. The modalities employed in science learning are a blend of real and symbolic modalities. The conceptual path of the learner is different depending on the choices of the teacher to employ one or the other modality and the meaning each modality carries. The problems that learners face in the science classroom were considered partly as problems to relate the concrete, real-world understanding to the abstract, symbolic representations of the science curriculum. It was suggested that to facilitate the transition between the concrete and abstract understanding the employment of multiple modalities from both worlds is required.

The employment of such multiple modalities provides learners with the opportunity to interact not only with objects but also with symbols via their senses. It can be noted, however, that virtual learning environments have been focused on the stimulation of the distant senses, vision and audition, neglecting the stimulation of the near senses which could provide learners with crucial information for understanding, engagement and reflection. Interactions with objects and symbols via distant and near senses occur within the multimodal digitally enhanced world (M-DEW). The aim of M-DEW is to ensure that real-world interactions would create a link with entities of the symbolic world; in other words, to support the transition between concrete understanding and abstract thinking and test abstract understanding through concrete experimentation. Viewing concrete and abstract thinking as faces of the same coin, M-DEW supports their coupling, their living together in a constant interplay to facilitate meaning construction. Within this world, people would be able to manipulate efficiently symbols and artifacts not only by vision or language but also by other senses and representations.

To succeed in this aim, M-DEW can provide learners with resources in the appropriate format for meaning construction. Depending on the meaning to be constructed, resources could employ a variety of modalities. In the case of learning about kinematics graphs, the resources employed kinaesthesia and vision from real-world modalities and graphs and language from symbolic modalities. The resources would come from both worlds and thus they would be multimodal; as a result, the digitally enhanced world would be multimodal.

Modalities of the M-DEW aim to augment learners' meaning construction. Bearing in mind that abstract concepts are expressed through symbolic representations, the interplay between real-world and symbolic modalities could facilitate the interplay between concrete and abstract understanding. Within M-DEW learners can interact not only with the technology but also with other, non digital, resources that are employed through their activities. Therefore, M-DEW is an environment where the technology and learners' activities are equally important.

Q3: Can a Framework for Multimodal Interaction inform the design of learning environments to support science education?

This research question, addressed in Chapter 4, aimed to explore how an M-DEW can facilitate learners. It investigated how people *interact* with artefacts and symbols within the different 'worlds' and what is the role of the modalities of each 'world'. A 2-dimensional framework was proposed, which related the degree of employment of multiple modalities to the 'world' where the employment occurs. It aimed to provide a structure for learners' interactions with technology.

Starting from studying real-world and symbolic world interactions, the result was an emphasis on the interactions that an M-DEW can support. Regarding interactions in the real world, it explored how interacting with objects can augment understanding. The outcome was a categorisation of the role of objects in the learning activity. The categorisation proposes how objects as supportive means can be seamless, can facilitate reflection, can keep the learners engaged with the activity or sometimes prohibit the activity. Such categorisation is useful for the design of the learning activity to advocate which artifacts to employ for manipulation, which to make transparent and which to avoid. This categorisation was put into practice and further explored by the 'Real-world case study'.

With object manipulation, learners become engaged, 'thrown into' an activity flow. Unexpected behaviour and breakdowns are chances for reflection, while in the activity or after the activity is over. Additionally, interacting within the real world (seen here as manipulation of objects) involves being engaged in three interleaved ways: physically, cognitively and environmentally. This engagement triggers learners' meaning making. However, it needs to be ensured that learners learn from such interactions with objects and they do not just become caught up with the activity: thus they need to be able to reflect on a static representation and couple real-world interactions with abstract thinking.

Abstract thinking was related to interactions in the symbolic world. Considering visual representations and the operations taken place when people interact with them, the 'external cognition' perspective was explored for assessing more effectively how technological innovations in graphical representations should be approached. The 'external cognition' perspective focuses on the cognitive processing involved when interacting with external representations, the properties of the internal and the external structures, and the cognitive benefits of different graphical representations. There are three main advantages that people gain while interacting with representations:

- computational offloading that refers to the cognitive benefits from a representation,
- re-representation that relates to their structural properties, and
- graphical constraining that relates to possible processing mechanisms.

Whether the user will take these advantages from interacting with representations depends on the level of expertise, the knowledge domain and the type of task (Scaife 1996). To be able to benefit from the advantages of using representations, learners need support in interpreting the graphs and be able to use them repetitively in context.

The view of mental interactions with graphical representations was extended to include physical interactions with them. To explore physical interactions with representations, the focus is on multimodal interactions within the digitally enhanced world (M-DEW). These M-DEW interactions were explored regarding the transition between the real-world and symbolic world, their impact in learning and in the symbolic world.

Regarding the transition between real-world and symbolic world interactions, it was argued that the process of combining real-world and symbolic modalities facilitate the linking between the two worlds. Coupling the physical activity with the relevant symbols and linking physical changes to symbolic variables is identified as a way to facilitate the smooth interplay from the real to the symbolic world and vice versa. Linking the real world to the symbolic was regarded as a repetitive circular process where learners' understanding is augmented each time they go around. Interactions within a digitally enhanced world can support this process where concrete actions find their abstract counterpart through physical manipulation of representations.

It was also argued that physical manipulation of representations which results through the employment of movement and vision (real-world modalities) and representations (symbolic modalities) can support learners in

- understanding the representation and its properties,
- being able to manipulate the symbolic world and interpret its changes,
- drawing inferences in terms of scientific principles,
- relating among representations with similar properties.

These arguments were further explored by two case studies.

The impact of a multimodal Digitally Enhanced World (M-DEW) in science learning is related to learners' engagement and reflection. Through interacting within M-DEW, it was argued that learners enact cycles of engagement and reflection. The act of generating a graph in real time can be considered as a type of writing: instead of writing letters or words, the learner writes lines on the monitor. The engaged learner devotes her full attention to the task of creating lines. Reflection consists of 'sitting back' and reviewing all or part of the displayed shapes, forming and transforming ideas, planning what new lines to create and how to do them. Interactions within M-DEW support pupils' ability to try out different ideas of moving, to create an understanding that relates to themselves. M-DEW does not aim to provide answers; it aims to encourage learners to find solutions through experimentation. Instead of trying to forget their errors, the intention is that learners will study the problem so that the process of correcting is part of the process of understanding.

The impact of M-DEW in interacting with the symbolic world is related to functions of virtual learning environments which aim to describe explicitly learners' existing interactions with the symbolic world through the use of representations. The functions were discussed with regard to what could happen if multiple modalities are employed. It was suggested that the use of multiple real and symbolic modalities can provide learners with valuable support throughout their actions in a learning activity.

In particular, to be provided with complementary information which can be different or partially redundant, learners need to employ two real-world modalities, kinaesthesia and vision to manipulate a symbolic representation. For example, they could try a specific hand movement repeatedly so that they realise the relationship between the symbols' behaviour and the movement. This repetition is redundant information. When movement to the left generates a line with a different direction than movement to the right, different information is provided. It aims to communicate the meaning of directionality of the graph. Thus the coupling of hand movement with the distance-time graph provides learners with complementary information important for their meaning construction.

Learners may also benefit from complementary cognitive processes supported by different representations. Representations that contain equivalent information can enable salient different inferences (Ainsworth 1999). Learners can realise that a distance-time graph describes movement in one dimension only; they could also realise that the x-axis of the graph is measuring time and not a different dimension of movement. What is more, they can also realise that 'doing' science means to be consistent with the initial decisions throughout the activity.

The employment of different modalities can also contribute in restricting misinterpretations. It was argued that when employing multiple modalities, a 'real' modality can facilitate inferences for the symbolic one.

Learning technologies that aim to support deeper understanding focus on supporting abstraction, generalisations or showing relations among different representations (Ainsworth, 1999). The employment of multiple modalities facilitates learners' abstraction: different symbolic and real modalities could provide associations that reify complex abstract concepts. Symbolic and real modalities can provide information and support processes that highlight structural relations between movement and graph, for example, and thus relate abstract graphs to real actions.

When two graphs are generated from the same movement, the learner is able to realise that the same movement (of their hand) can be represented by more than one graph, e.g. distance-time and velocity-time graph; each graph looking different. The continuous update of the graphs can enhance the linking among different representations and movement. With such conditions they can realise that there are different ways of representing the same event, and thus be introduced to the concept of re-representation.

Thus, providing learners with an M-DEW environment means that they are supported in a smooth transition between the real and the symbolic world, their learning activity is aided by keeping them engaged and triggering them to reflect, and also their interactions with symbolic world are augmented since they can take advantage of all the functions it supports.

Q4: Do multiple modalities have an effect on learners' engagement and reflection?

Learners' efforts to understand scientific concepts in this thesis are related to their ability to be engaged to the learning task and to reflect on their activities. It was argued that the employment of learners' sensory and symbolic modalities have a significant role in learners' engagement and reflection. It is argued that for situations where the representing concept is about changes in the environment, learners who are physically employed with representations will be involved in rhythmic cycles of engagement and reflection.

Engagement and reflection can be supported by multimodal interactions when two issues are in focus: 1. a coupling between the action and its symbols and 2. the subsequent de-coupling between them so that one is reminding the other without the presence of technology. For the coupling between the action and its symbolic representation to be strong, technology should have specific features. In particular, the proposed technological features were automaticity, synchronicity, sensitivity, continuity, ease of presentation, interpretability. Their effects on learners could be summarised as

- <u>automaticity</u> speeds up the process of representing, omits the difficulties of creating a symbol and allows pupils to focus on its interpretation,
- <u>synchronicity</u> helps learners believe the symbol and rely on it,
- <u>accuracy</u> guides learners to attend to salient points of the symbol,
- <u>continuity</u> highlights emerging patterns and anomalies and gives access to the whole symbol rather than focussing on separate components,
- <u>ease of presentation</u> keeps learners engaged in trying different configurations in a game-like manner rather than effortful considerations,

- interpretability supports learners' willingness to understand the symbolic representation and can provide an instant overview of the action in a form of a static symbol.

Furthermore, the de-coupling of action and its symbolic representation is argued to be supported by emphasising the activity. In particular, the support of physical manipulation of symbols, narration and self-evaluation provides learners with rhythmic cycles of engagement and reflection. The proposed activity-related features and their effects on learners are summarised below:

- Physical manipulation of symbols can match each movement to a symbol component. By exploring relationships between symbols, learners are 'doing' science providing them with an engaging activity.
- Narration can help them learn how to describe what they do in a 'motion-related' way; to create a terminology link and to provide an anchoring backdrop to the schooling procedures.
- Self-evaluation of their performance forms and transforms ideas through experimentation.
- Open-ended investigations facilitate experimentation and problem solving.
- Inclusion of different but similar symbols allows focusing on differences and common features.
- Clear learning objectives allows to set contextual questions and scientific entities become not only entities to 'think about' but also to 'think with'

These arguments were further supported by a series of experimental studies, which investigated how learners learned about the concepts of force and movement, when they had different degree of employment of real-world modalities. In particular, the first M-DEW case-study focused on pupils learning about distance-time graphs and it suggested that the employment of real-world modalities supported learners in understanding the symbolic representation of motion and its properties as well as in drawing inferences in terms of the scientific principle of speed. Learners' understanding was facilitated by strengthening links between real-world movements and symbolic-world notation: they were able to couple their movements with the changes in the graph. Through this coupling, they were able to interpret the special features of the graph and overcome misunderstandings demonstrating that links were indeed built while interacting within M-DEW. The de-coupling was aimed to happen through the different activities.

Doers' greater ability to describe the graphs during the final test without any help from the provided technology (or any other available resources), demonstrate that this de-coupling was more successful for them.

In the second M-DEW study, undergraduate students were revising about two kinematics graphs: distance-time and velocity-time graph. It explored how multiple real-world and symbolic-world modalities facilitated undergraduate students in constructing relations among movement and multiple symbolic representations of motion. Studying the differences between students that could physically manipulate graphs and students that could not, there was a difference for the first group suggesting that physical manipulation strengthens the links among different graphical, linguistic and kinaesthetic representations of motion. The study supported the argument that real-world modalities can extend learners' understanding when relating among representations with similar properties. By being able to move their hand and watch the graphs to be informed, doers could structure their ideas of representations of motion in an enjoyable learning experience. Students who did not have access to kinaesthetic information did not have so strong links among the movement, the narratives and the graphs.

8.3 Future work

This thesis aimed to structure multimodal interactions with interactive technology and study how these interactions can be enriched by the employment of multiple sensory and communicative modalities. It has been argued that the employment of appropriate sensory modalities can provide learners with the required information to construct relations between the real and the symbolic world e.g. in the particular task of learning about 'forces and motion'. A crucial question that arises however is how this could apply to other learning tasks, in different subjects, in different situations and settings. It would be interesting to study the effect of multimodal interactions in mathematics or language learning, and also outside the school curriculum.

The usefulness of employing multiple modalities in a learning activity was not related to a particular age, thus different age groups were considered for the three case studies. Undergraduate students were as willing to see the effects of their movements on the visual display as 14-year-old pupils, even though the content had to be adjusted to their abilities. Therefore, the positive effects of physical manipulation do not appear to be age-oriented nor school-oriented. This finding could be a starting point for more investigations of the effects of movement and physical manipulation of abstract concepts at the university level or in workplace learning. Physical manipulation of abstract concepts occur in specific professions regularly, e.g. when handling complex equipment in power plants. Such professional activities could be further investigated to gain insights of real practices and multimodality.

In these situations, complexity is increased and therefore the framework for multimodal interactions would be enriched. The essential research question to address would always be which modality to accommodate when. The suggestion of this thesis was that the learning task denotes which modality to employ: it depends to the connection between the real-world activity and the representations used. Such an argument however needs to be further explored for different subjects, in different situations and settings, either through different experimental studies (bottom-up approach) or through hypothesising a theory of use (top-down approach).

8.3.1 Limitations

It was beyond the scope of this research to address possible internal forms of representation or cognitive architecture. This is an area of much research and theoretical debate both within and outside science education. However, the question of how visual external representations, whether newly or conventional developed, can be linked to real life situations and their descriptions was addressed with the goal of better understanding the design and use of technology in teaching and learning.

Additionally, the employment of modalities in the educational literature has been related by other researchers to different learning styles; see for example, Gardner's (1983) Theory of Multiple Intelligences. This thesis explored the effects of multiple modalities in science learning, assuming that it applies to all learners independently of their learning style. However, the relation of different modalities to different learning styles is an issue that could be further explored.

Furthermore, it was argued that while interacting with M-DEW, learners could be employed with playful and enjoyable activities. However, this leads to the *play paradox* (Noss and Hoyles, 1996): playing can communicate meaning to an activity but it blurs the specificity of the intended meaning. When the teacher or the researcher stresses a new idea to students' attention, the student is no longer playing, but if it is not imported the student might never encounter the idea (Noss and Hoyles, 1996). The balance between exploration and guidance is not easy to achieve and it needs focused investigation.

This thesis stresses the importance of using haptics and kinaesthesia when learning about forces and motion. The real-world case study (learning about forces) used real objects without any interactive technology. The use of more advanced technology, in terms of force feedback or smart objects, would be an interesting issue to explore. Such technology could initiate comparisons between real/concrete objects and computational ones: in what dimensions tangible objects differ from those seen on screen and how interactions with them can augment the links between concrete and abstract concepts, between the real and symbolic world.

The use of the proposed M-DEW in the real classroom situations is another interesting issue that could to be further explored. According to a teacher's feedback, the activities of the first M-DEW case study could easily occur in a lab session giving the opportunity to study the effects of M-DEW in longitudinal investigations.

During the second M-DEW case-study, it was noticed that learners were using hand movements while they were interpreting graphs in writing. This observation, which unfortunately could not be further studied, could be an indication that there is a relation between verbal and body language in terms of learning performance. Learners' body movement may provide them with a notation or even a language for understanding graphical representations which could have further implications to other learning situations.

Furthermore, the employment of movement while writing as well as the generated graphs of learners could be a window on their thinking and how their understanding was structured and re-structured throughout the activity. The current research analysed learners' writing and not learners' generated graphs (graph writing). Information from graph writing could enrich further our understanding of how technology augments learners' meaning construction.

8.4 Epilogue

Multimodal interactive systems for educational purposes could introduce a new era in computer aided learning. The process of designing such systems involves studying the benefits of multimodal interactions in learning. This thesis aimed to contribute to such process in two ways: 1. through introducing and testing a theoretical framework for multimodal interaction to structure the interactive space between learners and the content to be learnt, and 2. through studying how multimodal interactions, i.e. physical manipulations of representations, can employ learners in rhythmic cycles of engagement and reflection that enhance their meaning construction.

Developing environments to support learners' engagement and reflection can enrich the whole learning experience. Giving access to information that was previously hard to obtain and visualise, supports learners in creating strong links between symbols and real world. Towards this end, the role of designers is to investigate learners' difficulties, not in terms of interacting with the technology but in terms of interacting with the subject to be learnt; then to decide how interactions with technology can facilitate learners in their meaning construction.

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Appendix A: Real-world interactions: a case study

Teaching Session Plan

<u>'Hands-on'</u>

This experiment is about forces.

Force is a pull or push.

We apply a force to something and make it move or change its shape, e.g. to a spring.

Try to feel what a force is, e.g. take the spring and pull it or squash it. You apply a force to it now.

How does it feel?

Do you feel any force coming back from the spring?

The spring applies a force to you as well. Hold one end of the spring and give the other end to someone next to you. Tell him/her to pull.

What does it feel? Is it different from when you did it by yourself?

Pick up an object. Try to understand how heavy it is.

With your other hand, pick up another object. Try to feel their differences in weight (which feels heavier and which is lighter?).

Now, hold a spring in one hand and with the other hang an object on it.

What happens to the spring now?

Is it different from what you did before?

Try a heavier object and try to understand if it feels differently. Try an even heavier object (hang two objects together).

Do you think you understood what a force feels like?

<u>What to do next:</u>

Find out how to operate the pointer of the stand

Explore what happens to the length of the spring when objects are hung on it and fill in the results table on your sheet.

Look at the stand with the spring on it and measure the spring's length.

Make sure that your eyes are in line with the black line when you measure

Always measure the same point of the spring (the red spot)

Write the measurement on the Recording sheet

Hang an object of 250gr at the end of the spring

The researcher says: *Notice what happens to the spring. Can you think of a reason why?*

Does the object do anything to the spring?

Does the spring do anything to the object?

Measure the new length and write it on the Recording sheet

Remove the 250gr object and hang a object of 500gr

Notice what happens to the spring. Can you think of a reason why?

Measure the new length and write it on the Recording sheet

Now add the object of 250gr beside the 500gr object (giving 750gr in total)

Notice what happens to the spring. Can you think of a reason why?

Measure the new length and write it on the Recording sheet

Try to fill in the remaining gaps in the recording sheet.

<u>'Imagine' condition</u>

The child reads:

This experiment is about forces.

Force is a pull or push. We apply a force to something and make it move or change its shape, e.g. to a spring.

Imagine a spring.

We can pull a spring or squash it. When we do so, we apply a force to it.

However, the spring applies a force back to us when we try to pull it.

Imagine that you are pulling and squashing a spring

Can you imagine what a spring that is pulled feels like?

The spring can be pulled by us and a friend when we hold the two different sides, can you imagine how?

The spring can be pulled by something else that is heavy.

Can you think what happens to the spring when it is pulled by a weight of 500grams?

From what you read above, do you think you understood what a force feels like?

what to do next:

- Try to imagine what happens to the length of the spring when weights are hung on it and fill in the table on your sheet.

- Try to fill in the remaining gaps in the recording sheet.

- Try to answer some more questions…

The sheets given to children: Initial set of questions

Child's Name …………………………………..   Date of Birth ……………….
School …………………………………   Date ……………….
Condition: Questions/see/hands on

Think about these two points first…..

- how a push or a pull can make an object start or stop moving
- how to measure length in standard (meters/centimeters/millimeters) units

Now try to answer the following questions

What happens to a spring when you hang objects off the end of a spring?

………

What happens to a spring if you hang a light object onto the end of a spring?

………

What would happen to a spring if you hang a heavier object on the spring instead of a lighter one?

…………..………………………………………………………………………………

Can you think of a reason why?

………

The sheets given to children: Recording Sheet

Recording Sheet

Aim: We were asked to find out what happens when we hang a

_ _ _ _ _ _ _ _ _ _ _ _ *on a* _ _ _ _ _ _ _ _ _ _ _ .

Method: The spring was fixed to a stand and measured its _ _ _ _ _ _ _ _ _ _ _ _ _ _. Next we hung a _ _ _ _ _ _ _ _ _ _ _ _ _ on it and measured its length again. We repeated the measurements for objects of _ _ _ _ _ _ _ _ _ and _ _ _ _ _ _ _ _ grams.

Results:

Weight (gr)	Length of spring (cm)
0	
250	
500	
750	

Conclusions: We found out that when we hanged an object to a spring, the spring is _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _.

We also found out that when a spring is stretched, it _ _ _ _ _ against whatever is stretching it.

We also realised that the greater the load, the _ _ _ _ _ _ _ _ _ the spring extended.

The sheets given to children: Final Test

Child's Name ……………………………….….	Date of Birth ……………….
School ………………………………….	Date ……………….
Condition: Questions/see/hands on	

Some more questions…(circle the correct answer)

Is weight a kind of force?

i. yes
ii. no
iii. I don't know

An object pulls a spring. Does the object apply a force to the spring?

i. yes
ii. no
iii. I don't know

An object pulls a spring. Does the spring apply a force to the object?

i. yes
ii. no
iii. I don't know

When we apply a force to a spring, what happens to the spring?

i. it remains the same
ii. it stretches
iii. it shrinks

As the weight increases what happens to the length of the spring?

i. the greater the weight, the greater the spring will stretch
ii. the greater the weight, the less the spring will stretch
iii. the greater the weight, the spring remains the same

What is making the spring travel up and down?

……

Estimate what would be the length of the spring when we apply an object of 1000grams to it.

……

Estimate how many grams do we need to hang in order to have a spring length of 30cm

……

The sheets given to children: Certificate of completion

THE UNIVERSITY OF BIRMINGHAM

This is to confirm that

____

successfully completed

The force's Experiment - investigating forces in springs

on the
Tuesday 24th of October 2001

at Osmington Bay Centre, 3D Education & Adventure

Stamatina Anastopoulou
Postgraduate Researcher

Educational Technology Research Group

Appendix B: M-DEW interactions: first case study

Plan of Teaching Session

I can tell you that the first graph of the previous page shows no movement; can you tell me why?

The second graph shows movement; can you tell me why?

Now, we will try some movements with the tracker and look how the graph is plotted.

You could move your hand 'left and right' or 'forward backwards'

You will attach a sensor to your wrist and move your hand about. You will see a graph plotted on the display that shows the graph of your hand's movement.

Let's see how it works!!

[play for 3 mins]

what would the graph be called?

What would be the name of the x-axis?

What would be the name of the y-axis?

When do you think the y-axis *values* would be positive/negative?

What would a negative value in the distance-axis *mean*?

How would a negative distance value be *shown* on the graph?

Could the x-axis (time) have negative *values*?

Try to move your hand very fast or very slow;

What happens when you move faster?

What can you tell from the distance-time graph?

How fast the hand is going, that is it's speed! [5 mins]

The sheets given to pupils: Initial set of questions

Name ………………………………….	Date of Birth ……………….
School ………………………………….	Date ………………
Condition: **hands on/T**	

***Graphs** are used to detect an object's motion.*

Do you know…

*In what units do we measure **distance**?* ....

*In what units do we measure **time**?* ....

Can you think of what a distance-time graph shows?

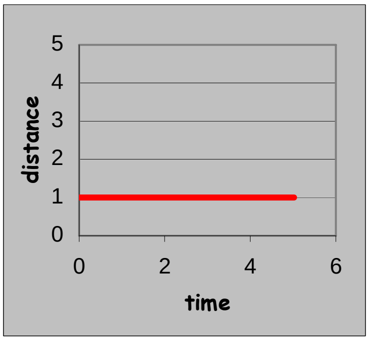
....

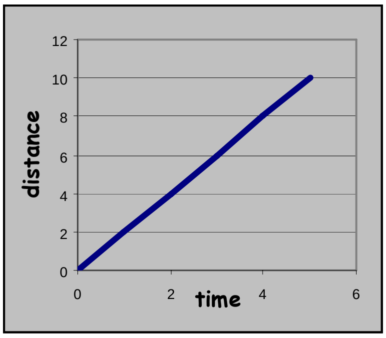
or

how the ……………… changes with …………………………...

do you know what that is? ……………………………..

Look at the graphs below and tell me what do you think they show.





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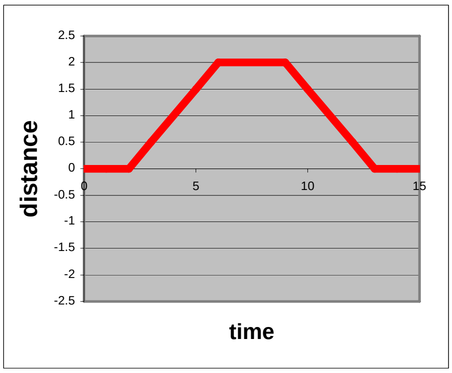
How about our hand's motion?

Let's see what we can tell from a graph…

Now try to move your hand according to those graphs and write the movements down:



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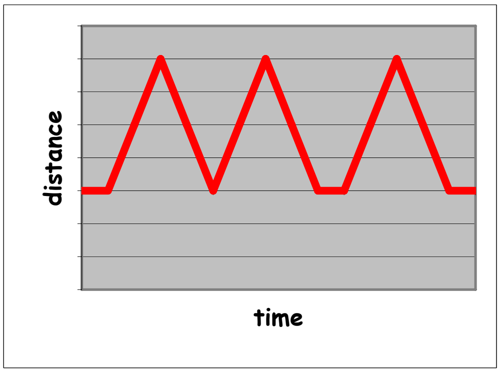

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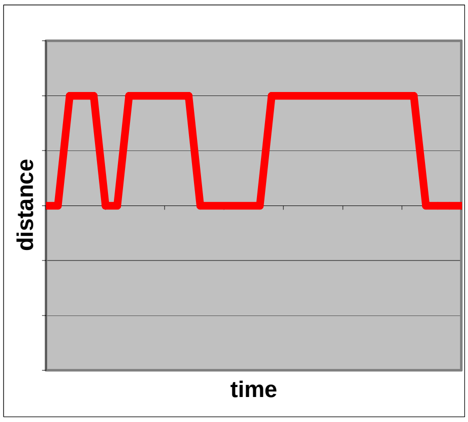

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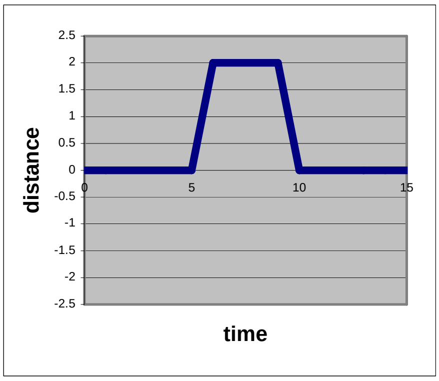
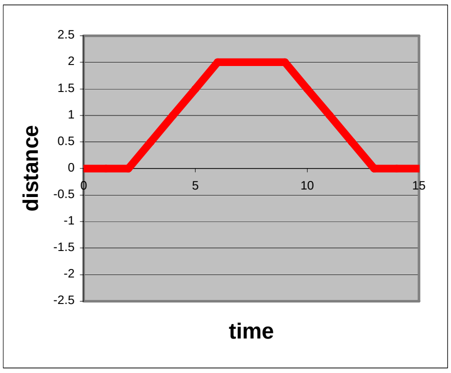
....

Try to create straight lines: is it hard? ....

Why? ....

Can you plot these two graphs?





Can you tell which is their difference?

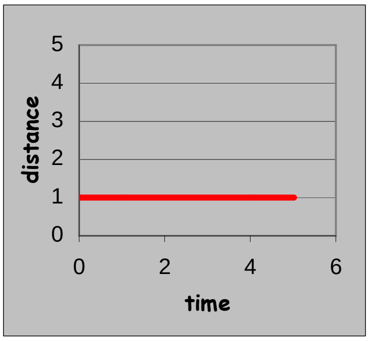
....

What does the slope of the line tell us?

....

Some Questions:

Please write down what each graph illustrates:



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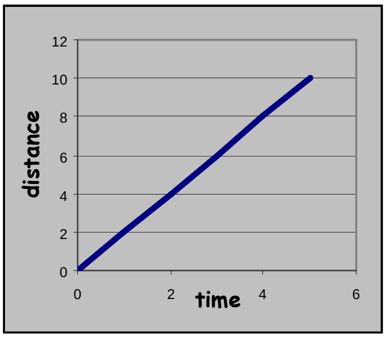

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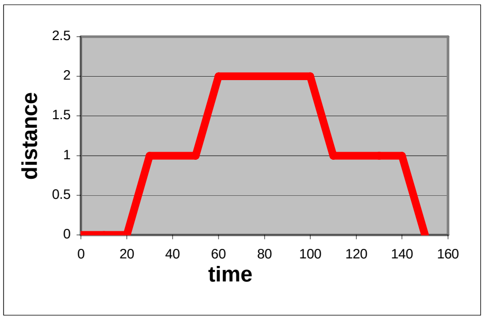
Describe how the hand moves during the 150 seconds



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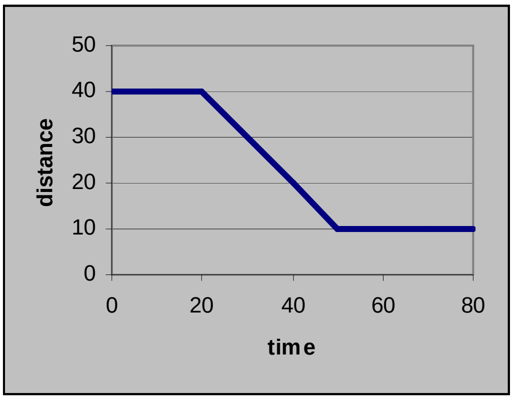
Describe how the hand moves during the 80 seconds



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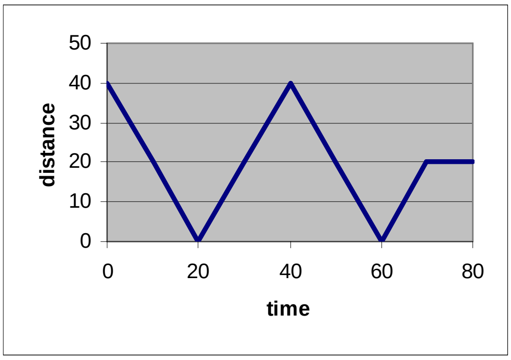
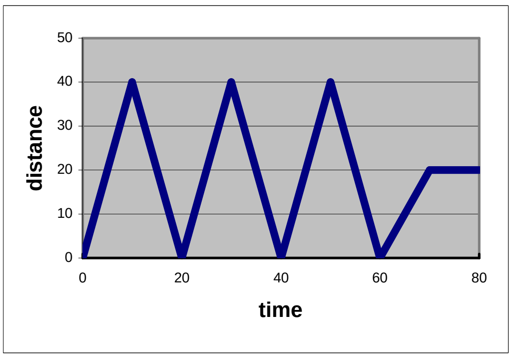




Can you tell which are the differences between the two graphs?

....

....

....

What does the slope of the graph tell us?

....

The sheets given to pupils: Attitude survey

Just a moment, please…… your opinion counts….

Did you like what you did?

Not at all [1 2 3 4 5] Very much

Did you find the whole session interesting?

Not at all [1 2 3 4 5] Very much

If you had a choice, would you want to do the activity or look at it?

Do the activity [ ]
Look the activity [ ]
Wouldn't mind [ ]

Would have been interesting to watch your own data?

Not at all [1 2 3 4 5] Very much

How difficult was the questions?

Not at all [1 2 3 4 5] Very much

Do you feel that you understand distance-time graphs?

Not at all [1 2 3 4 5] Very much

Thank you!!
:o)

Appendix C: m-DEW interactions: second case study

Plan of Teaching Session

Pre-test

Could you describe how you would move your hand to generate the graph?
From this d-t graph, how would the v-t graph look like?

Teaching Session

Check if the graphs you drew are correct and write the narrative

Generate the next d-t graph,
How did you move your hand?
Would you write what you just said?
Could you draw the v-t graph without looking at the display, either from d-t graph or by heart?

From the written narrative, could you draw the d-t- graph?
Check it

From the written narrative, could you draw the v-t graph
Check it

Generate the d-t- graph
Answer questions about special features
Draw the v-t graph

Generate a v-t graph
Answer questions about special features
Draw the d-t graph

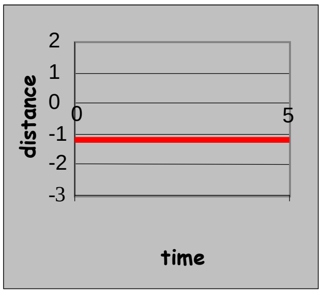
Do you mind answering some (more) questions?

The sheets given to students: Initial set of questions & Teaching session

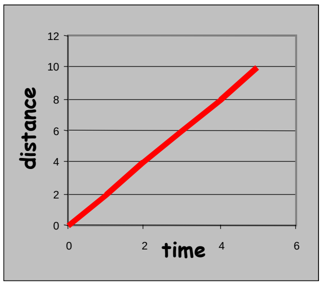
Name	Date of Birth	Date ....
Doer/Watcher		

Can you describe the graphs below?

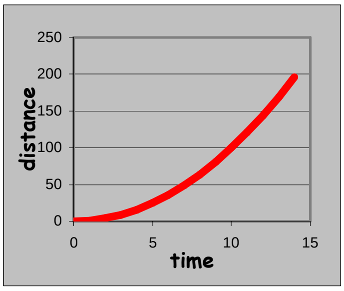
A



B.



C.



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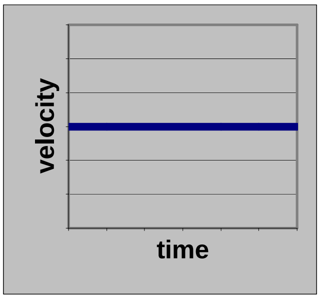
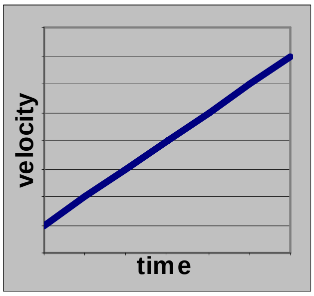
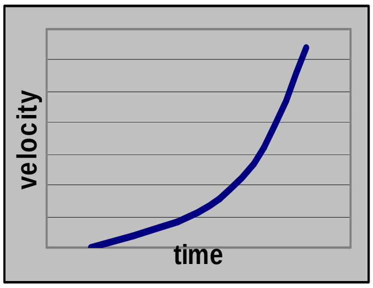
D.



E.



F.



....

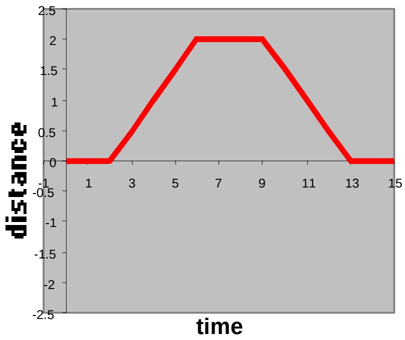
....

Do you know…

what does a **distance-time graph** show? ....

what a **velocity-time graph** shows? ....

Now, try to think of the graph in terms of your hand movements. Can you predict how you should move your hand to create the following graph?



First you kept your hand still for ______ seconds

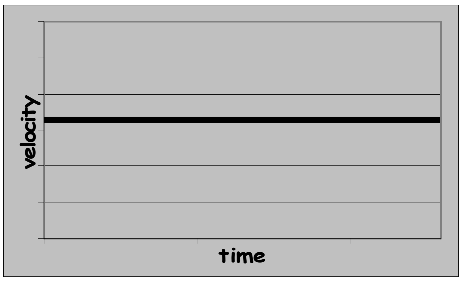
……………………………………………………………………………………………

……………………………………………………………………………………………

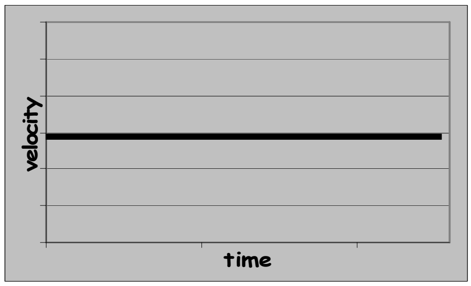
……………………………………………………………………………………………

……………………………………………………………………………………………

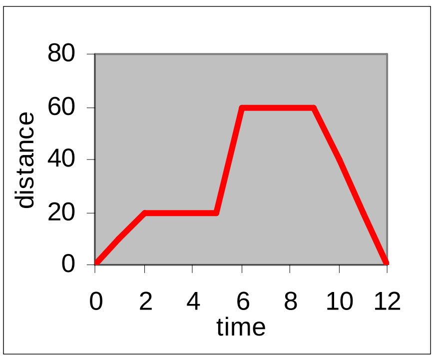
How would the velocity-time graph look like?



Is the velocity-time like the predicted one? If not, plot the correct one below.



Try to draw the following graphs and write down the movements afterwards:



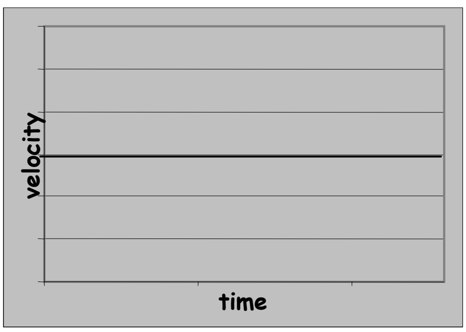
……………………………………………

……………………………………………

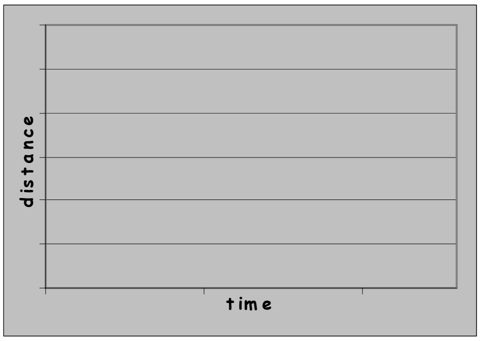
……………………………………………

……………………………………………

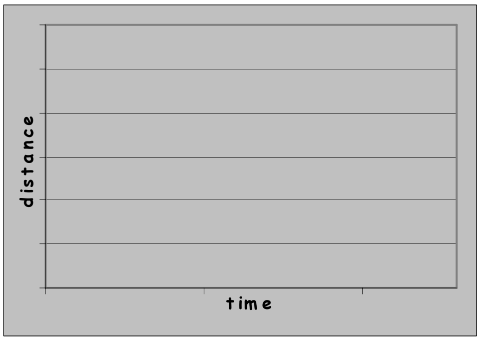
Can you draw the velocity-time graph without looking at the display?



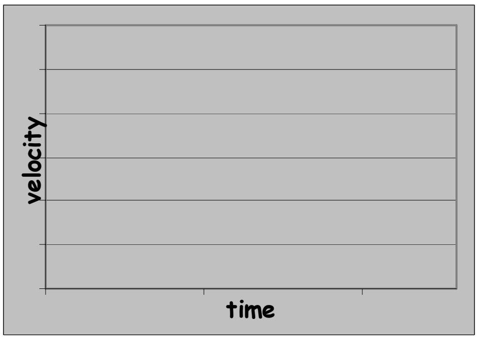
If you had to move your hand to the left at a slow constant speed, and then to the right at a fast constant speed, how would the distance-time graph be like (left is positive direction)?



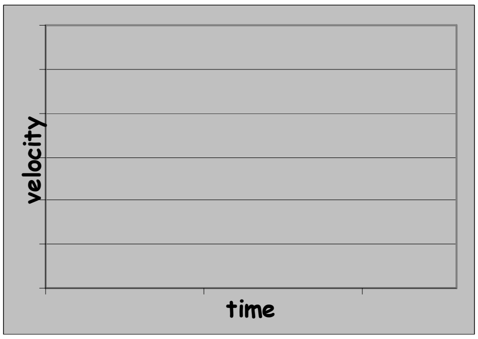
Is it right?
How does the graph really look like?

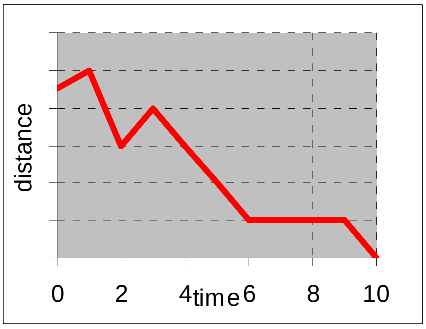


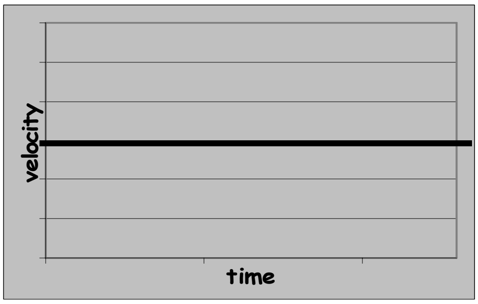
If you had to move your hand with a constant speed to the left and then move it with a negative acceleration, how would the velocity-time graph be like?



Is it right?
How does the graph really look like?







When is the hand not moving? Why? ....

When does it change its direction? Why? ....

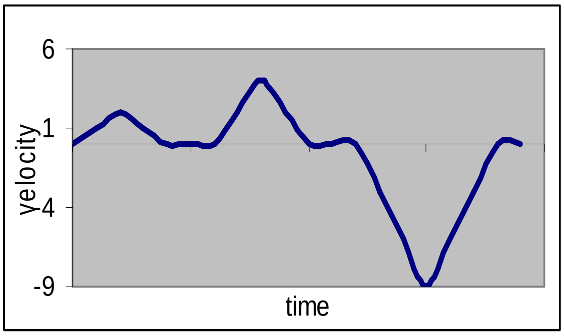
When is it travelling fastest? Why? ....

When is the hand travelling slowest? ....

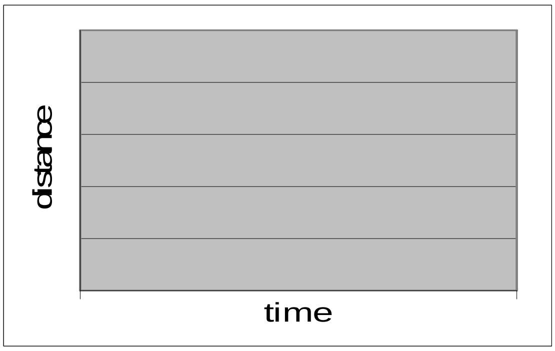
When is the hand accelerating? Why? ....

When does it have the greatest acceleration? Why? ....

Now, try to make a graph like this:



How would the distance-time graph look like?



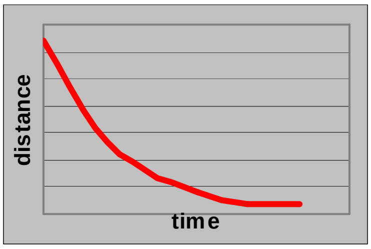
when do you think the hand is …

- moving with a positive acceleration (write A)?
- moving with a negative acceleration (write B)?
- moving with a negative velocity (write C)?
- moving fastest (write D)?
- moving slowest (write E)?

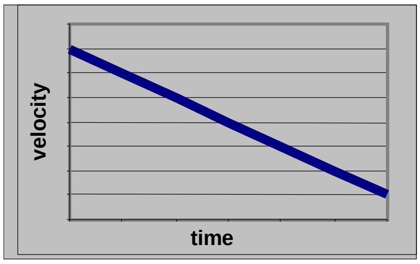
Is there a time slot where the hand is….

- not moving? ....
- changing direction?...............
- moving with a constant acceleration? ....
- moving with a constant velocity? ....

Some Questions:



the graph above shows



the graph above shows

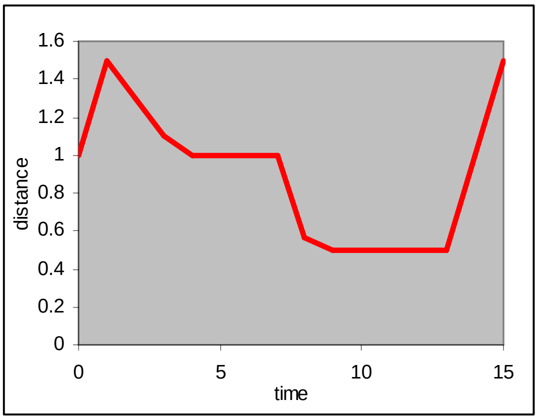
....

The slope of the distance-time graph shows the _______ of the movement.

The slope of the velocity-time graph shows the _______ of the movement.

....

Describe the hand movements the graph below shows:



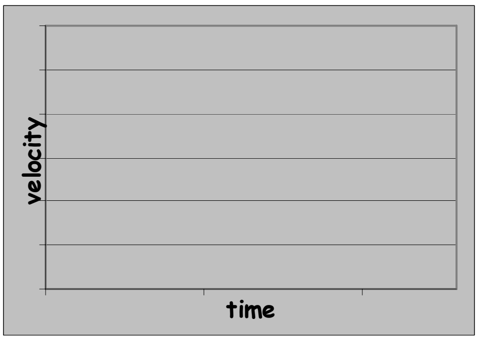
....

....

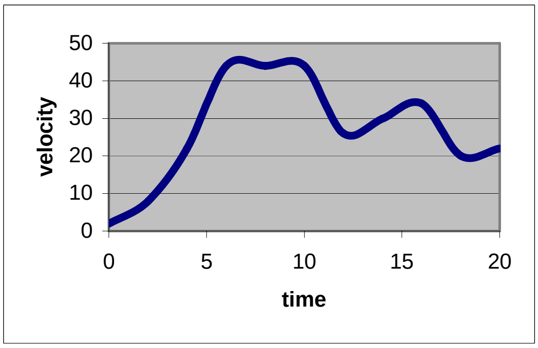
....

....

How would the velocity-time graph look like?



For the velocity-time graph below



When is the hand accelerating? ....

When is the hand not moving? ....

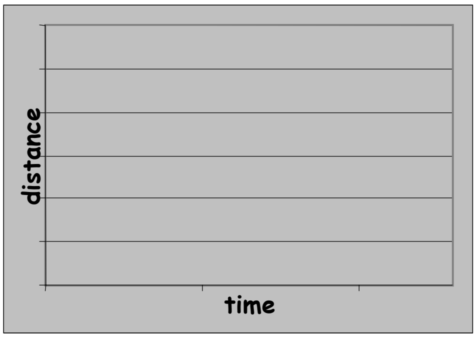
When does the hand change its direction? ....

When is the hand travelling fastest? ....

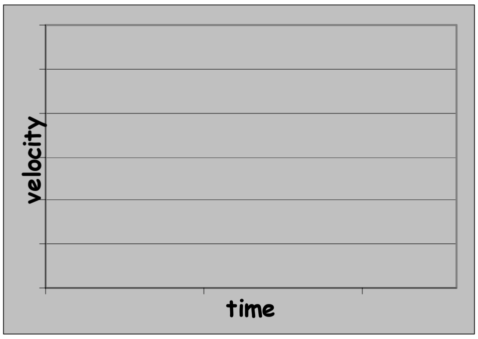
When is the hand travelling slowest? ....

When does it have the greatest acceleration? ....

Sketch a distance-time graph for a hand moving to the left and accelerating from a high velocity to a low velocity.



How would the velocity–time graph look like?



The sheets given to pupils: Attitude survey

Just a moment, please...... your opinion counts....

Did you like what you did?

Not at all [1 2 3 4 5] Very much

Did you find the whole session interesting?

Not at all [1 2 3 4 5] Very much

If you had a choice, would you want to do the activity or look at it?

Do the activity [ ]
Look the activity [ ]
Wouldn't mind [ ]

Would have been interesting to watch your own data?

Not at all [1 2 3 4 5] Very much

How difficult was the questions?

Not at all [1 2 3 4 5] Very much

Do you feel that you understand distance-time graphs?

Not at all [1 2 3 4 5] Very much

Do you feel that you understand velocity-time graphs?

Not at all [1 2 3 4 5] Very much

Thank you!!
:o)