EXPLICIT VERSUS TACIT KNOWLEDGE IN EARLY SCIENCE EDUCATION:

THE CASE OF PRIMARY SCHOOL CHILDREN'S UNDERSTANDING OF OBJECT SPEED AND ACCELERATION

This thesis is submitted to the University of Cambridge for the degree of Doctor of Philosophy by

Michael Hast

Clare Hall and Faculty of Education, University of Cambridge

Supervisor: Professor Christine Howe

ABSTRACT

Children are not blank slates when they begin school; instead, they bring prior conceptions about the everyday world with them. Situations of motion are ubiquitous in everyday life, and because of much interchange with the physical world conceptions are affected from a very early age. Yet prior conceptions of motion usually do not comply with accepted scientific views, and therefore conceptions need to be changed within the course of education. A differentiation can be made between explicit declarative knowledge and tacit procedural knowledge. 144 children aged 4 to 11 years were assessed on their explicit understanding of object speed and speed change along a horizontal, down an incline, and in free fall. Study 1 assessed the children's predictions of motion using a range of everyday objects. Their conceptions were further assessed in Study 2 using a tube and two balls of different weights. Study 3 was a computer-presented quasi-replication of the tube-and-balls study. The results of these three studies suggest that children's explicit predictions of motion are limited or incorrect. At the same time, many infancy studies have unveiled underlying knowledge about the physical world, which is considered tacit in its nature. Some researchers posit the idea that this knowledge does not change at its core and persists throughout the lifespan. While infancy research methods would be difficult to apply in a sample of children, judgement tasks may help in tapping tacit understanding in this age range. In Study 4, the children were shown video clips of the same set-up used in Study 3 but with motion occurring, either correctly or incorrectly. The children had to judge whether what they saw in the clips looked correct or not. The results indicate a mismatch between tasks requiring explicit predictions and a task relying on tacit judgements, suggesting judgements are more accurate than predictions. A dual-pathway model incorporating explicit and tacit reasoning is proposed, limitations of the current work are discussed, and suggestions for future work are made. Overall, it is evident that two kinds of understanding about the same topic are available in young children, and it is hoped that early science education can eventually consider this differentiation in order to facilitate conceptual change.

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A journey has come to its end, and in the last moments of proofreading and editing this thesis, I have come to realise there are several people who deserve a mention of gratitude.

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I am also immensely thankful to my family and my friends who have supported me in all of my endeavours throughout these years. There were times when I was in doubt about my work, lacking the certainty of knowing why I did anything I did. But I found that their constant questioning about my work has actually helped me immensely in understanding it myself. For that I am truly grateful.

Gratitude is, of course, also due to the teachers and particularly the children whose contributions to my research have helped to bring this thesis into existence in the first place. The many hours spent in research activities with them have been so enjoyable and rewarding, and I hope that the work presented in this thesis may eventually return a favour to primary schools.

DECLARATION OF ORIGINALITY

This thesis is the result of my own work and includes nothing which is the outcome of work done in collaboration except where specifically indicated in the text. No parts of the thesis have been submitted for any other qualification.

STATEMENT OF LENGTH

This thesis does not exceed the limit of 80,000 words in accordance with the Degree Committee regulations of the Faculty of Education, University of Cambridge.

To E. H., with love.

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> "What does the fish know about the water in which he swims all his life?"
>
> (Einstein, 1950, p. 5)

INTRODUCTION:

AN OVERVIEW OF THE THESIS

Albert Einstein posed an interesting and rather important question when asking what the fish knows about the water in which he swims all his life. The quest for knowledge – what it constitutes, where it comes from – has fascinated and occupied minds for a long time, and there are still answers to be uncovered. What *does* the fish know about the water? What do *we* know about the world we live in? What do we know about the physical world that we see and interact with so often? And what do we *really* know about the physical world?

One particularly ubiquitous element of the physical world is motion, and we are very familiar with it due to extensive everyday experiences, practically from the first day of our lives. And yet it appears that many people hold beliefs about motion that do not correspond to accepted scientific views, despite constant experiences. In order to assist students in mastering the related concepts successfully, science education needs to help modify these beliefs. Unfortunately, many students struggle with physics. Speed and acceleration are parameters of motion that are fundamental to many other higher-order physics concepts. So in order to master advanced physics,

an understanding of the basics is essential. At the same time, speed and acceleration are concepts that relate to the physical world that we engage with consistently. Given the issue of a lack of accurate knowledge in many adults, it seems commonsense to tackle the issues at stake as early as possible. With the introduction of science in primary education in England (Department for Education and Employment, 1999), young children are already expected to learn about concepts relating to motion, thus it provides an ideal starting point to remedy dissociations between naïve physics and science.

Yet science education is often not able to effectively induce a change in conceptions, as naïve beliefs often persist into adulthood. So the question that arises is whether alternative strategies could be sought that could facilitate change more effectively. Here, again, the distinction needs to be raised about what we know and what we *really* know. Is the knowledge that is reflected in decision-making, in explaining and predicting events accurate? While the scientist no doubt possesses accurate relevant knowledge, it would seem that very many, if not most, people do not. But is there an alternative with which the non-scientist can learn to overcome naïve beliefs somehow?

This thesis examines three main issues with regards to young children's understanding of object motion:

1. What can be said on the topic of children's general beliefs about object motion – which variables are important to them in their reasoning, and how do these variables affect children's predictions of dynamic events?

2. What can be said about children's ideas as to how motion types inform each other, if they do so at all – how do reasoning about horizontal motion, reasoning about motion in fall and reasoning about incline motion interact, and how can this information assist in developing a single model of young children's conceptions of motion?

3. Given that one might anticipate young children to have limited or incorrect beliefs about motion, considering the literature, do children have alternative

knowledge about dynamic events available to them that could potentially be integrated into early science education and utilised in modifying their limited or incorrect beliefs more effectively?

To address these general objectives, the first seven chapters of this thesis explore the theoretical background leading up to these objectives and up to more specific key research aims.

Chapter 1 on the naïve knowledge of the physical world first takes a historical approach to a central issue in folk physics – conceptions of motion that are in discordance with accepted scientific views. It illustrates the long-lasting stability of Aristotelian physics from the pre-Christian era into our current age, highlighting the particular case of motion. The chapter also introduces the early development of psychological and educational research in relation to conceptions of motion. It then continues by highlighting the issue of prior conceptions in the classroom as well as the potential problem with having these prior conceptions. The chapter concludes that young children do not begin school as blank slates but instead bring with them conceptual knowledge about the physical world (cf. Duit, 2009). Yet despite its richness, children's naïve knowledge is limited, or even simply incorrect, and the role of the educator is to facilitate a change in conceptions.

The notion of conceptual change is then introduced in Chapter 2. Jean Piaget's ideas on conceptual change are presented, and its – much-criticised, and largely ineffective – application to science education is discussed. Alternative theories of conceptual change are then covered. The chapter reviews ideas of knowledge as theory, ideas of knowledge as elements, and ideas of knowledge as an integration of both theory and elements. It then continues by discussing different approaches to conceptual change in the classroom, making particular reference to the construction of mental models, to model-based reasoning and to the use of thought experiments in science. These models are based on previous experiences and may provide particular insight into children's predictive models of object motion. However, while they provide an insight into predictive knowledge, and while they may be useful to

science education per se, they do not provide ultimate solutions and cannot facilitate conceptual change effectively. Overall, Chapter 2 highlights that the approaches to conceptual change in the classroom are not proving to be fruitful, and that it may instead be worthwhile considering alternatives to the standard approaches.

In Chapter 3, a crucial distinction is thus introduced, by contrasting two forms of knowledge – declarative explicit knowledge and procedural tacit knowledge. The two forms of understanding are defined, and the relevance of this distinction is established. In particular, the chapter highlights research with infants by describing the violation-of-expectation paradigm and the resulting descriptions of infants' tacit knowledge of the physical world. This raises the fundamental query as to whether tacit knowledge persists beyond infancy, and if so what its potential role in early science education might be, given the problems that have arisen in Chapter 1 on prior conceptions and Chapter 2 on conceptual change. Finally, Chapter 3 establishes the possibility of judgements as a useful methodology in assessing children's tacit knowledge. This is coupled with the possibility of using computers to assess tacit knowledge beyond infancy by ascertaining the current use of computers in primary education and by establishing why computers may provide a useful tool in determining children's tacit knowledge of object motion.

In order to prepare the reader for the subsequent extensive literature reviews on the understanding of speed and object motion, Chapter 4 is intended to provide an intermissive collection of the physical laws that govern motion. Following a definition of terms, the concept of speed is briefly described in three different motion types – motion along a horizontal, motion in free fall, and motion down an incline. In addition, the principle of speed change and the effect of object mass on motion are covered.

Chapter 5 provides an elaborate review of the literature that discusses children's general understanding of the concept of speed. It illustrates how children are able to deal with the interaction of speed, time and distance. Piaget's substantial work in this field is described first, followed by a number of Piagetian replications. Despite

much consensus among this research, the choice task paradigm employed in these studies is nonetheless open to criticism. Friedrich Wilkening's work, which relied on a non-choice task paradigm, is covered next, which is followed by a critique of Wilkening's paradigm. Regardless of the methodological approaches used, the research reviewed in this chapter signals that – developmental trends aside – children do have a reasonable understanding of the concept of speed, and how it functions in terms of the underlying elements time and distance. This paves the way for assessing children's understanding of object motion.

The crucial information relating to object motion is then covered in Chapter 6. This chapter discusses research on the specific understanding of naturally induced object motion. The importance of weight as a variable in object motion reasoning is established. Building on the distinction between explicit and tacit understanding introduced in Chapter 3, the chapter then looks at a variety of studies examining children's and adults' explicit reasoning about motion along horizontals, about motion in free fall, and about motion down inclines. Moreover, it explores the literature assessing understanding of speed change, as this understanding appears to be a crucial element in the recognition of naturalness of motion. What emerges is that while there is a substantial amount of work on children's explicit understanding of object motion, none of the studies integrate more than one motion type, and therefore little can be concluded about how different dimensions are associated in children's object motion reasoning. Chapter 6 then continues by looking at the small number of studies assessing tacit knowledge of general object motion, both studies with infants and studies beyond infancy. These, in turn, suggest that while explicit understanding of motion may be limited or incorrect, tacit judgements relatively accurately reflect correct knowledge.

Finally, Chapter 7 offers a summary of the introductory chapters, and provides a rationale and general overview of the subsequent research chapters. It highlights the key research questions to be explored and answered by the research, and presents an outline of the current work by considering ethical issues, general information

about the participants of the research, as well as information about the use of computers in this particular sample.

The seven introductory chapters are then followed by four studies – Chapters 8 to 11 – that address the key research questions raised in Chapter 7, supplemented by Chapter 12, which presents some additional cross-study analyses. These, in turn, lead to a general discussion in Chapter 13, pertaining to the theoretical approach that has led up to the four studies as well as pertaining to the specific outcomes of the research. The emerging findings contributing to the understanding of how children predict dynamic events are considered, as well as how their tacit judgements of such events compares with explicit predictions. The general discussion furthermore outlines a dual-pathway model resulting from an integration of the theoretical background with the present research. This model takes into consideration both explicit and tacit models of motion, and how they may fit into a general system of reasoning. In addition, the discussion considers limitations of the current work and makes suggestions for future undertakings; both in terms of exploring further the theoretical distinction between explicit and tacit understanding, and in terms of its applications to educational practice.

> "Science is not just a collection of laws, a catalogue of facts, it is a creation of the human mind with its freely invented ideas and concepts."
> (Einstein & Infeld, 1938, p. 310)

CHAPTER 1:

NAÏVE KNOWLEDGE OF THE PHYSICAL WORLD

There are distinct disciplines in everyday science, a dozen or so in number (Carey, 1987), all of which seem to be, to some extent, essential for individual survival and prosperity as a species (Hatano, 1990; Wilkening & Huber, 2002) − biology, chemistry, mathematics, just to name a few. Among these disciplines, humans also hold 'naïve physics', which deals with how an object behaves in the physical world. We have a lot of interchange with the physical world; we engage with it both visually and tactically. We see what happens around us, we pick up objects, push them, throw and catch them, and so on. There can be no doubt that people have naïve physical knowledge on the basis of all this interaction, particularly regarding mechanics (diSessa, 1996). But what is the connection between this naïve folk physics and the physicist's physics taught in schools?

1.1 A historical approach to naïve physics

The roots of the problem with which this thesis is concerned can be traced back to at least the fourth century BC, to the writings of the Ancient Greek philosopher

Aristotle. In his *Physics*, a collection of philosophical treatises on the most general principles of motion, he wrote that "it is a fact of experience that the greater the impulse of weight or lightness things have, the faster (other things being equal) they complete a given journey, in accordance with the ratio the magnitudes have to one another" (Aristotle, trans. 2008, p. 98). So according to Aristotle's ideas, the heavier an object the proportionally faster it should fall – an object should take twice the time to fall the same distance as another object twice as heavy.

Taking, for instance, a hammer and a feather and dropping them simultaneously in a normal environment would indeed show that the hammer – the heavier of the two objects – falls faster than the feather and reaches the ground first when the two are dropped from the same height at the same time. Similar observations of nature had led Aristotle to write his assumptions in *Physics* (cf. Stinner, 1994), and the example of hammer and feather above shows that it is certainly conceivable why he would have drawn his conclusions. Interestingly enough, Aristotle was not at all far from the correct idea, and even mentioned it in *Physics* – "it follows that in a void everything will travel at the same speed" (Aristotle, trans. 2008, p. 98). Certainly since the famous 1971 live demonstration during a lunar expedition where a hammer and a feather were dropped simultaneously in the moon's environment, we know that in a void all objects do indeed fall at the same rate. Unfortunately the very same sentence in *Physics* then continues saying that this would have to be impossible.

One might forgive the errors of a single person, and think that surely one man's erroneous views of the physical world cannot have too grave an effect. But the problem reaches beyond Aristotle's own mind – his claims were largely accepted by science (and non-science) for almost two millennia after *Physics*, and only publicly refuted during the scientific revolutions of the 17th century AD.[1] However, the

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[1] It is worth noting here that there were already some revisions of Aristotelian physics throughout the Middle Ages, for instance by Philoponus, Avicenna, di Marchia, Buridan or Oresme (cf. Kozhevnikov & Hegarty, 2001; Stinner, 1994), though none of these directly affected the major Aristotelian claims listed here.

problem persists: Even following the scientific analyses of Galilei (1638), Hugens (1669) and Newton (1687), showing that Aristotle's beliefs and therefore, more or less, those of the entire known world were erroneous, the naïve theories that people hold about object motion today very often correspond to the Aristotelian physical theories (Heuer & Wilhelm, 1997; Mildenhall & Williams, 2001; Shanon, 1976; Whitaker, 1983). Because these views, like Aristotle's own views, are seemingly based on experiences with the everyday world, they are thus known as naïve physics.

1.2 Naïve physics in psychological and educational research

Champagne, Gunstone and Klopfer (1983) write that "even students who do well on textbook problems often do not apply the principles they have learned to predicting and describing actual physical events", which is "not due to an absence of theories, but rather to the persistence of naïve theories" (p. 173). Young people and adults commonly have macroschemata for motion that are more Aristotelian than Newtonian, and remnants of the Aristotelian macroschemata persist in many successful physics students (Gunstone & White, 1981). Macroschemata are mental structures encompassing microschemata, which in turn are mental structures than guide the analysis and interpretation of an identifiable class of phenomena, incorporating propositions and concepts (Champagne et al., 1983).

Indeed, in concordance with Champagne et al. (1983), McCloskey (1983a, b, c), too, notes that people sometimes have *strange* conceptions about physical phenomena, and the discrepancy between spontaneous judgements and the actual physical events may indeed surprise, especially given the amount of relevant everyday experience that is available. But what is more, Champagne, Klopfer and Anderson (1980), for example, have shown that belief in the proposition 'heavier objects fall faster than lighter objects' is not readily changed by instruction; similar findings associated with Aristotelian macroschemata for the motion of objects have been reported in other studies of physics students (e.g. Gunstone & White, 1981; Leboutet-Barrell, 1976). The macroschema for motion results from years of

experience with events involving moving objects and talking about these objects, and these events suffice for children and adults to satisfactorily describe the world of motion that they experience. Yet this macroschema differs from the formal system of Newtonian mechanics.

The assessment of prior understanding of physics is not actually a very recent phenomenon. More than 60 years ago Oakes (1945a, b) published an early study of adults' understanding of falling objects and of Bernoulli's principle. However, despite the work suggesting that when adults' explanations were incorrect they did not differ substantially from those of children (cf. Oakes, 1947, as cited in Bingham & West, 1948), it did not seem to have much impact on educational or psychological research. Slightly over a decade later, Oakes made another attempt with a paper that both revisited the earlier work and reported examples of his own college students' explanations given in response to his conventional examination questions about a wide range of biology and physics topics (Oakes, 1957). Yet despite finding, overall, that adults', children's and college students' beliefs were often inconsistent with scientists' views of phenomena, no related studies followed for some time to further probe any of these findings. Then, quite suddenly, in the 1970s a surge of studies of conceptions in the classroom and beyond appeared in the world of educational and psychological research, amounting relatively quickly to over 8,000 studies (cf. Duit, 2009).

The area of physics, and object motion in particular, was not spared from this research movement. Several early studies on naïve knowledge of object motion exist, where participants were asked to make predictions about naturally induced motion in a variety of tasks – for example, trajectories of released pendulums (Caramazza, McCloskey, & Green, 1981), curvilinear motion (Kaiser, Jonides, & Alexander, 1986; Kaiser, McCloskey, & Proffitt, 1986; McCloskey, Caramazza, & Green, 1980; McCloskey & Kohl, 1983), or parabolic paths of falling objects (Kaiser, Proffitt, & McCloskey, 1985; McCloskey, Washburn, & Felch, 1983). In his time, Oakes may have been outside the then popular main stream of behaviourism and thus remained largely unnoticed (White & Gunstone, 2008). By the 1970s, however,

psychology had recovered its interest in the mind. The 'misconceptions' movement exploded to particular prominence in the early 1980s, produced the bulk of the vast literature, and then tailed off somewhat in the early 1990s. Nonetheless both its presence and its influence remain strong (diSessa, 2006). What is particularly interesting, however, is not only that adults have views about the world that are not always in concordance with science, but that divergent views have already begun to emerge by the very beginning of school education.

1.3 Prior conceptions in the classroom

It is now widely accepted that children do not come to school as tabula rasa, but instead that they possess rich prior conceptions about the physical world. They have beliefs about how things happen and expectations which enable them to predict future events. Children construct this knowledge on the basis of their everyday experiences of and interactions with the world around them (King, 1960; Klaassen, 2005; Vosniadou & Ioannides, 1998), and children seem to hold these beliefs and expectations very strongly (Leboutet-Barrell, 1976). These are not simply isolated ideas; instead, they are a part of conceptual structures that provide a sensible and coherent understanding of the world from the child's point of view (Champagne et al., 1980). Despite its richness, this knowledge, however, is often inaccurate and differs fundamentally from the scientific conceptions to be taught in the classroom (Clement, 1983; Duit, 1999; Halloun & Hestenes, 1985; McCloskey, 1983c; McDermott, 1984; Vosniadou & Brewer, 1992). One recent survey of 122 primary school science teachers in England, for instance, identified 130 conceptions that children bring to the science class (Pine, Messer, & St. John, 2001), conceptions that are inconsistent with the concepts to be taught.

A variety of terms exists to describe such prior knowledge structures that children hold. Even though the research essentially takes place within the same paradigm, certain researchers tend to favour particular terms over others because of the underlying attributions they may give to the status of these ideas (Gunstone, 1988; diSessa, 1993). Some researchers use the term 'preconceptions' to describe naïve

ideas (Arons, 1997; Ausubel, 1968; Cahyadi & Butler, 2004; Dykstra, Boyle, & Monarch, 1992). This term does not make judgements as to the correctness of the belief. The terms 'alternative frameworks' (Driver & Easley, 1978), or 'children's science' (Osborne & Freyberg, 1985), on the other hand, are generally taken to imply that children generate, within the limitations of available evidence, coherent views of phenomena. Other terms used within the literature include 'common sense beliefs' (Champagne et al., 1980), 'intuitive models' (Fischbein, 1987), and 'misapplications' (Elby, 2001). The term 'misconceptions', on the other hand, implies that the ideas students have are simply wrong and in need of modification because they are inconsistent with the target concepts to be taught (E. J. Dijksterhuis, 1961; Halloun & Hestenes, 1985; Mildenhall & Williams, 2001; Tytler, 1998). Despite the term 'misconceptions' being applicable because it implies a belief that the scientific community no longer holds and which is therefore simply incorrect, it nonetheless retains pejorative connotations. Therefore, in the present work the term 'misconception' will not be used to describe relevant ideas that children bring to the classroom, but instead these ideas are simply referred to as 'prior conceptions', thus not qualifying them in any way.

1.4 Prior conceptions – a problem?

So despite the grand scientific revolutions of the 17th century (e.g. Galilei, 1638; Hugens, 1669; Newton, 1687) showing that Aristotle's beliefs and therefore, more or less, those of the entire known world were erroneous, the naïve theories that people hold about object motion today very often still correspond to the Aristotelian physical theories (e.g. Heuer & Wilhelm, 1997; Mildenhall & Williams, 2001; Shanon, 1976; Whitaker, 1983). But what is the problem with having prior conceptions? Students have constructed various conceptions over many years of experiencing the everyday world. These conceptions can certainly be useful to students in that they provide *reasonable* explanations of the behaviour of objects (Hammer, 1996, 2000) and *satisfactory* predictions of motion (Tao & Gunstone, 1999), and this knowledge may be perfectly adequate for survival in the everyday world (Reif, 2008). However, the nature of such naïve conceptions poses a problem for learning science: "The

main barrier to learning the curricular materials […] is not what the student lacks, but what the student has, namely, alternative conceptual frameworks for understanding the phenomena covered by the theories we are trying to teach" (Carey, 2000a, pp. 13-14). Halloun and Hestenes (1985), too, highlight the need for physics instruction that takes the initial common sense beliefs of students into account, and several others have identified relevant specific common sense beliefs that are in conflict with Newtonian mechanics and thus interfere with physics instruction (Clement, 1982; Gunstone & White, 1981).

However, the problem reaches beyond this point. Not only are the conceptions that children bring with them incorrect and at variance with commonly accepted scientific views, but also there is much agreement that these conceptions are highly resistant to instruction and conceptual change (Bloom & Weisberg, 2007; Chi, 2005; Chi & Roscoe, 2002; Duit & Treagust, 2003; Duit, Treagust, & Widodo, 2008; Ferrari & Chi, 1998; Finegold & Gorsky, 1991; D. Kuhn, 1989; Stepans, Beiswanger, & Dyche, 1986; Tao & Gunstone, 1999). It has also been pointed out that many incorrect conceptions persist even after students finish physics courses, and that even high-grade students often cannot apply basic physical principles to solve problems for realistic situations (Haertel et al., 2003; Mestre, 1991). The fact that these conceptions are erroneous or inaccurate also means that, while they may be useful in an informal setting and in everyday life, they can actually hinder the child's ability to learn further about a topic in the context of more formal education (Driver, 1981; Driver & Erickson, 1983; Klaczynski & Narasimham, 1998; Reif, 2008; Schauble, 1996; Sherin, 2006; Singh, 2001). The high resistance means educators need to be aware of these conceptions and work to modify them, rather than simply introducing and superimposing the correct concepts. In addition, they need to incorporate the learner's active involvement in their personal knowledge construction of the world around them, and help them to interpret new situations effectively (Carey, 1986; Gilbert & Swift, 1985; West & Pines, 1983; von Glasersfeld, 1989).

Naïve scientific notions appear to be particularly prevalent in the area of mechanics and dynamics because moving objects can be commonly observed in action in

everyday life (diSessa, 1996; Tao & Gunstone, 1999), and the importance of kinaesthetic and sense experiences as a possible source of children's prior conceptions has been suggested in the literature (e.g. Strauss, 1981; Viennot, 1979; Wilkening & Huber, 2002). Yet because phenomena involving motion have been acquired since early in life and are very familiar from everyday interactions with the world, naïve notions about them are probably particularly difficult to change (Planinic, Boone, Krsnik, & Beilfuss, 2006).

The role of education is, in principle, quite simple: Education needs to promote a change in conceptions about the world. But this is much more difficult in practice than it may sound in theory – "it becomes apparent that what is needed is a bridge between cognitive developmental and science education research" (Vosniadou, 1999, p. 9). Additionally, all the factors just mentioned highlight the usefulness of *early* conceptual change intervention. A claim being made is that major restructuring of the already existing knowledge is necessary (Duit, 1999). How can this restructuring be achieved? Additionally, when should this restructuring best be induced? Tracing the disjunction between science and the everyday world back to its source and remedying this can probably best be done in the earliest stages of education, and the question arises of whether instruction could be set up in such a way, right from the beginning, so "that this false disjunction could never arise at all" (Isaacs, 1930, p. 351). Despite the suggestion coming from an educational perspective from 80 years ago, there seems no reason why it should be much different today.

1.5 Summary

It has become evident that we are dealing with an age-old problem, reaching back at least to Aristotle's times. And despite the major scientific revolutions of the 17th century, many people still hold naïve theories of physics that correspond to those notions proposed in Aristotle's *Physics*. Even young children come to the classroom with rich and varied knowledge of the physical world, yet their understanding is often incomplete or misconstrued, and these naïve theories often persist beyond

school education into adulthood. Essentially, the role of the educational system should thus be to facilitate a change in ideas, bringing children closer to the concepts to be taught in science, and yet this is often problematic. A case has been made for tackling the roots of the problem at an early age, and by finding alternative ways around the traditional approach to science education in order to promote conceptual change.

> "A theory of conceptual change is a prerequisite for any comprehensive account of learning and can have important implications for instruction." (Vosniadou, 1994b, p. 3)

CHAPTER 2:

CONCEPTUAL CHANGE AND MENTAL MODELLING

Chapter 1 has illustrated that there is a fundamental problem in naïve beliefs about the physical world, particularly about object motion. The chapter has highlighted the issue of prior conceptions in the classroom that are inconsistent with accepted scientific views, instead matching ideas that, despite intermissive scientific revolutions, have been around for more than two millennia. Yet evidently these prior conceptions pose a problem, and they often remain limited or incorrect. It has been noted that science education must deal with changing these conceptions somehow, and yet on the larger scale this does not seem to work very well, as prior conceptions persist into adulthood. But how can conceptions be modified?

2.1 Conceptual change

Conceptual change is among the most central areas in the learning of sciences. In fact, "conceptual change has long been recognized as a fundamental aspect of science learning" (Mayer, 2002, p. 101). Many of the most important ideas in science seem to be affected by the challenges of problematic learning (diSessa, 2006). In

order to understand scientific concepts, students cannot simply rely on the memorisation of facts, or on the enrichment of their naïve, intuitive theories. Instead, they need to be able to restructure their prior knowledge about the world, which is based on everyday experience. This approach rests on the assumptions that knowledge is established within domain-specific structures, and that knowledge acquisition leads to a change in theories. Such structures are generative, thereby making it possible for children to explain and predict, thus being able to deal with unfamiliar scenarios, answer questions and solve problems (Vosniadou, 2002a, 2007a).

Some topics in science education appear to be particularly difficult for students. Learning and teaching in these areas are seen to be problematic. Many areas in the sciences, from elementary school through university level, have this characteristic, including, in physics, Newtonian mechanics. Students need to build new ideas in the context of old ones. The source of the difficulty is widely held to be the fact that students come to their physics classes with prior conceptions about the nature and processes of such phenomena as motion that, though not fully developed and integrated, interfere with learning science. Thus, students are thought to have to undergo major conceptual change in the learning process (Nersessian, 2003). Yet much research has shown that these conceptions and ideas are firmly held and are resistant to change.

But what would change of conceptions entail anyway? Conceptual change research is difficult to review, because of the range of disciplines from which conceptual change theories have emerged – including biology, physics, chemistry and astronomy. In fact, despite the consistent agreement that there is no debate about whether conceptual change occurs or not there is currently no singularly accepted theory of conceptual change; instead, multiple tested theories exist (cf. Suping, 2003). The term conceptual change was first introduced by Thomas Kuhn (1962) to indicate that the concepts that are embedded within a scientific theory change their meaning along with a change in the theory. When a theoretical framework changes, the meanings of the concepts within it also change, thus making them

incommensurable with the concepts they were incorporated under within the previous theoretical framework. Conceptual change results from a pattern consisting of accumulation of anomalies, a resulting crisis, and finally the emergence of a new conceptual structure that forms part of a new paradigm, though one which is still related to the old paradigm both in "vocabulary and apparatus" (T. S. Kuhn, 1962, p. 148).

2.2 Piaget and conceptual change

Two questions are central to Piaget's (1952, 1954) work on children's acquisition of knowledge and intelligence. Firstly, *what* do children build? They build schemata, internal representations of specific physical or mental actions that are basic building blocks of intelligent behaviour, which help to understand the world. Infants, for instance, are born with reflexive action schemata such as sucking, and only later on are symbolic mental schemata acquired. They continue to develop and increase in complexity over time. At the same time, the child also constructs operations, which are acquired in middle childhood. These are higher order mental structures enabling the child to understand complex rules about how the world around them functions and to deal with the relationships between schemata. Through building new schemata and acquiring new operations, children can advance in their intellectual development, reaching successive stages that have greater complexity and representational power than previous stages.

The second central question is *how* children build, and *how* they reach successive stages. Piaget's constructivist approach is based on two processes, namely, assimilation and accommodation. The former is a process by which new objects or new events are understood in terms of already existing schemata, while the latter is a process by which existing schemata have to be modified to fit these new objects or new events. Schemata can be expanded, or new ones can be created. Piaget (1978, 1985) viewed equilibration as a key mechanism in the process of conceptual change – "the activities of the subject directed to assimilate, integrate, and regulate all cognitive perturbations due to either external contradictions or internal limitations"

(Lourenço & Machado, 1996, p. 150). Two key elements of this process of equilibration are assimilation and accommodation, which cause a restructuring of conceptions.

During assimilation, the external world is interpreted in terms of existing schemata. When new objects or events are encountered that fit into a particular schema, the objects or events can be dealt with appropriately or accommodated, despite not having come across the particular instances of object or event before. The objects or events are incorporated into the appropriate schemata. Infants place various objects in their mouths, by which they are assimilating them all into their sucking schema. When, on the other hand, objects or events are encountered that cannot be dealt with by relying on existing schemata, there are two possibilities. Either existing schemata are adjusted in order to hold the new objects or events, or new schemata are created. Infants will begin to suck differently on objects than on nipples, for instance – the sucking schema has begun to be modified. At times children assimilate more than they accommodate, so their thinking structures do not change very much. They are at a stage of cognitive equilibrium. At other times, however, children realise that new information does not match current schemata, and they find themselves at a stage of cognitive disequilibrium. They have to accommodate more than they assimilate, but once their schemata have been modified appropriately, assimilation begins to take over again. Piaget referred to this movement between equilibrium and disequilibrium (and back again) as equilibration. Whenever equilibration occurs, more effective schemata are constructed. This way, the environment can be better dealt with, and as infants progress through childhood to adulthood, they generally become more sophisticated in dealing with the world.

However, Piaget's notion of conceptual change remained rather too vague to satisfy anyone (cf. Meadows, 2006). A more definitive fault line, however, is that Piaget tried to develop a domain independent stage theory of intelligence where changes in conceptualisation in several domains all reflected common differences in thinking. Vygotsky (1986), on the other hand, suggested that students need to internalise newly presented scientific knowledge by integrating it with their existing knowledge.

Both approaches are seen as problematic, though. Current conceptual change approaches to learning are domain specific and are better described in terms of growth of scientific knowledge via conceptual change and a complete replacement of theories (Clement, Brown, & Zietsman, 1989; Karmiloff-Smith, 1992; Thagard, 1992; Vosniadou & Ioannides, 1998; Vosniadou, Vamvakoussi, & Skopeliti, 2008; West & Pines, 1986). If new knowledge is built on the basis of old knowledge, these prior notions about science that children bring with them to the classroom must clearly play an important role in the process of learning (Gilbert, Osborne, & Fensham, 1982).

Several researchers (e.g. Hewson & A'Beckett Hewson, 1984; Posner, Strike, Hewson, & Gertzog, 1982; Strike & Posner, 1985) have drawn an analogy between Piaget's (1978, 1985) concepts of assimilation, accommodation and equilibration and the concepts of normal science and scientific revolution offered by philosophers of science such as Thomas Kuhn (1962) and constructed a theory to promote equilibration in the learning of science based on the use of cognitive conflict. Accordingly, there are four fundamental conditions that need to be fulfilled before conceptual change can happen. Firstly, there needs to be dissatisfaction with existing conceptions. Secondly, there must be a new and intelligible conception. Thirdly, the new conception must appear plausible. This implies that problem situations ought to be based upon phenomena of which individuals have some general awareness and common understanding (Biemans & Simons, 1999). Finally, the new conception should suggest the possibility of a fruitful program.

This so-called classical approach to conceptual change involves the teacher first making students' prior conceptions explicit and then applying an approach where ideas that do not fit existing ideas are articulated, thereby creating dissatisfaction. A formal scientific concept explaining the anomaly is then introduced. Despite Posner et al. (1982), for instance, claiming that their framework is merely epistemological and that it is not intended as a scheme for instruction, it has been frequently applied by science educators in their instruction (cf. Nussbaum & Novack, 1982; C. Smith, Macklin, Grosslight, & Davis, 1997). Yet at the same time this classical approach to

conceptual change receives much criticism – students' conceptual progress towards understanding and learning concepts in science often remained limited (Alvermann & Hague, 1989; Dole & Sinatra, 1998; Vosniadou, 2008).

2.3 Alternative theories of conceptual change

2.3.1 Knowledge as theory

Carey (1985, 1991, 1992, 1999, 2009), too, has suggested an application of Thomas Kuhn's (1962) ideas to how a child's conceptions develop, and draws parallels between children's conceptual change and historical developments in science. Wiser and Carey (1983), for example, built the case that naïve conceptions of heat and temperature parallel the ideas of an early group of scientists. Nersessian (1992), however, advocates the use of 'cognitive-historical analysis' to determine empirically the processes involved in scientists' change of theories. She, too, uses the notion of incommensurability between concepts that children hold and experts' concepts to describe conceptual change in cognitive development. Conceptual change requires a re-assignment of concepts to different ontological categories, or the creation of new categories. Classic conceptual change studies by Carey (1985), Vosniadou and Brewer (1992) or Gopnik (1996), among others, have led to what is known as the 'theory theory' account, according to which conceptual change takes the form of theory formation and change. A similar view had been proposed by McCloskey (1983c) and Clement (1983), among others. Their account proposes that students of all ages construct naïve theories of phenomena encountered in their experience. These naïve theories are merely rudimentary, and not as systematic and articulated as scientific theories.

Vosniadou (1994a, 1999, 2002b, 2007a, 2008) also considers beliefs to be tied to and constrained by a set of ontological and epistemological presuppositions. As a result, beliefs form a coherent structure. In this theoretical framework, the main difference between the novice and the expert is that the novice's knowledge is tied to ontological and epistemological presuppositions that provide a radically different

explanatory framework than the principles and laws of physics. The view that concepts are embedded in theories also receives support from research with infants. These results have challenged Piaget's (1952, 1954) view that infants start the knowledge acquisition process equipped only with a set of sensory reflexes and some domain-general processes and have suggested that the human mind is more specified innately to deal with the complexity of environmental stimulation. Findings in this area are explored in detail in Chapter 3 and in Chapter 6. However, it is not necessary to equate the notion of innate predispositions with a static, genetic blueprint, for the initial, innate, endowment of the infant appears to be much less detailed than the nativists have proposed, leaving enough room for flexibility and creativity in cognitive development (Karmiloff-Smith, 1992). One area of knowledge for which it is likely that domain-specific principles have been developed is the domain of knowledge about the physical world.

2.3.2 Knowledge as elements

As shown, some use the term 'theory' explicitly. Others imply it or use less loaded terms, such as the construct of 'schema' (e.g. Chi, 2008). Learning and development is then seen as requiring the reorganisation of such a structure and not simply its enrichment. An alternative view of conceptualisation of the development of naïve physical knowledge, however, is that our knowledge about the everyday world is not embedded within theory frameworks but that each concept exists within an unstructured collection as a separate and basic element. Minstrell (1982, 1989, as cited in diSessa, 2006) viewed conceptual change where intuitive ideas are threads connecting facets that, rather than simply being rejected, need reweaving into a different, stronger, and more normative conceptual fabric.

DiSessa (1993, 1996, 2006, 2008) dubs the individual elements phenomenological primitives, or 'p-prims', of which humans have hundreds, if not thousands, at roughly the same size scale of Minstrell's facets. These p-prims are generated from a learner's experiences and observations of phenomena, through interactions with the physical world and reflecting events and actions such as pushing, pulling or throwing.

P-prims are loosely organised within a conceptual network and are highly contextual in some cases. They are not activated under a highly organised system, which is why the term 'theory' is not deemed applicable by diSessa (1993, 1996, 2006, 2008). They are activated by recognition mechanisms that depend on the connections that p-prims have to the other elements of the system. The process of learning science is one of collecting and systematising the pieces of knowledge into larger systems of complex knowledge structures such as laws of physics, and conceptual change occurs through the reorganisation of p-prims and a change in their function (diSessa, 1993). Conceptual change requires a cognitive reorganisation of these naïve knowledge elements into complex systems (diSessa, 2002).

2.3.3 Knowledge as an integration of theory and elements

There is likely no single explanation for the complex processes of conceptual change and naïve knowledge structures (Özdemir & Clark, 2007). Nonetheless, despite the differences in the two general approaches to conceptual change described above, that is, theory versus elements, they are not necessarily incompatible with each other. There seems to be strong evidence for both views, as illustrated by Özdemir and Clark's (2007) summary comparison. Yet the knowledge-as-theory position does not have to be inconsistent with the view that something like diSessa's idea of p-prims constitutes an element of the knowledge system. D. E. Brown and Hammer (2008) propose a conceptual system which consists of different kinds of knowledge elements, such as beliefs, presuppositions and mental models, and they believe their system remains consistent with diSessa's proposal that there is a need to focus not on single conceptions but on rich knowledge systems composed of many constituent elements. According to D. E. Brown and Hammer (2008), their complex systems theory is able to describe the full spectrum of phenomena in the conceptual change literature. Each phenomenon can be described in terms of cognitive structures which arise from the interactions of smaller conceptual elements or resources not unlike the p-prims. Initial beliefs about phenomena are probably context-bound, upon a first experience of a new phenomenon. But over time, the child must see

commonalities across situations, and will build presuppositions that constitute a naïve theory of events (Stavy & Tirosh, 2000).

2.4 Approaches to conceptual change in the classroom

Despite the variety in theories it has been clearly established that conceptual change is difficult to achieve. However, all normally developing children have the capacity for conceptual change (Carey, 2000a). Thus teaching and learning for conceptual change require substantial amounts of effort on the part of the teacher, as well as on the part of the learner. For this effort to be invested, there needs to be an environment within which this is both necessary and appreciated. Teachers need to design relevant activities (Vosniadou, Ioannides, Dimitrakopoulou, & Papademetriou, 2001), and students need to be actively engaged. One important step in the design of such activities is that the underlying prior conceptions need to be specified as precisely as possible. How can they be assessed, and how do children predict physical events that show their misunderstandings? It is assumed that humans have a cognitive system that allows them to create mental representations of physical objects that embody the internal structure of the concept and can be run in the mind's eye to generate predictions and explanations of phenomena (cf. Nersessian, 1998, 1999, 2008a, b).

2.4.1 Mental modelling and model-based reasoning

A distinction needs to be made between bottom-up, conservative, additive and largely unconscious mechanisms and top-down, radical, deliberate, and intentional learning mechanisms. The first of the two is manifest in the Piagetian adaptation mechanisms of assimilation, accommodation and equilibration (Piaget, 1978, 1985), or the process of internalisation (Vygotsky, 1978). The others can be mechanisms such as model-based reasoning, which rely on the deliberate use of mental modelling and the use of thought experiments (Helm, Gilbert, & Watts, 1985; T. S. Kuhn, 1977; Nersessian, 1992; Vosniadou, 2007a). While the bottom-up mechanisms can be productive in spontaneous conceptual change, this is not the case for

instruction-induced conceptual change, which requires a deliberate use of the top-down mechanisms – on the contrary, it usually leads to the formation of incorrect conceptions, and Posner et al. (1982) did acknowledge that their framework is not ideal for educational practice. The problems of prior knowledge that children bring to the classroom have been laid out in Chapter 1 on prior conceptions in the classroom. In order to avoid the construction of alternative or synthetic models (cf. Vosniadou & Brewer, 1992), students must be made aware of the inconsistencies between their naïve theories and the scientific ones, and use must be made of the top-down, conscious and deliberate mechanisms for intentional learning (Alonso-Tapia, 2002; Sinatra & Pintrich, 2003; Vosniadou, 2003, 2007b, c).

Mental models have been introduced in relation to long-term memory representations of knowledge used in understanding and reasoning processes, particularly where physical systems are concerned. This literature posits the notion to explain a wide range of experimental results indicating that people use organised knowledge structures relating to physical systems in employing qualitative domain knowledge of physical systems to solve problems (Forbus, 1983; Gentner & Stevens, 1983). But what exactly are mental models? A mental model is not simply a mental image of one particular instance, although in some cases a particular image can, of course, be relied on. It is analogous to a real-world or imaginary situation, event or process, since it preserves constraints that are inherent to dimensions of the real-world system (Johnson-Laird, 1983; Nersessian, 2002b). According to Lesh and Doerr (2003), models are conceptual systems consisting of elements, relations, operations and rules. Mental models thereby act as prototypes of particular kinds of conceptual models, such as the behaviour of objects in free fall, which can then enable a person to simulate similar behaviour with new objects (Nersessian, 1992, 2002a, 2003). A person's intuitive mental model of motion, for instance, is a model built up in that way following many years of experience of things that move within the real world (Mildenhall & Williams, 2001; Reif & Larkin, 1991; Vosniadou, 2007c). Mental models embody a representation of the spatial and temporal relations among, and the causal structures between, the events and objects concerned. Since mental models need to be causally coherent, it should be possible to carry out simulative reasoning

about the behaviours of a model for those tasks that are dynamic in nature (Johnson-Laird, 1983).

As mentioned above, then, mental modelling and thought experiments appear to be crucial elements in conceptual change instruction. Mental modelling is a fundamental form of human reasoning, evolved as an efficient means to navigate the environment and to solve problems in order to survive in the world. Humans have been able to extend this ability to the construction of scientific representations. The scientist's specific problem solving therefore does not differ from the problem solving used in everyday circumstances (Nersessian, 1995, 1999), thus reflecting rather appropriately the view of children not being fundamentally different from scientists in their thinking approach (cf. Gopnik, 1996). Given the differences between novices' and experts' reasoning skills in scientific problem solving, the skill of modelling is something that seems to develop with learning (Chi, Feltovich, & Glaser, 1981; Nersessian, 1995).

When solving a problem, learners construct a mental model of that problem and use the model as the basis for prediction and inference (Jonassen, 2003, 2004; Morgan, 1999). When individuals construct mental models or retrieve them during cognitive functioning, new information is incorporated into the knowledge base. As such, a mental model can constrain the knowledge acquisition process in ways rather similar to prior conceptions. Mental models and model-based reasoning can provide important information about the underlying knowledge structures from which they are generated. Understanding the generic mental models that individuals use to answer a variety of different questions related to a given concept can provide important information regarding the theories that constrain the knowledge acquisition process (Vosniadou, 1994a). This highlights the relevance of mental modelling in the process of establishing conceptual faults in children's reasoning about the physical world.

2.4.2 Mental models and thought experiments

How are mental models used when having to make predictions about object motion events? In many instances people reason by carrying out thought experiments on internal models of physical situations, where a model is a structural, behavioural, or functional analogue of a real-world phenomenon (Craik, 1943; Yu, 2002). Thought experiments in scientific reasoning are by no means a new concept. Famous thought experiments from the scientific revolution include Galilei's (1632) Ship, an experiment created to disprove the then popular argument that the Earth did not rotate, Newton's (1728) Cannonball, used to hypothesise that the force of gravity was universal, or Galilei's (1638) well-known Leaning Tower of Pisa experiment. In these thought experiments, an individual is invited to imagine an experimental situation being described. The person is asked to picture objects, for example, and to imagine various things happening to these objects, or to imagine doing something with them, such as rotating objects mentally. Eventually, the person reaches conclusions about these objects and what would happen to them given certain conditions.

Consider the following example to illustrate this. The traditional story of the Leaning Tower of Pisa experiment is that Galilei himself dropped two objects of different mass from the top of the Leaning Tower of Pisa in order to invalidate Aristotle's theory of gravity by which objects fall at constant speeds relevant to their mass. The general consensus is, however, that Galilei did not actually perform this experiment himself (cf. Cooper, 1935) but rather that he relied purely on theoretical reasoning to reach his conclusions. His simple idea was that if two objects of different mass are connected by a string and this ensemble is dropped from a tower, according to Aristotelian physics the string should soon pull taut because the lighter object would slow down the fall of the heavier object and the heavier object would speed up the fall of the lighter object – therefore the ensemble as a whole should be slower than the heavy object alone. But at the same time, the ensemble would be heavier than either of the individual objects and therefore should fall faster than the heavy object

on its own. From this contradiction Galilei concluded that the Aristotelian assumption had to be false.

So how can mental models be created and thought experiments be carried out, given that there are no objects to physically work with? The real difficulty of carrying out thought experiments is merely establishing models of entirely new phenomena never encountered before. Once this has happened, the jump from data to theory is quite small and can be made fairly effortlessly (J. R. Brown, 1986). Mental models are typically relied on when trying to understand stories, or in ordinary planning of activities, and they are highly specific, representing concrete situations, objects and relations (Johnson-Laird, 1983). When, for example, a reader encounters a description of a situation, a model is built, a quasi-spatial picture of it. Whenever the storyteller provides new details, the model gets updated.

There are differing views on what knowledge thought experiments are based on. One view is that the background conditions are dictated by the thought experimenter's general knowledge about the world. The insight yielded by thought experiments is therefore a posteriori – "the material with which the individual works is experiential, and so his or her conclusions will be, in the last resort derived from experience" (Miščević, 1992, p. 215). So here, too, past experience is deemed important in the development of understanding of how objects behave, and the reliance on prior knowledge can seemingly be done fairly easily and quickly, given the process of having to identify the appropriate theory or elements of knowledge in order to reach a conclusion. Furthermore, mental models allow for reorganisation of past knowledge, therefore acknowledging the ability to integrate new information when accessing a model that is insufficiently appropriate for a particular scenario (Miščević, 2007). An alternative view is that thought experiments draw on imagined transformations that depend on innate knowledge of three-dimensional space (e.g. Shephard, 2008).

Because of the extensive experience that we have with motion, it should be relatively easy to construct mental models of dynamic events. Yet despite motion

being a key element of the physical world, it is one that has largely resisted conceptual change, both on a global scale as well as on an individual level. Although some mental modelling might employ static representations, those derived from thought experimental narratives are essentially dynamic in nature; animation is central to Craikian mental modelling (Craik, 1943). What this means is that mental models can go beyond simple spatial transformations and can incorporate transformations occurring within physical systems. Constructing and conducting thought experiments makes use of existing representations as well as scientific and general world knowledge to make realistic transformations from one possible physical state to the next (Nersessian, 2008b). This makes the use of mental models in predictions of object motion obvious, and the understanding of object motion is, after all, the central issue here – the importance and relevance of it having been raised in Chapter 1.

2.5 Summary

What has been established so far is that children come to the classroom with prior naïve knowledge about the physical world that is highly resistant to conceptual change. The means by which children, and adults, reason about scientific problems is by constructing mental models on the basis of previous experiences they have collated over many years and carrying out thought experiments to reason about new problems related to such previous experiences. The importance of modelling in understanding scientific phenomena has been recognised for some time (e.g. Confrey & Doerr, 1994; Frederiksen & White, 1998; Lehrer & Schauble, 2000, 2003). This is important to be aware of when considering the work on children's understanding of motion, which will be discussed in Chapters 5 and 6. More importantly, however, what this chapter has done is illustrate that, whilst being a necessary task in early science education, current conceptual change approaches do not appear to be particularly effective in achieving change. This beckons for considering alternatives to the standard teaching approach, which will be discussed in the next chapter.

"It is my belief, you see, that thinking is a double phenomenon, like breathing." (Asimov, 1975, p. 159)

CHAPTER 3:

THE EXPLICIT-TACIT KNOWLEDGE DISTINCTION

Certain situations in everyday life require an accurate interpretation of an object's behaviour in terms of its speed and its acceleration, such as when in traffic. In order to know when it is safe to cross a busy road and when not, with no pedestrian crossing in sight, a child – or an adult, for that matter – needs to be able to estimate with reasonable accuracy how fast a car is going, and how much longer will be needed until that car has reached the point of crossing. From this the child can then deduce whether it is safe enough to cross the road before that car reaches the point of crossing (cf. te Velde, van der Kamp, & Savelsbergh, 2008). Though much further down any life-maintaining scale, a further scenario can be considered: If children have to walk to school, they need to be able to judge how fast they must walk from home within a given time if they do not want to be late for classes, or if they need to hurry up while walking there, increasing their stride. Additionally, children play games, such as cops and robbers, or any derivations thereof, that require a reasonable estimation of different speeds in order to win the game.

It is therefore evident that an appropriate knowledge of motion, and specifically of speed and acceleration, is necessary. Yet as Chapter 1 indicated, naïve Aristotelian knowledge interferes with an accurate understanding of this, and what Chapter 2 has done is show that the standard approach to conceptual change in educational practice is by making current conceptions *explicit* and imposing the correct concepts. Firstly, though, what is meant by explicit knowledge? And as indicated at the end of Chapter 2, because of the fruitlessness of current approaches to conceptual change, the question arises whether alternative forms of knowledge are available to consider in the facilitation of conceptual change. Such a possible alternative is discussed in this chapter.

3.1 'Explicit versus tacit knowledge'?

To allow learning of appropriate judgements of speed and acceleration, a plenitude of everyday events where objects are in motion is available to the child, allowing objects not only to be observed, but also to be interacted with. Adults also instruct children on safe behaviour. However, this knowledge may either be limited to learning the behaviour of specific objects within specific situations; alternatively, generalisations may well be established from multiple observations of same or similar behaviour, and implicit theories of object motion may be constructed from this (McCloskey, 1983c). But does the expressed knowledge reflect the actual knowledge held? This thesis is first and foremost concerned with the distinction between children's *explicit* beliefs about objects in the physical world and their *tacit* understanding thereof. But how do these two forms of knowledge differ from each other? It is crucial to establish what is meant by explicit knowledge, what is meant by tacit reasoning, and to then ascertain the importance of this distinction.

The acknowledgement of the existence of implicit or intuitive knowledge, as opposed to simple instinctive reflexes, reaches at least as far back as Darwin (1859), who interprets the hive bees' art of cell making as an instinct evolved from numerous successive and slight modifications of simpler instincts, by commenting on "the exquisite structure of a comb, so beautifully adapted to its end", and yet "it

seems at first quite inconceivable how they can make all the necessary angles and planes, or even perceive when they are correctly made" (Darwin, 1859, p. 248). However, the more crucial general *distinction* between two forms of knowledge can be associated with Ryle's (1949) work, which referred to two separate kinds of reasoning – 'knowing that' versus 'knowing how'. The former refers to an express understanding of in what ways something operates, or what the specific processes are that lead to an outcome. The latter, on the other hand, refers to the knowledge that people rely on to ascertain familiarity with objects or events, or a subjective feeling of oldness about them, without a person necessarily being aware of any specific underlying rules – the person is drawn to a particular location because it *feels* right but there is no conscious basis of reasoning to support that decision (Dorfman, Shames, & Kihlstrom, 2002; Fu, Dienes, & Fu, 2010a; Scott & Dienes, 2010; Sun, Mathews, & Lane, 2007; Whittlesea & Wright, 1997). This knowledge that remains unarticulated yet can be demonstrated in use or action is called tacit knowledge (Polanyi, 1967; Wagner & Sternberg, 1985).

Of course one could question at this point, perhaps understandably, whether referring to *knowledge* in 'knowing how' performance is appropriate, or whether 'knowing how' should just be seen as a form of effective guessing. How can we be certain that, even if performance on a task is above chance levels, participants are falling back onto some underlying knowledge systems instead of simply being rather good guessers? A possible answer comes from a number of recent studies that not only make the case for a distinction between conscious and unconscious structural knowledge (e.g. Dienes, 2008; Fu et al., 2010a), but take this even further by distinguishing between simple guessing and reasoning on the basis of unconscious structural knowledge (e.g. Dienes & Scott, 2005; Fu, Dienes, & Fu, 2010b).

3.2 The relevance of the explicit-tacit distinction

Hogarth (2001) identifies two principal thinking and knowledge systems. While the 'deliberate' system involves explicit reasoning and requires effort and attention, the 'tacit' system is set to operate automatically, and typically provides quick responses

without conscious awareness. Quite compatible with Hogarth's (2001) model is that of Plessner and Czenna (2008). Their 'reflective' system is concerned with handling explicit knowledge, which becomes effective under deliberate judgement and making of decisions. Their 'intuitive' system, on the other hand, functions on the basis of implicit knowledge and expresses itself in spontaneous judgements and decisions. Both models share the assumption that there are two systems differing from each other in terms of presence or absence of cognitive effort. Plessner and Czenna (2008) state that these models only apply to judgement situations where several options are involved and the decider has some amount of prior experience – however, in their opinion this requirement is already fulfilled by most everyday judgement and decision situations.

Consider the following example. Throwing and catching a ball is, in actuality, a rather complex task in terms of the physical and mathematical laws involved. Professional ball players can judge rather well – out on the playing field – where, when and how a ball will reach them (e.g. Gigerenzer, 2004, 2007; McLeod & Dienes, 1996; McLeod, Reed, Gilson, & Glennerster, 2008). Yet when asked to do related prediction tasks on paper, their performance is nowhere near as accurate. Reed, McLeod and Dienes (2010) required people with above average ball playing skills to imagine catching a ball thrown towards them and to describe how they would know where to be and how they would know they were moving fast enough to catch the ball. Their study suggests that the participants were not able to describe correctly how they would make relevant decisions.

It thus becomes apparent that two different modes of thinking must be involved in these two types of tasks: While the theoretical tasks required explicit knowledge and reasoning, which is not always accurate, in practice these same players are able to rely on quick yet accurate unconscious thinking, which clearly is an advantage for them. Gigerenzer (2007) entitles such unconscious thinking 'gut feeling'; a judgement that appears quickly in consciousness and whose underlying reasons we are not fully aware of, yet is strong enough to act upon – "by definition, the person with the feeling has no idea" (Gigerenzer, 2007, p. 17). There is widespread

agreement that tacit knowledge is an important phenomenon; many regard tacit knowledge as fundamental to all human knowledge (e.g. Gourlay, 2004), perhaps even unique to humans (Evans, 2003), and it is perceived to even be critical in activities like scientific experiments (Collins, 2001).

3.3 Learning a lesson from infancy research

School-aged children, and adults too, often give mistaken explanations for the motions of objects and make erroneous predictions about future object motions (cf. Clement, 1982; Krist, Fieberg, & Wilkening, 1993; Piaget, 1977). These observations may suggest that the tacit conceptions underlying adults' perception of object motion are distinctly separate from the explicit conceptions that underlie predictions, judgements and explanations (Kim & Spelke, 1999). Piagetian speed tasks and alternative tasks, which will be discussed in Chapter 5, only allowed accessing explicit knowledge, but have suggested that there is some intuitive understanding of the relevant concepts; perhaps there is even more knowledge that can be unearthed. But where would this tacit knowledge come from?

Let us for a brief moment return to ancient Greece, to the philosopher Plato (trans. 2009). In his work, Socrates takes Meno's slave boy through the steps of a geometric proof. The boy, an uneducated child, acknowledges the truth of each step and ends up proving the theorem. Socrates concludes that because the boy, who has had no experience of geometry, can do this, he must already somehow know the proofs of geometry without consciously being aware of them. The new research with infants suggests that Socrates' stunningly counter-intuitive idea was perhaps exactly right: Even babies must know much more than we think (cf. Gopnik, Meltzoff, & Kuhl, 2001).

A quote used in many developmental psychology texts describes an infant's perception of the world as being "one great blooming buzzing confusion" (James, 1890, p. 488). By a century later the picture that started developing quite rapidly was not only that infants are not quite the tabula rasa depicted by James (1890), but that

infants are in fact "budding intuitive physicists, capable of detecting, interpreting, and predicting physical outcomes", whose "physical world […] appears very similar to that of adults" (Baillargeon, 1993, p. 311). If the young infant does not possess sufficient language capacities at that early stage to make knowledge explicit but does possess appropriate understanding, what form does this understanding take, how can it be assessed, and finally, what happens with this knowledge as infants become toddlers and learn to express their ideas in an explicit manner?

3.3.1 The violation-of-expectation paradigm

Piaget (1952, 1954; also see Harris, 1983) concluded, upon extensive observations and research, that young infants lack any ability to reason about objects as material beings and about their physical properties, and that this takes time to develop – up to two years – by observing their own actions on objects. Assessing any knowledge in infants is "notoriously difficult" (Munakata, 2000, p. 471); however, with the emergence of a new research technique about 25 years ago it would appear that Piaget's conclusions can be contradicted; the emergence of the violation-of-expectation paradigm. The violation-of-expectation paradigm is based on the assumption that we have particular expectations about events or properties of objects, based on physical laws such as gravity, solidity or continuity, which cannot simply be altered.

In a characteristic experiment where the violation-of-expectation paradigm is employed infants are typically presented with a small number of habituation or familiarisation trials, although this need not necessarily always be the case, depending on the complexity of the events. These are then followed by test trials with both possible and impossible events. The possible trials tend to present an alternative event that is conceptually related to the habituation or familiarisation trials and is therefore perceptually different, but nevertheless remains physically possible. The impossible events in turn are both perceptually and conceptually different. So the objects or events displayed in the test trials bear resemblance to habituation or familiarisation but incorporate a change to at least one aspect,

thereby creating two entirely novel scenes in a perceptual sense but one being possible and one being impossible in terms of the concepts involved. Because the impossible event is seen as violating expectations based on prior beliefs or naïve theories, this event should receive longer looking times (Spelke, 1985) and more surprise; an "emotional reaction to an upset belief" (Casati & Pasquinelli, 2007, p. 171).

The belief violation paradigm has been applied extensively in research involving infants, as it does not require coordinated motor actions, in contrast to what is demanded in typical Piagetian tasks (Baillargeon, Spelke, & Wasserman, 1985). With regard to infants who detect violations in such tasks following the principle of violation-of-expectation, Baillargeon (2004) deems it rather unlikely that these infants could be attributed explicit knowledge about these violations, or indeed explicit knowledge about anything at all. Instead, their reactions are attributed to some form of internal physical reasoning system that monitors events, scrutinising those that do not occur as expected. Similarly, Hood (2001) notes that whilst infants cannot "provide a commentary related to their knowledge" (p. 1283), before acquisition of language their knowledge may well be reflected in adaptive actions, and gaze would certainly be one means to do so.

3.3.2 Infants' knowledge of the world

Baillargeon and her colleagues have applied the violation-of-expectation paradigm in a number of studies in which they assessed young infants' understanding of the physical world and an appreciation of some of the basic principles underlying object motion. For example, very young infants already appear to appreciate that adequate support is needed in order for a box not to fall, contrary to Piaget's (1952, 1954) assumptions (Baillargeon & Hanko-Summers, 1990; Baillargeon, Needham, & DeVos, 1992; Needham & Baillargeon, 1993). It seems that infants implicitly consider an object's centre of gravity in deciding whether it is adequately supported, though estimation of where that centre of gravity lies is very crude. Alternatively, they may rely on primitive rules, that when an object has little lower surface support it must

topple and fall. Additionally, infants aged 2½ to 3½ months are aware that objects continue to exist when masked by other objects, that objects cannot remain stable without support, that objects move along spatially continuous paths, and that objects cannot move through the space occupied by other objects (Baillargeon, 1994).

Some researchers (e.g. Bogartz, Shinskey, & Schilling, 2000; Bogartz, Shinskey, & Speaker, 1997; Cashon & Cohen, 2000; Shilling, 2000) have raised scepticism about the interpretations of violation-of-expectation tasks, suggesting that these looking time studies do not necessarily reflect what infants know in a conceptual manner. Instead, they offer alternative accounts by which looking times can often be attributed to perceptual preferences. However, despite this issue being unresolved per se, many infancy studies employing the violation-of expectation paradigm enacting appropriate controls for such perceptual preferences collectively provide evidence that infants do indeed display conceptual knowledge of the world (cf. Hood, Carey, & Prasada, 2000).

On the basis of findings from an array of research so vast that it cannot possibly be covered and reviewed here, Spelke and colleagues (Kinzler & Spelke, 2007; Spelke, 1991, 1994, 2000, 2004; Spelke, Breinlinger, Macomber, & Jacobson, 1992; Spelke & Kinzler, 2007; Spelke, Phillips, & Woodward, 1995) have proposed the notion of core knowledge. Despite some controversy over this hypothesis, several other researchers sanction the existence of some form of core cognition system (e.g. Baillargeon, 1995, 2001; Carey, 2009; Carey & Sarnecka, 2006; Carey & Spelke, 1994, 1996; Karmiloff-Smith, 1992; Leslie, 1994). The consensus is that infants are born with certain core beliefs about objects, such as the belief that objects move along connected unobstructed paths. Non-core beliefs, such as the belief that objects require support to remain stable, would be acquired through observations and manipulations of objects.

Studies of human infants, focused on the ontogenetic and phylogenetic origins of knowledge, provide evidence for four core knowledge systems, including for

representation of inanimate objects and their mechanical interactions (Spelke, 2004). These core beliefs represent the infant's initial theory of the physical world and stand at the centre of the adult's intuitive understanding of that world – according to the core knowledge view, therefore, adults possess their basic intuitions about objects and motion from birth, and this basic knowledge is, at its core, not subject to any change during the rest of the lifespan (Carey, 2009; Keysers et al., 2008; Santos & Hood, 2009; Spelke, 2000).

3.3.3 Tacit knowledge beyond infancy?

Children, according to Karmiloff-Smith (1992), display from the very beginning a range of specific cognitive skills, such as imitating movements or recognising faces. She suggests that humans are born with pre-wired modules that, while unrelated to begin with, start interacting during development. While early learning is done by instinct, as thinking develops, the world has to be redescribed from an implicit form to more explicit forms. This process of representational redescription occurs through three phases. In the first phase, a child learns mastery of an activity. Information is extracted from the environment and added to the representational system without changing or interacting with existing representations. These representations are dubbed Implicit (I-level) representations, and while they can generate successful behaviour in interactions with the world, the behaviour is inflexible. In the second phase, I-level representations are redescribed to Explicit 1 (E1-level) representations. These deal with explicit representations that can be changed and that can be related with each other – they are not consciously accessible but are no longer simply procedural. In the third phase, the external world and the internal representations are integrated and representations are redescribed to Explicit 2/3 (E2/3-level) representations. While both are consciously accessible, verbal report is only possible at the E3-level.

Representational redescription can be illustrated by a study by Karmiloff-Smith and Inhelder (1974/1975), where children needed to balance wooden beams across a fulcrum. Four- and 5-year-olds were able to complete tasks successfully due to

proprioceptive feedback about which way the beam would fall. Karmiloff-Smith (1992) presumes that these children were relying on I-level representations. Six- and 7-year olds were able to place beams at their geometric centres but only if they were symmetrical, not if they were asymmetrical. According to Karmiloff-Smith (1992), these children had some general but consciously inaccessible problem solving strategy at the E1-level. Eight- and 9-year-olds were able to balance beams of all types, incorporating some knowledge about torque, by having reached E2-level or E3-level representations. Overall, like Piaget Karmiloff-Smith (1992) acknowledges cognitive progress. However, unlike Piaget's (1978, 1985) notion of equilibration, which was introduced in Chapter 2, Karmiloff-Smith (1992) proposes that progress in development happens as a result of reaching a *stable* state, that is, mastery, rather than a state of cognitive disequilibrium.

It has been argued that the relative orthodoxy – as viewed from a scientific perspective – of tacit knowledge unveiled in studies with infants continues as age increases (see e.g. Carey & Spelke, 1994; Keysers et al., 2008; Spelke, 1991; Spelke et al., 1992). This would imply that young children, too, hold similar tacit beliefs concurring, to some degree, with Newtonian physics. The existence of differences between explicit and tacit knowledge at the pre-school and primary school level would mean that conceptual development cannot simply be reduced to a process by which tacit knowledge is merely converted to explicit knowledge (Karmiloff-Smith, 1992). Additionally, Carey (1991, 2009) proposes that concepts change over time, enriched by the acquisition of further knowledge along the way, but that the core remains unchanged. Especially with regards to the notion of core cognition introduced earlier, which has been proposed by several researchers, what we know in infancy should still be there at a later age, albeit in an enriched form.

3.4 The role of language and experience

Some researchers posit the notion that humans are evolutionarily endowed with some innate knowledge of language, taking the form of a language acquisition device (e.g. Chomsky, 1965; Gleitman, Cassidy, Nappa, Papafragou, & Trueswell, 2005;

Pinker, 1984, 1989; Spelke & Newport, 1998). This device guides the learning of natural languages. How does the learning of natural languages relate to the development of concepts, especially to the underlying concepts embedded within core cognition? As regards concepts, the key aspect of language is semantics, and there appears to be no literature discussing the possible role of semantics in the development of tacit knowledge of the physical world per se. In fact, the indication seems to be that while syntactic components of language are tacit, semantic components do not appear to be so (cf. K. Johnson, 2004). However, there can be no doubt that the acquisition of language, semantics in particular, plays an important role in development of knowledge beyond the tacit level, given that "language acquisition and conceptual development are intimately related" (Carey, 2009, p. 464).

Children learn natural languages by hearing people talk about objects and events around them (Ganea, Shutts, Spelke, & DeLoache, 2005; Harris, 2002). But children cannot learn the meaning of a particular concept unless they are able to relate the spoken word to the presence of the physical object or event. Similarly, words that do not refer to concrete phenomena need to be relatable to some form of occurrence in which the concept appears. As Spelke and Kinzler (2009) write, while it is logically possible that exposure to painting courses could cause students to know calculus, the relevant experience for developing knowledge of calculus inevitably includes exposure to calculus. This highlights the importance of the relation between relevant experiences and the development of knowledge. This relation can only be established if the child already has a workable concept of that object or event as well as a workable procedure to identify instances of the concept (Spelke, 2003).

It would seem, therefore, that concepts are not learned through learning natural language, but that concepts must exist, to some extent at least, prior to the acquisition of relevant natural language. In particular, concepts must be acquired before their relevant semantics, and the appropriate word meanings must be associated with the concepts at a later point. Natural languages have a "magical property" (Spelke, 2003, p. 306): Once the terms of a language have been mastered,

as well as the rules by which they can be combined, different meanings on the basis of grammatical combinations of those terms can be represented without having to learn them. That is to say, once semantics of individual concepts have been acquired, the meanings of new conceptual *systems* can be established through the meaning of the individual concepts (Ganea et al., 2005; Spelke, 2003). For instance, a child may lack the concept 'under the big bed' but does not need to learn the concept to understand the phrase. If the child has learned the semantics of 'under', 'big' and 'bed', then the expression will be understood because the child is able to combine concepts that are already held in an appropriate manner.

A number of studies (see Carey, 2009, for a review) provide initial evidence that language learning plays an active role in *shaping* conceptual development. A crucial question in the development of conceptual knowledge is whether language and the learning thereof cause a difference in thinking about the world – does the prelinguistic infant think differently about the world than the child who is acquiring or has acquired language? Despite there not being any definitive answer to the question of the existence of core knowledge or core cognition, it seems clear that most of the knowledge we possess is not embedded within core cognition systems – "there are no innate perceptual analysers, nor innate learning mechanisms, that pick out the electrons, the tables, the stars, or the wombats in our environment" (Rosenberg & Carey, 2009, p. 184). Even if children did have rich innate conceptual knowledge of the world and of language, they would still need to learn their *particular* language, including its semantic and syntactic devices and how they are expressed (Carey, 2009).

But the issue of semantics goes beyond simple lexical representations of individual objects. According to Kuczaj and Hill (2003), children construct a semantic system instead of a list of independent words due to the existence of relations between words rather than their isolated existence. The development of such a system is facilitated by the acquisition of semantic relations, and children have to determine those relations. Some words are simply opposites, such as 'hot' and 'cold'. Other words form entire semantic dimensions, such as 'hot', 'warm', 'cool' and 'cold'.

When children learn the words in semantic dimensions, words at the far ends of the dimension, that is, the opposites, are learned before the words that fall between them (Kuczaj, 1975, 1982). The words at the far ends also appear to be more salient to young children than those between them (Kuczaj, 1999). But not only does there appear to be saliency towards the end points of semantic relations. Researchers have also noted a semantic congruity effect in judgements. People are faster at judging which of two small animals is smaller than they are at judging which of the two is bigger. Conversely, they are faster at judging which of two large animals is bigger than they are at judging which is smaller (cf. Jordan & Brannon, 2009).

One might expect that this semantic congruity effect would be driven by language; yet research with rhesus monkeys, for instance, has shown they are faster at choosing the smaller of two small numerosities than they are at choosing the larger of the two, and that they are faster at choosing the larger of two large numerosities than at choosing the smaller (Cantlon & Brannon, 2005). If, therefore, humans and rhesus monkeys share similar susceptibility to the semantic congruity effect, at least as far as numerical understanding is concerned, then language is unlikely to be the entire story. This would also be in line with infancy research, showing that in terms of object properties prelinguistic infants are already capable of distinguishing between individual entities such as objects and non-individual entities such as sand (Huntley-Fenner, Carey, & Solimando, 2002; Rosenberg & Carey, 2006), between heavy and light objects (Molina & Jouen, 2002), or between objects that are too big to fit into a container and objects that are not (Aguiar & Baillargeon, 1998). It seems reasonable to suggest that they do not, at this stage, hold semantic representations of mass or size. Yet clearly they must have some underlying conceptual understanding of these properties, or else they would not be able to distinguish between objects on the basis of such properties.

Knowledge that is represented by explicit symbols – in language, mathematics, or maps – differs from core cognition (Carey, 2009). It differs in its format, that is, core cognition is not represented by explicit symbols. Also, most knowledge is not recognised to be innate and does not remain constant throughout the course of

development, because relations among explicit symbols can be revised. Core cognition might, for instance, entail knowledge of the solidity principle whereby two objects cannot occupy the same space at the same time and cannot pass through each other. But learning about physics can create awareness that what are perceived to be solid objects are, in fact, not strictly solid; particles can pass through the lattice structure of wood. It thus appears that while we would be surprised to see a large object fall through a table, because it would essentially violate our *underlying* principle of solidity, we are still able to appreciate through explicit representations in form of language that the principle of solidity has its limits, too; representations incommensurable with core cognitive principles.

Humans appear to be alone in their ability to create external public representations of the conceptual world. Other animals may well hold such representations, comparable to core knowledge in humans, but they do not communicate about them. According to Carey (2009), domain-specific learning mechanisms enable language acquisition. Language learning is supported by representations in core cognition – they provide the meanings that lexical items express. And certainly, language learning makes representations more easily accessible and shareable. Language learning, therefore, plays an important role in creating representational resources that are too abstract to be represented without the help of semantics. Core knowledge is implicit and encapsulated, whereas knowledge embedded in intuitive theories is mostly accessible and explicit (cf. Carey, 2009). While semantics do not interfere with core knowledge, they enable to supplementation of its repertoire by establishing newly combined conceptual systems (Spelke, 2003). On the basis of a possibly innate language acquisition device, language learning – particularly semantics – is supported by core cognition rather than being the cause of it. But the role of language in the development of conceptual understanding beyond what is available in the core cognitive system remains important, as does its relevance in making underlying knowledge accessible and shareable. And it would seem that this is the crucial element in the elevation of core and tacit knowledge to explicit knowledge, without effecting a change in core or tacit knowledge themselves.

3.5 The possible role of tacit knowledge in early science education

As established so far, any knowledge about objects and events is either explicit or tacit. Cases of explicit knowledge of a fact about an object or an event "are representations of one's own attitude of knowing that fact", while tacit knowledge "consists of representations that merely reflect the properties of objects or events without predicating them of any particular entity" (Dienes & Perner, 1999, p. 752). However, a student's ability to articulate his or her thinking is limited by the language he or she possesses (Perkins, 1992; Tishman & Perkins, 1997). Instead, people can also acquire knowledge that enables them to deal with a complex stimulus defined by abstract rules, without consciously being aware of the existence of any rules, or any conscious analysis taking place.

As signalled already in Chapters 1 and 2, naïve physics research collectively suggests that children have explicit prior beliefs about the physical world, relating to the objects within it as well as their own behaviour, and that these beliefs are incorrect in the scientific sense. But unlike in the everyday world, where the problem solver deals with real or realistic situations, knowledge imparted in school is often counter-intuitive because of its text-based reality or the use of idealised situation where, for example, friction or air resistance can be ignored in physics problems. Furthermore, a particular issue with science education is that there tends to be a focus on teaching and assessing knowledge in an explicit manner. Of course, certain elements of science cannot perhaps be taught in any other way, particularly if the concepts to be taught are of a somewhat abstract nature, such as genetics, chemical bonds or atomic structure, for instance.

But those elements that are less abstract to the mind because they are readily visible, such as dynamics, are also taught in an explicit fashion. This may be understandable, as integrating tacit knowledge assessment into science education is a formidable task in itself due to the inexpressible nature of tacit knowledge and the related difficulty in assessing it. And at the same time there has to be some point in the educational process where explicit engagement with the concepts to be taught is

required, for how else could a student's understanding be verified without some form of explicit communication of that knowledge? There can certainly be no denial that the conventional explicit physics teaching approach must, in general, be preparing students sufficiently well for higher-level work in the field – otherwise we would live in a world without scientists. But as Stinner (1994) points out, quite rightly, this may only have been achieved at a price, by losing many potential scientists who might have benefited from alternative approaches. The theoretical use of tacit knowledge in gaining knowledge has been sanctioned (A. Dijksterhuis, Bos, Nordgren, & van Baaren, 2006), and its access and integration in the process of problem solving is seen as an important goal for educational practice (e.g. Sun et al., 2007).

3.6 How can tacit knowledge be assessed?

Applying the procedure of the violation-of-expectation paradigm and measuring looking times in relation to displaying knowledge of physical events, as is done with young infants, becomes increasingly difficult beyond 12 to 14 months of age (cf. Rosenberg & Carey, 2009), due to increased mobility and restlessness often observed in such experiments. Instead, manual search tasks have been used to explore children's beliefs. Relevant search tasks by Hood and colleagues, on horizontal and free fall motion (Baker, Gjersoe, Sibielska-Woch, Leslie, & Hood, in press; Hood, 1995, 1998; Hood et al., 2000; Hood, Santos, & Fieselman, 2000; Hood, Wilson, & Dyson, 2006), suggest that even if core knowledge does continue to exist beyond infancy, then by the end of infancy, that is, by around two years of age, children no longer appear to make appropriate use of this knowledge when having to search for objects and show poor performance levels of correct reaching in object motion tasks. Hood et al. (2000) do note, however, that in addition to object knowledge these tasks also rely on executive control, and this may well provide a problematic barrier. As opposed to looking, reaching requires a stronger manifestation of the hidden object in memory, though with continued learning these representations become more robust and can be accessed more readily (Munakata, McClelland, Johnson, & Siegler, 1997).

Adding to that, Goldin-Meadow and Alibali (1999) stress that eye glances, in contrast to pointing or reaching behaviour, are in fact of an implicit nature. Indeed, a substantial accumulation of search studies (Ahmed & Ruffman, 1998; Berthier et al., 2001; Clements & Perner, 1994; Garnham & Ruffman, 2001; Hofstadter & Reznick, 1996; Hood, Cole-Davies, & Dias, 2003; Mash, Keen, & Berthier, 2003; Ruffman, Garnham, Import, & Connolly, 2001) suggests that while manual search behaviour of toddlers is often incorrect, their gaze behaviour implies they do, in fact, know the correct locations of objects. Similarly, toddlers' verbal responses in belief tasks are often incorrect and do not tend to match their correct looking behaviour (e.g. Low, 2010). Clearly, explicit knowledge about objects and events underlies developmental processes that can only be overcome during early childhood. And even then they do not necessarily provide correct understanding, as Chapter 2 of this thesis has indicated. So given that tacit knowledge about everyday physics, object motion in particular, is still there (cf. Carey, 2009; Santos & Hood, 2009; Spelke, 2000), but presumably cannot be accessed by measuring looking times or by verbal or manual search tasks – how *can* it be accessed beyond infancy and made available to the child, if it can be at all?

3.6.1 Judgements as an indicator of tacit knowledge?

As has already been indicated earlier in this chapter, occasionally there appear to be dissociations between explicit and tacit knowledge. While explicit predictions may be incorrect, relevant tacit procedural tasks can be performed accurately. Several studies have indicated that learners are able to successfully complete tasks without being able to explain how they were able to do so (e.g. Berry & Broadbent, 1988; Karmiloff-Smith, 1986; A. S. Reber, 1989; P. J. Reber & Kotovsky, 1997; Siegler & Stern, 1998). It has been indicated that judgement tasks can be used to access and reveal underlying knowledge structures (cf. Broaders, Cook, Mitchell, & Goldin-Meadow, 2007). In judgement tasks, participants are typically offered a limited number of options, and they are required to identify the correct option, or whether options are true or false.

Broaders et al. (2007) suggest that one way to access tacit knowledge is to include judgement components into experimental tasks. In a study by Bowers, Regehr, Balthazard and Parker (1990), for instance, adults were asked to figure out common word associations when provided with three other words – when given the words 'playing', 'credit' and 'report', for example, the participants had to produce the associate 'card'. They were presented with two triads at a time, of which one had an associate and the other did not. First, the participants needed to solve the triads by finding associates. If they did not succeed, they were asked to judge which of the two triads was likely to be solvable. Bowers et al. (1990) found that the participants were able to correctly identify the solvable triad even if they could not find the correct associate, suggesting they had an underlying tacit understanding that the triad was solvable. With children, too, similar results have been observed in judgement tasks. Siegler and Crowley (1994) found that 9-year-olds were able to judge which of two strategies was the better way to play a game of tic-tac-toe, even when they were not yet able to use the better strategy themselves, and actually used a different tactic when playing the game.

3.7 Using computers to assess tacit judgements

It is clear, then, that judgement tasks could provide an insight into young children's tacit understanding of object motion. One approach to assessing judgements of the correctness of dynamic events is by simulating events, thus giving children the opportunity to choose between correct and incorrect events, much like in the violation-of-expectation paradigm. And one means of presenting simulations of events is by using computers. The effectiveness of the use of information and communication technology (ICT) and assessment of tacit knowledge within education as such are not seen as central issues in the research context of this thesis. However, it is worth noting two points, particularly in the light of possible implications of the research, but also as a methodological justification for those studies that involve computers. Firstly, assessing tacit knowledge, at least in this case, is rather difficult. ICT provides a means to carry out the research. And secondly, if the assessment of tacit knowledge proves to be successful and it can be used

within education in some form or other, then it may be important to note the degree of usage of ICT in primary schools.

3.7.1 Computers and conceptual change

Systematic studies of student learning have revealed a gap between the objectives of most physics teachers engaged in traditional forms of instruction and the actual level of conceptual understanding achieved by most of their students (Heron & Meltzer, 2005). A better approach to teaching physics might be to use new technology tools effectively (Wieman & Perkins, 2005). One advantage of the so-called digital age in which we now find ourselves is that ICT is being used more commonly within education. It is seen as a way of transforming teaching and learning, and helping to facilitate learning processes "for those who struggle with traditional forms of learning" (Barker & Gardiner, 2007, p. 16). The benefit and potential had been recognised and appreciated fairly early on in the development of computer-based teaching research (e.g. diSessa, 1986; Lindström, Ekeblad, & Neuman, 1987). Twenty years later ICT is still believed to significantly enhance science teaching and learning, and there are plenty of recent books (L. R. Newton & Rogers, 2001), edited collections (Barton, 2004; Holliman & Scanlon, 2004) as well as a variety of reviews (Glover et al., 2005; Murphy, 2003; H. J. Smith et al., 2005) to support this view.

A range of authors has suggested specific means of inducing conflict and thereby stimulating reflection and conceptual change by relying on the use of so-called computer micro worlds (e.g. Andaloro, Bellomonte, & Sperandeo-Mineo, 1997; diSessa, 1982; Doerr, 1997; Hennessy et al., 1995a, b; Papert, 1980; Twigger et al., 1991). Here, computer simulations can be used to provide discrepant events that might promote conceptual change. This has the advantage that students can freely experience the micro world by visualising immediately the consequences of their actions (Bliss & Ogborn, 1989; Papert, 1980) or explicit predictions. Despite the questioning of the usefulness of ICT in science education in general (see e.g. McFarlane & Sakellariou, 2002), several researchers have now acknowledged that ICT bears one particularly important advantage for science classrooms, and that is

creating simulations. In certain situations, ICT would probably be more effective than any other medium when relying on simulations instead of coursework (Poole, 2000). More importantly, simulations or virtual experiments make it possible to depict physical situations where conducting the real experiment would be dangerous (Howe, Tolmie, & Anderson, 1991) or indeed even outright impossible. Students can thus make abstract and direct observations of phenomena or processes that they would not be able to by any other means (Gould, Tobochnik, & Grant, 2006; Hennessy, 2006; Hennessy et al., 2007; Rogers, 2004; Steinberg, 2000).

3.7.2 Current use of computers in primary education

Over the last decade the usage levels of ICT have increased in all areas of education within the United Kingdom, with decreasing computer-to-student ratios and a higher willingness both by teachers and by students to make use of ICT within the processes of teaching and learning (Barker & Gardiner, 2007). The use of ICT in primary education in particular has greatly increased over the past years. While in 1998 on average one computer was available to 17.6 pupils (Department for Education and Skills, 2004), the average number of pupils per computer has sunk to 6.9 in British state schools (British Educational Suppliers Association, 2009). The percentage of primary schools with electronic interactive whiteboards rose from 48 per cent in 2003 to 63 per cent in 2004 (Department for Education and Skills, 2004) – a substantial increase within just a single year. Currently, there is an average of 8.6 whiteboards in every primary school in England (British Educational Suppliers Association, 2009).

In the National Curriculum for England (Department for Education and Employment, 1999), the use of ICT across the curriculum is clearly stated. Even at the primary school level, pupils are expected to be given opportunities to apply and develop their ICT capabilities in all subjects, with the exception of physical education. They are expected to use ICT to support their learning in all subjects, and to share information through electronic media. Barker and Gardiner (2007) further note that in 2004 92 per cent of primary school teachers in England were reported to make regular use of

ICT. Much early work on ICT use in science education and group work has usually had to state that the computers capable of running software with the necessary fidelity are expensive, and would therefore be unlikely to be available for one-to-one use (e.g. Howe et al., 1991; Howe, Tolmie, Anderson, & Mackenzie, 1992; Light et al., 1987). However, given the aforementioned numbers of recent ICT availability and usage in schools, this would not really pose a problem anymore.

3.8 Summary

There seems to be a clear distinction between two different kinds of knowledge, one being explicit and the other being tacit in nature. Examples above have shown that while explicit reasoning is not always accurate, tacit understanding can make up for this. However, the assessment of this distinction might be difficult, despite research implying that differences in reasoning do exist. Here, a lesson can perhaps be learned from infancy research. A wealth of work following the violation-of-expectation paradigm leads to the consensus that young infants display knowledge about the physical world, and this knowledge is not considered to be explicit. At the same time, it is assumed that this knowledge persists throughout the lifespan. The acquisition of language, while possibly having its roots in core cognition, does not appear to alter core knowledge but is seen as a crucial tool in making underlying tacit knowledge explicit. Seeing as the classic approach to science education relies on explicit knowledge yet fails to promote conceptual change sufficiently, the incorporation of tacit knowledge certainly seems worthwhile exploring. The possibility of using judgements to tap young children's tacit understanding has been introduced, and the current use of ICT in schools can certainly contribute to this.

"Aristotle is not dead." (Whitaker, 1983, p. 352)

CHAPTER 4:

THE PHYSICS BEHIND OBJECT SPEED AND ACCELERATION

So far, it has been established that motion, due to its ubiquitous nature and the long lasting persistence of incorrect ideas, makes an interesting case to investigate. Chapter 1 of this thesis has shown that the scientific revolutions, particularly those by Galilei (1638) and by Newton (1687), have clearly confuted Aristotle's views laid out in *Physics* (trans. 2008). Yet folk physics in individuals still resists revolutions and maintains an Aristotelian manner, often even after substantial exposure to educational practice. Chapters 5 and 6 will be discussing research examining the conceptions of motion. However, before considering any of the research into the understanding of speed and speed change, it is crucial to establish some of the laws that govern these concepts, thus highlighting their actual complexity, as opposed to the comparatively simplistic Aristotelian views. This intermissive chapter presents these laws.

4.1 A definition of terms

Although from a scientific view the term 'velocity' should be used rather than 'speed', it is one that is not often recognised correctly by students – a study by Jones (1983), for instance, found that out of 30 students aged 11 to 16 years only one was able to define velocity correctly. However, this issue does not pose a real threat for the current work. Despite velocity being central to formal analyses of motion, velocity is merely speed in a given direction. Speed is a concept that is both meaningful to children as well as linkable to science (Howe, 1998), so velocity and speed are conceptually close enough for this error in definition to be put aside for current purposes. Similarly, although 'mass' would be the correct term to use rather than 'weight', as weight is the result of a mass-gravity interaction, much of the literature focuses on children's use of what is referred to as weight. Although in this chapter the term 'mass' will have to be used, as it appears separate from gravity in equations, the literature reviewed later on will be found to refer to object weight. Newtonian mechanics state that speed, time, and distance interact by specific multiplication and division rules. An object's uniform speed v is determined by the distance d covered within a given time t, that is, $v = d\,/\,t$.

How different factors may affect speed in different dimensions will be covered next, as well as an important element that separates Aristotelian from Newtonian physics – speed change. Speed change is an important factor to consider in object motion. While Aristotle (trans. 2008) claimed that objects do not change speed during travel, we now know this is not the case. Instead, objects accelerate and decelerate when in natural motion, unless terminal velocity is reached in free fall after some time (i.e. where air resistance can no longer be overcome), surface friction can no longer be overcome in supported motion, or a barrier is reached. The laws of Newtonian mechanics state that acceleration, speed, and time interact by specific multiplication or division rules as well.

Figure 4.1 below shows a diagrammatic depiction of the forces acting on an object during propelled horizontal motion. The frictional force *f* exerted by the surface would cause the object to decelerate until it eventually comes to a halt. The deceleration (or negative acceleration *a*) is determined by the coefficient of friction x mass x gravity or μ *mg*. An object's uniform acceleration *a* is the rate at which it changes its speed, with *u* being its initial speed and *v* its final speed, within a given time *t*, that is, *a = (v − u) / t*. Additionally, Newton's second law states that the acceleration of an object can be determined by the interaction of the object's mass m with the net force *Fnet* acting on that object, that is, *Fnet = ma*. By rearranging this acceleration equation to *a = Fnet / m* and integrating the forces, the equation becomes *a = − μ mg / m*, or *a = − μ g*. In the case of sliding objects, the coefficient of friction depends on the materials of the object and the surface of contact. The typical value for the coefficient of rolling friction (i.e. friction where spheres are involved) is 0.001.
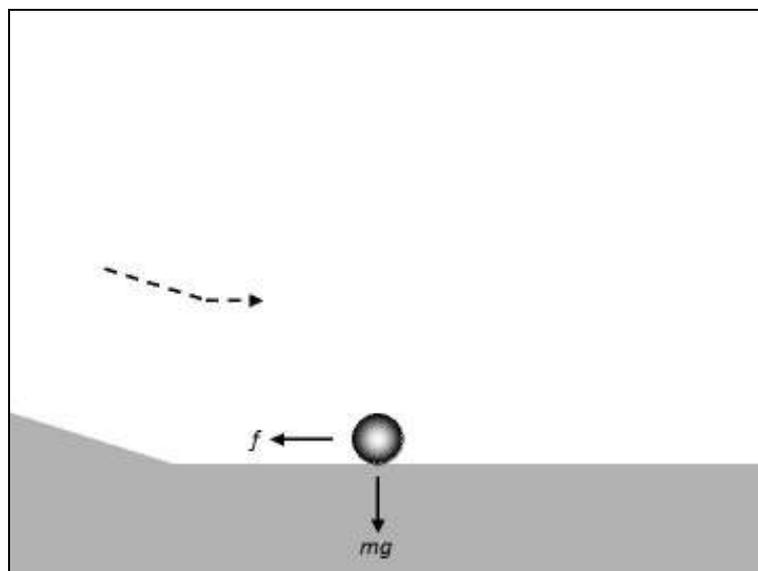
Figure 4.1   A diagrammatic depiction of the forces acting on a ball in horizontal motion

Figure 4.2 (p. 76) shows a diagrammatic depiction of the forces acting on an object in free fall. In free fall, an object falls along a linear path downwards at an acceleration determined by gravitational force only. This results in a constant acceleration of approximately 9.81 m/s^2. Therefore, object mass in fact becomes irrelevant when determining an object's speed and its acceleration. The equation $a = [(mg\ sin\theta) – (\mu\ mg\ cos\theta)] / m$ can be reduced to $a = [(g\ sin\theta) – (\mu\ g\ cos\theta)]$; sin 90° = 1, and since in free fall there is no friction, μ = 0, the equation thus being further reduced to $a = g$. However, it is important to note that the cases for motion down an incline and free fall only hold true in an ideal environment where there is no resistance due to air: in a vacuum. When a body is allowed to fall in real situations, its motion is influenced by two factors. Its weight, that is, the gravitational attraction which the earth exerts upon it, gives the body its tendency to fall, while the resistance due to the air, including the buoyancy, opposes this tendency and diminishes the rate of fall. This effect is more noticeable in the case of a feather or a leaf, because the ratio of the magnitude of the effect to that of the weight of the body is greater than it is for bodies of high density such as stones or pieces of metal. So in any real-life event where objects are in motion, there is an additional resistant force to take into consideration, and that is buoyancy, or displacement.
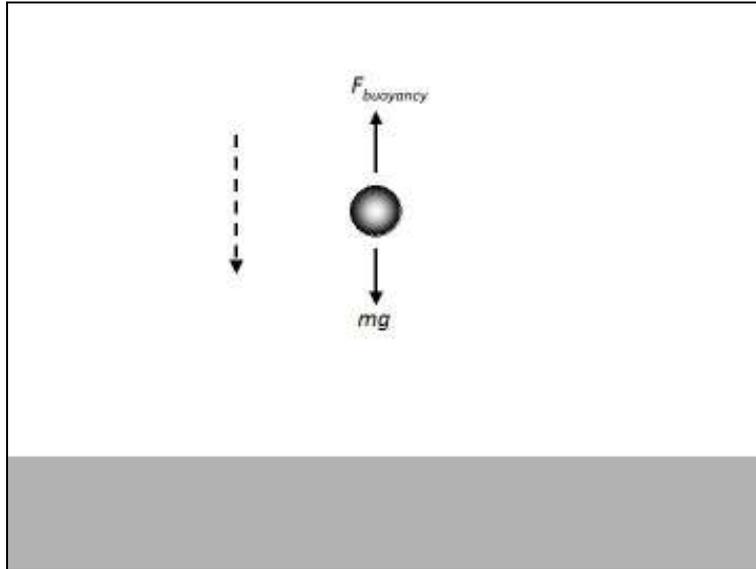
Figure 4.2　　　A diagrammatic depiction of the forces acting on a ball in free fall

The density of air depends on its temperature and the atmospheric height, but under normal atmospheric conditions, that is, at 1 atm, it varies only slightly from 1.164 kg/m^3 at 30 ˚C to 1.342 kg/m^3 at −10 ˚C. This pressure decreases with height. Any object with a non-zero height will see different pressures on its top and bottom, with the pressure on the bottom being higher. This difference in pressure causes the upward buoyancy force. Buoyancy is expressed by the formula $F_{buoyancy}$ = − ρVg, where ρ is the density of the gas, or air in this case, V is the volume of the object, and g is the standard gravity. This formula holds true for any shape. The buoyancy of an object therefore depends on two factors: the object's volume and the density of the surrounding gas. The greater the object's volume and surrounding density, the more buoyant force it experiences. The total force on an object in free fall is thus the net force of buoyancy and the object's weight, that is, F_{net} = mg − ρVg. The negative magnitude of the buoyancy implies that it is in the opposite direction to gravity. Applying this to acceleration in free fall extends the equation stated earlier to a = $(mg − ρVg) / m$.

4.1.3 Speed down inclines

Figure 4.3 (p. 77) shows a diagrammatic depiction of the forces acting on an object in motion down an incline. Releasing an object from the top of an incline with a given

angle of incline θ results in the object rolling or sliding down the incline, given that frictional forces can be overcome. Two relevant forces now act on the object: the parallel force $F_{||}$, which acts downwards and parallel to the incline (determined by mass x gravity x *sin*θ or *mg sin*θ), and the frictional force *f*, which acts upwards and parallel to the incline (determined by the coefficient of friction x mass x gravity x *cos*θ or μ *mg cos*θ). There are two other forces involved: the perpendicular force and the normal force, which act oppositely to each other. However, as an object only moves parallel to the slope, these two forces are balanced (Newton's third law) and therefore do not need to be considered. By rearranging the acceleration equation from above to *a = F_{net} / m* and integrating the forces gives *a = [(mg sinϑ) − (μ mg cosθ)] / m*. Again, with sliding objects, the coefficient of friction depends on the materials of the object and the slope, and the typical value for the coefficient of rolling friction is 0.001.
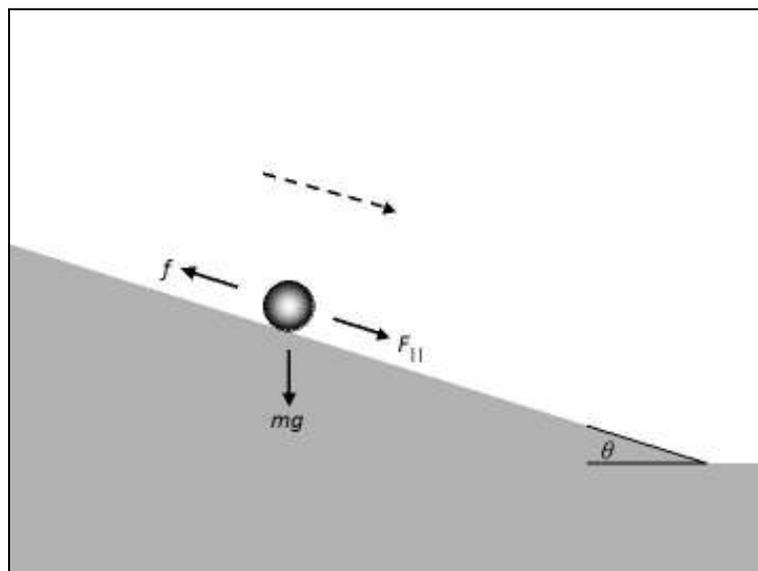
Figure 4.3   A diagrammatic depiction of the forces acting on a ball in motion down an incline

4.1.4 The effect of mass on motion

Relating to the everyday world it may appear that heavy objects do indeed fall faster than lighter objects. Yet, to illustrate, if dropping two balls of the same material and the same size, with a radius of 10 cm, but with different masses due to one being

hollowed out, resulting in a heavier ball of 10 kg and a lighter one of 5 kg, and taking air density to be about 1.2 kg/m^3, their accelerations would show to be 9.7996 m/s^2 for the 10 kg ball and 9.7992 m/s^2 for the 5 kg ball. This minimal difference in a rate of change cannot possibly be perceived with the naked eye. Yet according to Aristotelian physics, the 10 kg ball should fall twice as fast as the 5 kg ball, and neither of the two should accelerate but fall at a constant speed (Aristotle, trans. 2008). Conversely, a sheet of paper falls faster when crumpled up, even though there has been no increase in mass, only in volume. This shows that the proposition 'heavy objects fall faster than lighter objects' is erroneous. It may be a common belief in all meaningful respects, yet it is inconsistent with the physics.

"Now the concepts of movement and speed especially touch upon […] general science teaching, in which it would be of great value to know precisely the way in which these concepts develop." (Piaget, 1970a, p. ix)

CHAPTER 5:

CHILDREN'S GENERAL UNDERSTANDING OF THE CONCEPT OF SPEED

One particular element of motion to consider is the underlying concept of speed, and its two constituent concepts time and distance. These are explicit concepts in relation to motion, and they underlie all formal analyses of motion. So is naïve Aristotelian physics perhaps the result of a distorted or limited understanding of the underlying concept speed and its interactions with time and distance? The literature reviewed in this chapter looks at children's understanding of speed in relation to time and distance, and will show that while such understanding may develop as children grow older, the general understanding emerging from a range of methodological approaches is good.

5.1 Piaget's work

As Driver and Easley (1978) point out, and quite rightly so, it is "inevitable that any survey of the literature on the development of children's concepts in science will reflect the large contribution which Jean Piaget has made in this field" (p. 63). This view has not changed, as Piaget's work exerts a heavy influence on research into

children's explicit understanding of speed and acceleration. In fact, the first major research into children's understanding of speed and the related concept of time stems from a discussion between the physicist Einstein and Piaget in 1928 (Lovell, 1961; Piaget, 1972). Einstein was interested to know in what order, if in any at all, young children acquire the concepts of time and of speed, since he defined speed and time in terms of each other, where neither concept is more basic than the other – as opposed to Newton, who defined speed in terms of time. Piaget, intrigued by Einstein's view, subsequently carried out research into these areas.

Piaget's (1970a) book on the child's conception of movement and speed differentiates between three kinds of research – assessment of children's understanding of *qualitative* speed, assessment of their understanding of *relative* speed, and assessment of their understanding of *quantitative* speed. Qualitative speed refers to a basic intuition of 'rapidity' and operations where speed is simply based on the order of objects. Relative speed, on the other hand, is a coordination of two speeds into a single apparent speed. In quantitative speed tasks, relations between speed, time and distance have to be understood, whether just in proportional terms or in more specific metrical forms. Examples from Piaget's (1970a) work for all three kinds of assessments are described next.

5.1.1 Qualitative speed

Looking at qualitative speed, Piaget (1970a) showed children two tunnels, one being longer than the other. Two dolls entered the tunnels at the same time and emerged from them at the same time. Correct judgements of their respective speeds – whether one doll went through its tunnel faster than the other – were taken to mean that the child had mastered the concepts of time, distance, and speed. Piaget (1970a) identified three stages of development here. In Stage I, the younger children, aged 5 to 6 years, entirely failed to solve the task correctly and instead claimed that the dolls travelled at the same speed. When the tunnels were removed and the motions of the dolls repeated in full view of the children, they would state that the doll travelling the longer distance did so at a faster pace, yet when the

tunnels were put back, they again believed that they travelled at the same speed. In Stage II, at around 6 years, children initially affirmed that the speeds were the same, but following the removal and replacement of the tunnels they would appreciate the qualitative differences in speed. Finally, in Stage III, at around 7 to 8 years, children were readily able to solve the task correctly. Similar results were found when using two lines of travel that were not parallel to each other.

5.1.2 Relative speed

Further, Piaget (1970a) assessed children's understanding of relative speed. This was done by having toy cyclists rotate on an endless belt, past a doll, at such a speed that in 15 seconds 8 cyclists passed the doll. The children were asked to predict how many cyclists would pass the doll if the doll were to move in the same direction as the cyclists, having established that the doll does not travel quite as fast as the cyclists. Here, Piaget (1970a) noted four stages. In Stage I, no relativity of speed was present, and an additional task involving a simple passing situation, which was introduced to ensure a basic understanding of the scenario, could not be solved correctly either. In this additional task, one cyclist would start and the children were asked whether the doll would take more or less time to reach the cyclist if it stood still, if it travelled in the same direction as the cyclist, or if it travelled in the opposing direction. In Stage II, the additional task could be responded to, but the crucial aspect of relative speed remained without correct responses. The first two stages occurred between about 6 and 8 years of age. In Stage III, between 8 and 10 years, the child did not manage to solve the prediction task correctly, but once shown the doll and cyclists' motion, they were able to obtain the correct answer. Finally, in Stage IV, from around 11 years of age, the children were able to obtain the general solutions through formal operations – where the relations between individual relevant concepts are coordinated correctly and logically (e.g. speed, time, and distance), both with actual observed events as well as with hypothetical propositions – and predict the outcome prior to seeing the event.

5.1.3 Quantitative speed

Additionally, children were also given quantitative speed tasks. Essentially, the task was similar to the qualitative speed task, but with the implementation of specific times and distances – where unequal distances were travelled in unequal times (or rather, lines were drawn within given amounts of time) – to use in the inference of speed. This required a precise understanding of how speed is affected by the interaction of distance and time. As Piaget (1970a) had previously identified that young children rely on speed as an intuitive concept, only older children that, by age, fell into Stage III in the relative speed task were assessed, that is, from the age of 8 years onwards. Piaget (1970a) identified two substages per stage. In Stage IIIa, at 8 to 9 years, speeds could not be compared. In Stage IIIb, at 9 to 10 years, children could succeed on questions where one variable, time or distance, had to be equal. In Stage IVa, at 10 to 11 years, tasks could be solved, but merely on a trial-and-error basis, and in Stage IVb, from 12 years onward, the tasks were then solved systematically.

5.1.4 Summary

From his research, therefore, Piaget (1970a) was able to conclude that young children do indeed possess a general understanding of speed. First, according to Piaget (1970a), when the child is still in the preoperational stage, this understanding is of a primitive, intuitive nature, and it is based on perceived overtaking. When it comes to deducing speed from the relationship between distance and time, however, these children's judgements tended to be incorrect. Where concrete operations are applied, at around the age of 7 or 8 years, relative speed is understood as an interaction of time and distance, in the form of $v = d \, / \, t$. Where the interrelations become more complex, or where hypothetical reasoning is necessary, formal operations are required, and only older children tended to succeed at these tasks in Piaget's (1970a) work.

5.2 Piagetian replications

Several studies directly based on Piaget's speed (1970a) experiments have been carried out subsequently, and these are outlined here.

5.2.1 Délorme and Pinard (1970)

Délorme and Pinard (1970)[2], for instance, showed children aged 7, 9, 11 and 13 years two model escalators parallel to each other, similar to the cyclists in Piaget's (1970a) relative speed task. On one of these, ten toy children travelled upwards, always at a constant speed. On the other, a toy observer was watching the children pass him; he could move up and down, and his speed was variable. On some tasks the observer and the toy children would move in the same direction, on other tasks they would move in opposite directions. Additionally, sometimes the observer would be faster, sometimes slower, and sometimes at the same speed as the toy children. The participating children were tested on both task types. They were asked to count the number of toy children passing the observer within a certain amount of time, and they were then asked to predict whether the observer would be able to count a different number of toy children if he were to move himself, either up or down, at varying speeds.

Where the observer moved in the same direction as the toy children and at the same speed, only the 7-year-olds failed to predict correctly. The three older age groups were successful. Where the observer moved in the same direction but either faster or slower, only children in the oldest age group were able to predict correctly. Contrarily, if the observer moved in the opposite direction at any of the three relative speed levels, it was not until 11 and 13 year of age that more than 50 per cent managed to predict correct outcomes; the younger children generally failed (though they again performed slightly better on the first task where the speeds of

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[2] Délorme and Pinard published their research in 1970 based on Piaget's original French work from 1946, rather than on the English translation from 1970.

both the observer and the toy children were the same). Overall Délorme and Pinard (1970) concluded here that the developmental stages observed in their study were comparable to the stages constructed by Piaget (1970a), and that same-direction motion tasks are more easily solved than different-direction tasks. On the other hand, the authors suggest that the use of formal operations for this concept – predicting correctly and logically, and justifying predictions of hypothetical scenarios correctly – seemingly evolves slightly later than anticipated by Piaget.

5.2.2 Siegler and Richards (1979)

A further direct replication of Piaget's (1970a) tasks was carried out by Siegler and Richards (1979). They remarked that despite Piaget's claims that the concepts of speed, time, and distance are all mastered simultaneously (i.e. each concept can develop with neither of the other two necessarily having been mastered); he seemingly had never tested the same children on all three concepts. Further, the tasks testing the three concepts were not entirely comparable because of different materials being used, and different questions being asked. Hence, Siegler and Richards (1979) revised the methodologies by creating a single task that could assess all three concepts at the same time. Like in one of Piaget's (1970a) studies, children saw two parallel train tracks with a locomotive on each of them. However, the trains could start from the same or different points at same or different times, could stop at the same or different points at different times, could travel the same or different distances or for the same or different times, and could travel at the same or different speeds. In Siegler and Richards' (1979) work, at least one variable was always manipulated. This was followed by questions about how long each train took, how fast each train went, and how far each train travelled. After testing a range of ages – 5, 8, 11 and 20 years – Siegler and Richards (1979) found that the younger children based their judgements of time, distance, and speed solely on the spatial stopping points of each train, whereas the oldest age group displayed full understanding of all three concepts. The 8- and 11-year-olds displayed a mix; their responses showed they fully understood speed and distance, but not time.

5.2.3 Acredolo and Schmid (1981)

As an extension of Siegler and Richards (1979), Acredolo and Schmid (1981) showed 7- to 12-year-old children two toy trains moving down parallel tracks, and the children were then required to judge the relative speeds, distances, and durations of travel. However, as opposed to Siegler and Richards (1979), at least one of speed, distance, and duration was equal, and sometimes all three were, for "if children truly understand a concept, they ought to be able to judge equalities as well as inequalities" (Acredolo & Schmid, 1981, p. 491). From their findings, Acredolo and Schmid (1981) concluded that mastery of speed precedes mastery of distance, which in turn precedes mastery of duration. Thus all three concepts mature at distinctly different ages. The findings by both Siegler and Richards (1979) and Acredolo and Schmid (1981) may appear to contradict Piaget's (1970a) hypothesis that all three concepts are mastered simultaneously, and the findings do suggest that time is appreciated at a later stage. Yet at the same time they are consistent with a further notion that *intuitive* speed in young children is not strictly related to time constructs, and that the concept of time is appreciated at a later point in childhood (Piaget, 1970b). This too may appear to be in conflict with the statement that speed, time and distance are mastered simultaneously. However, as opposed to the concept of speed, which is seen as the relationship between a spatial and a temporal interval, that is, between distance and time, intuitive speed does not necessarily require an understanding of the notion of time (Piaget, 1970b). This has been illustrated by Piaget's (1970a) aforementioned speed studies.

5.2.4 Levin (1977, 1979)

The relation between speed and time was also a topic of research for Levin (1977, 1979). According to Piaget (1969, 1970a), the intuitive conceptualisation of time is characterised by its confusion with space and speed. In the time-space confusion, farther travel is associated with more time, despite any differences in speed; similar findings have been observed by Levin (1977). The time-speed confusion has two substages to it. A child first believes that more speed covers more distance and

because more distance requires more time to be covered, it is concluded that more speed must require more time, no matter how far is being travelled. The child then associates slower movement with more effort or activity, which in turn is associated with taking more time, and therefore the child concludes that less speed requires more time, regardless of distance travelled. This erroneous conclusion seems to stem from the inability to construct duration when coordinating distance and speed, and the child may ignore distance, thus concluding that the body moving at a slower pace requires more time (Levin, 1979).

However, it seems that the second notion has not received full support. Levin (1977), for example, found that children between 5 and 9 years of age rarely associated slower speed with longer durations. Levin (1979) focussed on three concepts that may help to explain time-speed and time-space confusions: Firstly, there is a general difficulty in clearly distinguishing between dimensions; secondly, some dimensions are possibly more salient than others; and thirdly, there is a tendency to concentrate on differences rather than similarities (also see Levin, 1977; Levin, Israeli, & Darom, 1978) – "the confusion of time and speed is only one of children's many confusions stemming from their difficulty in distinguishing between dimensions" (Levin, 1979, p. 470). In her study, Levin (1979) presented children with two figures on axes, which rotated at either 16 or 78 rotations per minute, for either four or seven seconds. The children's ability to compare durations correctly was found to be interfered with by speed. It is assumed that when children are asked to choose the event that takes longer they use a two-step process to make their decisions: First, they spontaneously compare the two events on all salient dimensions, of which time is only one, and decide which of the events is 'more' on each dimension separately. Then, they combine these conclusions to determine which one is 'more' in an overall sense. Where there is conflict (i.e. when both events have 'more' dimensions) this conflict is resolved by compensation, leading to a same-time judgement, or deciding which 'more' is weightier.

5.2.5 Montangero (1979)

In a further study by Montangero (1979) 5- to 8-year-olds were shown two toy houses, which represented two towns, and two toy cars. The experimenter told the children that one of the cars would take an entire day to travel between the two houses, and that the other car would only take half a day. The children then had to state which car they thought would take more time to get from one house to another, whether the car that took an entire day travelled at the same speed as the other car, and whether the distance travelled was the same for both cars. Here, as opposed to Piaget (1970a) or Siegler and Richards (1979) one given dimension was constant, one given dimension was different, and the third dimension had to be inferred based on the two givens. From his results, Montangero (1979) concluded that at 5 to 6 years of age children understand that the car taking less time travels at a greater speed, but they no longer take this constancy into consideration when asked about the third dimension – a car would have travelled further because it took more time, suggesting that time is a more salient variable than distance. By 7 to 8 years of age they take all three dimensions into consideration. However, when asked to infer how distance affects speed, children make a detour that allows them to start with the variable speed and they first relate speed with time, then time with distance, and eventually they relate distance with speed, which can lead to erroneous judgements of this final relation.

5.2.6 Summary

It would appear, thus, that the range of Piagetian replications have, on the whole, been able to confirm the findings put forward by Piaget (1970a). Additional support also comes from research on the universality of Piaget's (1970a) findings across cultures. This research has generally been able to confirm the number and the sequence of the stages found by Piaget as well, for example in east African children (Bovet & Othenin-Girard, 1975), in Middle Eastern children (Al-Fakhri, 1977; Za'rour & Khuri, 1977), and in Swazi children (Bentley, 1986), though these children usually appeared to reach stages at later ages than their Western counterparts. Children's

understanding of speed develops in stages, where initially speed is merely conceived in an intuitive manner, followed by an understanding of particular relations in the form of *velocity = distance / time* ($v = d / t$), which finally is then understood in its entirety – though only Siegler and Richards (1979) and Acredolo and Schmid (1981) assessed children who, according to Piaget, would have already reached the stage of formal operations. However, inconsistencies remain in the findings. Studies have either found that speed, distance and time do not develop simultaneously, or that speed-time associations do not occur in the way proposed by Piaget. As a result of these inconsistencies, but also for other reasons, alternative approaches have been taken.

5.3 Non-Piagetian approaches

5.3.1 Choice versus non-choice tasks

The experimental paradigms used in research on the integration of distance, time, and speed have typically fallen into two categories. On the one hand we have the choice paradigm as used by Piaget and those who replicated his work. Children are presented with two moving objects and they need to choose the object that went faster, farther or longer – whatever the requirement of the task may be. Then there is the non-choice paradigm, where children are presented with a single object and they have to predict the behaviour of that object in relation to two given dimensions. For example, they may have to induce the speed of an object from given information about time and distance travelled. While there has been a wide range of tasks following Piaget's (1970a) initiative, largely confirming his findings, there are nonetheless particular problems with the classic choice-task used, as identified by Wilkening (1981, 1982).

Firstly, in order for children to succeed on such a task, they need to consider several different pieces of information at the same time. This amount of input may be too much for the child's short-term memory processing capacity and therefore relation knowledge may not be displayed correctly. Secondly, the choice task does not assess

children's understanding of the relationship among dimensions, that is, $v = d / t$: The easiest way to solve choice tasks, according to Wilkening (1981, 1982) is by ignoring time and distance and focussing on speed alone. "The choice-task paradigm […] is, in principle, not capable of investigating quantitative, functional relations as they are involved in the physical laws. Knowledge of these laws, however, is the issue of interest – even in a Piagetian framework" (Wilkening, 1982, p. 92) – findings on non-metric relations cannot be generalised to knowledge of continuous, quantitative relations (cf. Wilkening & Anderson, 1982). Support for this notion also comes from studies where, when non-choice prediction tasks were used rather than choice presentations, children exhibited a greater success with problem solving and were less likely to focus on single dimensions (e.g. Levin, Wilkening, & Dembo, 1984; Wilkening, Levin, & Druyan, 1987). So taking the aforementioned study by Montangero (1979) as an example, does the child know that the speed of the car that takes only half a day to travel is twice as much as that of the car that takes an entire day[3], and is there any means of predicting exact values of speed from time and distance information, in this task or in any Piagetian task as such?

5.3.2 Wilkening's work

Based on these criticisms, a move away from Piagetian methods was made by Wilkening (1981) through applying the so-called functional measurement methodology, which constitutes a part of information integration (cf. Anderson, 1981). Wilkening's (1981) first task tested the integration of time and speed information when judging distance. The participants were shown toy models of three animals – a cat, a tortoise and a guinea pig – running away from a toy dog barking for different amounts of time. One of the three toy animals was placed at certain distances, the dog then barked, and the participants were asked to estimate how far the other two animals would run in the same time in relation to the one animal that had already been placed at a location. The choice of animals reflected a general

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[3] Asking a child at a young age about the precise mathematical relations between two speeds would not be likely to achieve any results.

perception of how fast they can typically move in relation to each other; tortoises are generally known to be very slow, a guinea pig can move significantly faster than a tortoise, and a cat in turn significantly faster than a guinea pig. Although this only works under the ideal presumption that children are familiar with all three animals and their motion patterns – while adults *may* have reasonable relevant experience, this should not be taken for granted in young children and may have some effect on the results.

The results show that 5-year-olds, 10-year-olds and adults all have similar patterns of judgement: A diverging fan pattern, which implies that the correct multiplication rule $d = vt$ had been used to integrate the information. Where algebraic multiplication or division rules have to be applied to infer a third variable, and, for example, three distances are given as well as three speeds (which gives nine combinations of distance-speed), the distance-speed interactions, when plotted on a graph with time plotted against distance, will show an arrangement in form of a diverging fan, that is, the difference in time becomes greater for each increase in speed per particular distance.

In the second task, participants were required to integrate distance and speed information in the judgement of time. The animals were placed at particular distances, and the participants were asked to judge how long the dog would bark so that the animals could reach those distances. The results suggest that the 10-year-olds and the adults had used the division rule $t = d\,/\,v$. The 5-year-olds, on the other hand, seemingly applied a simple subtraction rule $t = d - v.$ As opposed to a diverging fan pattern, the results now merely displayed lines running parallel to each other. The final task looked at how distance and time information are integrated in the judgement of speed. The dog barked for a certain amount of time, distances were marked, and the participants had to judge which of seven animals would correspond to that speed. The results show none of the three age groups followed the division rule. Ten-year-olds and adults used the subtraction rule $v = d - t$. However, for the 5-year-olds it appears they only relied on speed in direct relation to distance without considering time as an additional variable. Overall, a factor of importance may have

been information retrieval from short-term memory, and the three tasks differed in the demands on short-term memory, thus young children may have had more difficulty in assessment.

In a second experiment by Wilkening (1981), only 5-year-olds and adults were tested, and only two tasks were carried out. In the first task, a dog barked, and only then were the animals moved. This was to prevent the use of direct eye movement as a strategy, as respondents were now required to imagine simultaneous movements of all three animals. In the other task, the dog barked, and a bubble with the words 'bow wow' appeared from its mouth and became longer. This allowed length of barking time to be compared directly with distance travelled. The results of the second task did not differ from those of the third task in Experiment 1. Even though a visual time aid was given, adults did not improve in their judgements. The first task, however, showed that the 5-year-olds, as opposed to the adults, were no longer able to make appropriate use of the rule $d = vt$, contrasting the results of the first task in the first experiment. Wilkening (1981) suggests this means that when removing eye movement strategy possibilities young children can no longer integrate the given information in an accurate manner, and instead they have to rely on subjective judgement – though information integration does still occur, albeit incorrectly.

Wilkening (1981) draws two main conclusions from his work. Firstly, processing visual representations of time may be as difficult for young children as retrieving time information from their memory, whereas speed and distance representations become much more concrete. Secondly, young children often appear to take speed to be an inherent variable, something that is a fixed property of an object or a living being. It almost seems strange to children that there is a factor, that is, time, that can influence speed. Hence the difficulty in understanding that time affects speed may explain their reliance on distance alone when judging speeds. It is important to note, though, that it cannot be concluded from this that young children have an explicit understanding of dimensional interrelations in the sense that they know all of their implications. Rather, it can be assumed that they know procedures that can

be used to relate dimensions in such ways that physical laws are not violated. Support for Wilkening's (1981) findings comes from a connectionist simulation by Buckingham and Schultz (2000) – though only a simulation, therefore not being able to be seen as evidence for the use of integration rules (cf. Wilkening & Huber, 2002), the findings are nonetheless convincing.

5.3.3 Critiques of the non-choice paradigm

However, it would seem that Wilkening's (1981) results are perhaps not as straightforward as they might be perceived to be. Using apparently simpler procedures, poorer performances can be observed, suggesting that there is something inappropriate about Wilkening's (1981) methodology in turn. Cross and Mehegan (1988), for instance, supplied children between the ages of 4 and 9 years with information about the differential speeds of two cars over given times. Using this information, primary school aged children needed to choose those routes that each car would have to follow for both to reach a particular goal at the same time. This procedure was simpler in that two cars were used whereas Wilkening's (1981) tests involved at least three animals. Moreover, when distance or time was given, it was the same for each car; all Wilkening's (1981) given variables, on the other hand, differed. Yet Cross and Mehegan (1988) – tentatively – conclude from their findings that children treat the three variables speed, time and distance as three separate variables rather than being able to consider the appropriate relationship among them.

Nonetheless it appears, from the research by Wilkening (1981), that direct relations *are* recognised before inverse relations. In direct relations, increasing one variable results in an increase of the other variable. For instance, an increase in distance when keeping speed constant results in an increase in time taken to travel the distance. In inverse relations, on the other hand, increasing one variable results in a decrease of the other variable. For instance, an increase in speed when keeping distance constant results in a decrease in time taken to travel the distance.

Wilkening's (1981) observation interestingly enough concurs with Piaget's (1969, 1970b) ideas.

However, while Wilkening (1981) criticised the Piagetian approach, Acredolo, Adams and Schmid (1984) in turn criticise Wilkening's (1981) methodology. In Wilkening's (1981) study only one animal ran at a time, thus children could never directly compare two animals' speeds and thus could not determine whether a guinea pig running over a long duration or a cat running over a short duration would run farther. They also looked at whether judgements are more preferably based on certain relations over others – in conservation of liquid tasks, for example, nonconserving children tend to rely on water level rather than glass width, even though both are crucial variables.

In Acredolo et al.'s (1984) experimental setting, elementary school children aged 6 to 11 years were shown a toy rabbit and a toy skunk that would both run away when an angry toy dog was barking. It was explained to the children that sometimes the rabbit and the skunk would run at the same speed, and sometimes one would run faster. Also, even though they started at the same time, sometimes one would run for longer. And even though they started from the same point, sometimes one would run farther. The children were assessed in three conditions, one for each of time, distance, and speed. The first problem in each condition was used primarily as a pre-test and buffer for the harder problems to follow – in the distance condition, for example, the two animals would run at the same speed for the same amount of time, and the children had to decide whether they ran the same distance or if one of the two ran farther. If children seemed to have difficulty understanding this first problem, they were given further instructions before proceeding. The second and third problems provided information about the children's understanding of the relationships between specific pairs of dimensions – running at the same speed for different times, or for same times at different speeds, in the distance condition – while the last two problems had the potential for providing information about the children's capacity to integrate relations and recognise conflicts – one of the two running faster, and either of the two running longer. The findings seem to confirm

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that children recognise direct relationships before inverse relationships; at the younger ages tested, speed-distance and duration-distance tasks were solved correctly more often that speed-duration tasks, and it was only at around 9 years of age in this sample that all three relationships were understood equally well. However, there is no concurrence with, for example, Montangero's (1979) claim that children first understand each of the relations in one direction, then in the other.

A similar method of assessing the ability to integrate information related to speed stems from a study in the field of mathematics education. Howe, Nunes and Bryant (2010) looked at children's ability to make appropriate use of the relationships between speed, time and distance. They gave 963 children aged 7 to 12 years a range of questions; in six of these questions the children were required to figure out which of two (children, hamsters, cars) went faster, on the basis of information that was provided about time taken and distance travelled. The level of difficulty increased over the course of the questions asked. The first two questions were easy questions where one of the two given variables remained constant and insufficient information was provided to solve the tasks computationally. The third and fourth questions were easy questions where again one of the two given variables remained constant, but adequate information was provided to solve the tasks computationally, though the questions could also have been solved without computation. The final two questions were hard questions where both time and distance varied and computation was necessary to solve the questions. Here, too, the overall results suggest that the ability to solve questions correctly increased with age, with the exception of the final question, which observed an inverse trend. It is suggested that perhaps the younger children did not actually take both variables into account but relied on time alone. This would propose that time is more salient than distance, which is in concordance with the previously described work by Montangero (1979).

5.3.4 Summary

By using alternative methodologies, studies have thus shown that the general Piagetian pattern remains. With increasing age, the interrelations of speed, time, and

distance are understood more clearly and tasks are more likely to be solved correctly. Despite the issues emerging from Cross and Mehegan's (1988) work, it appears that even young children show a basic understanding of $v = d / t$, though Wilkening's (1981) results could be re-interpreted along the lines that understanding here, too, is more of an intuitive nature – if children understand that one animal can run faster purely because it physically overtakes the other, they will place the animal they think runs slower before the animal they think runs faster, without necessarily having to take time into account, since time was the same for all three animals. It appears, thus, that while these alternative approaches certainly seem justified in the light of the critique of the Piagetian methodology, a compromise might need to be found, in form of combining quantitative with qualitative tasks – giving children ratios to work with (e.g. one object moving twice as fast as another) and investigating in what way the final responses are, in fact, achieved, by asking them in a Piagetian fashion.

5.4 Summary

Overall, the general understanding of the concept of speed, and with it the related concepts of time and distance, are generally well understood, with accuracy of understanding improving with age. Regardless of the methodological approaches used, then, the research reviewed here suggests that while there are developmental trends children do have a reasonable understanding of the concept of speed, and how it functions in terms of the underlying elements time and distance. But these tasks are all fairly general, and they are based on approaches that are not really something that one would observe in the everyday world, such as animals racing against each other, and the use of toy cars acting as representations of real life scenarios. While these studies indicate the ability to work with the concepts speed, time and distance, the relevance to Aristotelian physics remains untouched here. So what is children's understanding of speed and acceleration where real objects are considered in their real environment, behaving the way children would actually see them behave, given that they clearly have some understanding of the underlying concepts involved? This will be reviewed in the following chapter.

CHAPTER 6:

RESEARCH ON THE UNDERSTANDING OF NATURALLY INDUCED OBJECT MOTION

One problem that arises in some tasks is the nature of the environment in which object motion takes place. Cahyadi and Butler's (2004) work, for example, highlights the problem of scientific versus everyday reasoning. Their research on understanding of motion in free fall suggests that undergraduate students are more able to solve cases of idealised motion correctly, that is, where no air resistance needs to be considered, than real-world problems, despite understanding the interplay between air resistance and object size. Students appreciated that a flat sheet of paper would fall more slowly than a crumpled one, or observed that a person with a parachute falls more slowly after the parachute opens – despite weight not changing.

The previous chapter on children's general understanding of speed and acceleration concluded with a query about how children would reason about object motion that they would be able to actually observe in everyday life, when no extraneous variables such as pushing, pulling, car engines, or other variables that would depend on a person's actions would have an effect. One particular aspect of Aristotelian

physics is that objects were thought to move at constant speeds, even though in fact their speed changes, at least until they reach terminal velocity in fall, or until they stop moving due to barriers or surface friction. So in order to appreciate the naturalness of object motion, that is, motion in the Newtonian sense, it is crucial to have some understanding of speed change. The research on children's understanding of such motion, both of object speed and of object acceleration, can be separated into three categories: Research on the understanding of motion along a horizontal, research on the understanding of motion in free fall, and research on the understanding of motion down an incline. First, however, one particular variable, to which particular reference is made in Aristotelian motion, is considered.

6.1 The importance of weight as a variable in object motion reasoning

It appears that weight in particular has some effect on children's and adults' predictions of and beliefs about object motion. While in the chapter on the physics of object speed and acceleration it was shown that weight per se is a negligible influence upon falling or rolling objects (instead, speed is affected by other factors such as surface area or material density), this is probably one of the most predominant pre-conceptions held, and corresponds to a typically Aristotelian view of the world. In fact, many students hold the belief that an object falls with a speed that is proportional to its weight (Halloun & Hestenes, 1985). It has been noted – in order to highlight the importance of weight within the issue of object speed and acceleration – that after space and time (both of which are, of course, essential factors when measuring speed and acceleration), weight is one of the most fundamental concepts and therefore largely affects general knowledge of physics (Galili, 2001).

Some older studies (e.g. Gibson, 1969; Piaget & Inhelder, 1974) provided claims that young children do not make any distinction between size and weight. Gibson (1969), for one, made this claim due to the fact that children's performance on size and weight seriation tasks was identical; in both cases items were simply seriated according to their size. Piaget and Inhelder (1974) found, quite similarly, that size

intruded on weight judgement tasks. Some children thought that popcorn would become heavier once popped, simply because it then got bigger. They would also predict that a wax ball and a clay ball would weigh the same if they were the same size. Indeed, one might conclude from this that young children do not differentiate between the two concepts. However, C. Smith, Carey and Wiser (1985) assessed 3- to 9-year-old children on a range of verbal and nonverbal tasks, finding that there was indeed a concept of size that was fully differentiated from a concept of weight.

Concepts related to weight, that is, 'heavy' and 'light' and concepts related to size, that is, 'big' and 'small', appear to be, in fact, appreciated and recognised from a fairly early age – haptic studies, for example, have shown that by the age of 12 months infants can already differentiate between light and heavy objects (e.g. Molina & Jouen, 2002), and violation-of-expectation tasks suggest that young infants understand, for example, when an object is too big to fit into a particular container (e.g. Aguiar & Baillargeon, 1998). Therefore it does not seem surprising that these concepts play such an important role in children's perception of the world and eventually give rise to some misconceptions.

6.2 Motion along a horizontal

Despite the research covered in the previous chapter largely being concerned with horizontal motion, none of it makes a specific case for that dimension. In fact, the research could have been carried out using the same tasks with inclines or in free fall. So what is children's understanding of horizontal motion in particular?

A chapter in Inhelder and Piaget (1958) describes a study where balls of different sizes and weights were launched by a spring device such that they rolled along a horizontal, and the children had to predict the stopping points. This study already, it seems, took for granted that young children understand that objects eventually stop, though it does not assess their understanding of what exactly happens during this process. Instead, the focus was on how object size and particularly weight affect the general process of slowing down. The children at Stage I sometimes claimed that

light balls would go further because they were easier to set in motion, but also that heavier balls would go further because they were deemed stronger. During Stage IIA there was some attempt to eliminate these weight contradictions, though some still remained. Generally, a heavy ball was associated with having more force, and a lighter ball was deemed easier to launch. Stage IIB saw children taking a reverse approach. Instead of explaining motion, they explained the slowing down. However, these children were not aware of their tendency to reverse, and their responses were still comparable to those at Stage IIA. At Stage IIIA the reversal tendency became explicit, and children predicted that large balls would go further because they were heavier. Also, friction and air resistance were introduced as influential factors. Finally, during Stage IIIB fundamental explanations resulted from explicit reversal. The children now predicted that the heavier balls would go further because they had more force, that is, weight was simply regarded as a synonym of force, though at the same time heavier balls also, for them, meant more friction.

Weight as a variable in horizontal motion has also been assessed in a study by Howe (1991, as cited in Howe, 1998). One hundred and twenty-six children aged 6 to 15 years were shown photographs and were required to respond to questions related to the scenarios seen in them. In one of the photographs a large green ball, which was identified as being made of solid plastic, was being rolled across paving stones. A tennis ball, a table tennis ball, a golf ball and a bowls wood were to be seen in the picture as well. The children were asked questions about whether the green ball was the best choice or whether another of the balls would have rolled faster, and they were required to give justifications for their views. Twenty-two variables were identified. A clear majority of children at every age level thought that the kind of ball would make a difference, and they were always able to give reasons. Out of the variables used by at least ten children, variables related to weight featured right at the top of the list, heaviness being associated with more speed by 47 of the children, and lightness by 39 of them. Other variables included size and bounciness. In another photograph the bowls wood was being pushed across an ice rink, and again the children were asked the same questions as with the green ball. Fifty-one children

thought the heavier ball would go fastest, and 21 children went for the lightest. Other variables used included smoothness and size.

Maloney (1988) provided undergraduate students with a series of problems where they had to predict either distance travelled or time taken to fall under different combinations of variables. Howe (1998) notes a particularly clear reliance on object weight and the claim made by undergraduates that heavy balls resist motion in the horizontal direction. This is particularly noteworthy because this is the reverse of what Howe's (1991, as cited in Howe, 1998) findings suggest – in her study, there was a strong tendency for those aged 12 years and over to assume that along a horizontal heavy objects travel faster than light ones, and that the assumption of heavy objects being resistant to horizontal motion was present in the younger children of her sample. Clearly, this is as yet an unresolved issue.

Twigger et al. (1994) assessed 10- to 15-year-olds' preconceptions of object deceleration, among other scenarios where force and motion were considered. In the relevant task, the participants were asked questions about the motion of a model carriage when it was given an initial push along a horizontal track. Two main reasons were given for its slowing down, often in conjunction with each other. The carriage either slowed down, according to the children, because it ran out of energy or force, or because of external opposing forces such as friction and air resistance. The second reason was, in fact, stated by almost all of the children. In a study by Howe, Taylor Tavares and Devine (2010a), children aged 6 to 10 years were shown a billiard table surface on a computer screen. On the billiard table, a white ball hit a red ball, upon which the action froze. A line then appeared leading from the red ball, indicating the path the red ball would have followed if the action had continued. Along this line, two points were marked, and the children were required to decide whether the speed of the red ball would be the same at both points, or whether it would be faster or slower at either of the points. The results imply that while the older children in this sample (and children older than 10 years of age, as indicated by Twigger et al., 1994) may have some grasp of speed change along horizontals,

younger children seemingly do not. Instead, the younger children rarely acknowledged that speeds would be different between the two points.

6.3 Motion in free fall

Objects do not only move in supported environments, that is, along horizontals or down inclines, but they also fall unsupported. Because this seems to be the most common form of naturally induced motion experienced in everyday life (as opposed to horizontal motion largely occurring because of animate motion), a fairly substantial literature has established itself over the years. The findings from theoretical prediction tasks suggest that the weight of an object is expected to have an impact on its fall. Sequeira and Leite (1992), for example, concluded from a pencil-and-paper task that more than half of the undergraduate students they questioned about object fall stated that heavier objects would take less time to reach the ground in free fall. In another study, by van Hise (1988), both children and adults were questioned on their beliefs of what would happen if a heavy and a light ball were released from a height. Van Hise found that young children aged 4 to 6 years believed that both a heavy and a light ball would reach the ground first when released from the same height, simply because they would be released at the same time. Between 6 and 7 years of age the belief was that the lighter ball will reach the ground first. Those aged 7 years and above held the belief that the heavier ball would touch the ground first due to its weight, therefore assigning more speed to the heavier object.

In a study by Gunstone and White (1981), students were shown two balls of the same size, one made of metal, the other of plastic. The question asked how the time it takes the metal ball to fall to the ground compares with the time it takes the plastic ball to fall the same distance. A quarter of students claimed the speeds would differ, based on weight and air resistance. The remaining three quarters predicted equal times, but their justifications were not very consistent. Those students who had predicted the metal ball falling faster were also more likely to claim that the metal ball did, in fact, fall faster when they observed the falling. The latter claim

finds support in a similar study by Baker, Murray and Hood (2009) with primary school aged children. After predicting what would happen if two canisters of different weights were dropped, 6- and 8-year-old children witnessed them fall and they were required to report what they saw. Children developed an association between speed differences and object weight, implying that heavy objects would fall faster, and they would further claim to have observed this following the action. Baker et al. (2009) concluded that not only were the older children more likely to have persistent incorrect ideas about the weight-speed interaction but also that their confirmation bias was stronger. This certainly suggests that children's ideas become well entrenched at a reasonably early age, and lends support to the idea that conceptual change in science should be tackled early (cf. Isaacs, 1930).

In a slightly more extensive study, Nachtigall (1982) assessed German fifth-grade students[4] in order to establish their knowledge of speed and acceleration in relation to gravity. In one question he asked the children whether a person, standing on the ground beneath a window from which balls were dropped, would see a lead ball or an aluminium ball reach the ground first, or whether the balls would reach the ground simultaneously, and the students had to justify their predictions. The vast majority (91 per cent) thought that the lead ball would reach the ground first, as it was heavier, thus predicting and justifying in an Aristotelian manner. A few students (three per cent) thought that the aluminium ball would reach the ground first, because – based on their experience of building paper aeroplanes – lighter objects *fly better* than heavier objects. The remainder (six per cent) predicted that both balls would reach the ground at the same time, but their justifications showed there was no clear understanding as to why this should be the case.

Nachtigall's (1982) work also involved assessing children's understanding of speed change in free fall. In the first of these tasks, the children were told that person A would drop a ball from the window of a third storey, the ball would fall past person B

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[4] Although ages are not provided in this paper, it is worth noting that German fifth-grade students are typically 10-11 years old.

standing at the window of the second storey, and past person C standing at the window of the first storey. The children had to then predict and justify whether the ball was moving at a faster speed when falling past B or past C, or whether the speed would be the same at both points. Fifty per cent of the students thought the ball would be faster whilst falling past C, because the ball needed some time to reach its proper speed. Some of these students also explained that the force of gravity was stronger closer to the ground. Forty-seven per cent believed there would be no change in speed, as the ball did not change its weight. The remaining three per cent thought the ball would be slower when falling past C, because by then it would need to slow down. These students later explained this on the basis of their observations of the landing of an Apollo-spacecraft they had seen on television.

A further question again involved person A dropping a ball from the third storey, and an identical ball from the second storey. Person B was watching both balls fall past the window of the first storey. Twelve per cent of the students displayed inconsistencies with the previous task: While they may have predicted, in the first task on speed change, that the ball would be faster at the first storey than at the second storey, that is, closer to the ground, because it still needed to speed up properly, they predicted in the second task on speed change that both balls would fall past the first storey at the same speed, thus reducing acceleration to a short and intensive effort. A further 12 per cent of students predicted the ball dropped from the second storey would be faster because it had travelled a shorter distance upon reaching the first storey, implying that the fastest object is the one that travels a shorter distance, *or* that takes less time – a one-dimensional reasoning approach.

A more recent study, with primary school children as well, was conducted by Chinn and Malhotra (2004). All 228 children answered three questions after handling two rocks; rock A being heavy and rock B being light. In the uninformed condition the children were given unrelated questions and they were not given information about the rocks in terms of weight differences – any reasoning on the basis of weight would thus have been a result of own inference. Children in the prediction condition had one question requiring them to predict whether rock A or rock B would hit the

ground first, or if they would hit the ground at the same time. The other two questions were unrelated. The precise-prediction children had the same first question and were then asked to make more precise predictions – if they thought one would be faster they had to indicate how much faster. The two rocks were then dropped simultaneously. Of the 150 children in the prediction and precise-prediction groups 65 per cent predicted that the heavy rock would hit the ground first, 15 per cent that the light rock would hit first, and 20 per cent predicted that the rocks would hit at the same time. Following the action, the children were given more questions. They first had to identify whether one rock had hit the ground first, or whether they had reached the ground at the same time. Seventy-two per cent of the students who had expected the rocks to hit at the same time reported observing the rocks hit at the same time. In contrast, fewer than half of the students who had expected either rock to hit first reported observing their choice of rock hit the ground first.

In a study by Champagne et al. (1980, as cited in McDermott, 1984) high school students were asked to make predictions about object fall and to then compare their predictions with observations of the actions that followed, that is, when the objects were dropped. There was a general correct acknowledgement of acceleration, that is, that speed increases with fall. Similarly, Gunstone and White (1981) investigated knowledge of speed and acceleration in relation to gravity in first-year undergraduate students. They were shown a physical situation, and asked to make a prediction about what happens if a certain action is taken. This action was then demonstrated, and the students were asked to observe and explain discrepancies with their predictions. In the task, a blackboard eraser was resting on a book, which in turn was held at a distance above a surface. The students were asked why the eraser was not moving. The book was then quickly removed, causing the eraser to fall, and the students were required to explain what had caused the eraser's motion. The majority of the students gave satisfactory responses and explanations. The eraser was then held two metres above a surface. The students were required to predict and explain how speed halfway down would compare with speed at the bottom, just before reaching the floor. The eraser was then dropped. Gunstone and

White (1981) found that though the majority of students again predicted correctly, they claimed to have observed that the eraser had been faster further down – they insisted, after the eraser had been dropped, that they were able to *see* the eraser accelerating, albeit the eraser having only fallen for such a short distance. Only about a third of the students noted the difficulty of observing accurately in this setting. Again, a fairly strong confirmation bias can be noted.

6.4 Motion down an incline

In addition to assessing children's understanding of horizontal motion, Inhelder and Piaget (1958) presented children of a range of ages with a task relating speed down an incline with object weight. Children saw a plane that could be adjusted in its height, thus varying the angle of incline. Several balls of different sizes and weights were rolled down until they hit a springboard, and the children were required to establish the relationship between the height of the incline and the length of the bounds. From their results, Inhelder and Piaget (1958) were able to establish a three-stage developmental model. During Stage I, up to about 7 years of age, the child responded intuitively, based on personal experiences. A correspondence between the angle of incline and the length of bound was perceived, but height and angle were not distinguished. Weight was constantly assigned a role, though not always in a consistent manner. Individual children sometimes stated that the bigger balls would bound further because they were heavier, and sometimes they stated that the smaller balls would bound further because they were lighter (or even, occasionally, because the smaller balls were deemed heavier). During Stage II, from 7 to 11 years of age, children were able to make correct formulations of correspondences, though not systematically. They often managed to exclude weight, and there was some dissociation of height. During Stage IIIA, responses were made more readily than during Stage II, with the children eventually hypothesising that height was relevant, and during the final Stage IIIB, the hypothesis was actually proposed and verified.

Though the focus of their research was that of group interaction, Howe, Tolmie and Rodgers (1992) nonetheless provide relevant information about children's prior conceptions when it comes to weight as a factor in object motion down an incline. Eight- to 12-year-old children were tested on their preconceptions about motion down an incline in relation to angle of incline, height of starting position, surface friction and weight. The children were then grouped according to their pre-conceptions and assessed on their group work. They were shown slopes and toy cars. In the pre-test they were asked questions about the motion, in the group task they were required to predict and carry out experiments themselves with the same apparatus. Looking at the pre-test, which for present purposes is more interesting, Howe, Tolmie and Rodgers (1992) identified three levels of understanding from their results. At Level I, variables, such as the angle of the slope, friction, or the object's weight, were either not considered at all, or were considered but not understood correctly. At Level II, there was some understanding of how the slope variables operate and interact, for example that increasing the angle of the slope increases the distance travelled. However, whilst object weight was deemed important, too, it was not coordinated with other variables. At Level III, in addition to understanding how the slope variables operate and interact, the object's weight was deemed important and was coordinated with other variables as well. Only a very small number of children explicitly excluded object weight from having any effect on motion. Though there appeared to be some increase in level per age group, this increase was not significant.

What is important to note is that almost all children in this study by Howe, Tolmie and Rodgers (1992, see follow-up analysis cited in Howe, 1998) not only thought that object weight *was* relevant to motion down an incline but they were highly consistent in how they thought this would operate. They said either that the heavy objects would travel faster or that the light objects would travel faster on at least seven of the eight occasions on which they had been questioned. A third of the 8- to 9-year-olds felt heavy objects would travel faster. For the 9- to 10-year-olds the number of children choosing heaviness was less than a third, and for the 10- to 11-

year-olds just under one quarter. For the 11- to 12-year-olds, on the other hand, two thirds of the children chose heaviness over lightness.

In addition to assessing understanding of speed, as shown in the chapter on children's general understanding of speed, as discussed in Chapter 5, Piaget (1970a) also identified four stages in the development of children's understanding of acceleration. He did this by showing children a slope with a ball and asking them about the speed of the ball if it were to roll down that slope – whether the speed would always be the same, whether it would be more to start with or whether it would be more towards the end of the slope – and by flagging intervals along the slope, either based on same distances between the flags or on same temporal intervals, and asking about the speeds at each interval. Initially, acceleration appears, from Piaget's (1970a) results, to be perceived as a short and intensive effort where the object quickly changes speed at the beginning, but not as a constantly changing variable (Stage I) – this observation is similar to that made by Nachtigall (1982) of children's understanding of acceleration in fall. At around 6 years of age, the child already possesses an intuitive conception of acceleration – an object's speed is perceived to be less when it starts rolling down a ramp and more when it reaches the end of the ramp. However, acceleration is still not understood as a *continuous* or *regular* change in speed over time. When creating shorter intervals, each interval's speed is intuitively seen as faster than the previous interval, but there seems to be no suggestion that this is due to an understanding of the necessary relationship between speed and time (Stage II). Between 7 and 8 years, acceleration down the ramp is perceived as more continuous, but children still have difficulties in relating a series of successive speeds in terms of times and distances travelled (Stage IIIa). At 9 to 10 years, children develop the ability to translate successive movements in a limited way, and to compare distances or times travelled between intervals – they understand distances are travelled in shorter times because speed increases (Stage IIIb). Finally, by 11 years children can compare distance-time relationships over a series of successive changes in speed; acceleration requires separating speed into its distance-time relationships and at the same time making comparisons of successive speeds, and they are now able to do so (Stage IV).

In order to assess these stages further, Raven (1972) administered a range of acceleration tasks to elementary school children aged 8 to 11 years, where all children performed all tasks. The first task required the children to judge whether or not there was a change in speed when a toy car travelled down an incline. The second and third task showed an incline that had been sectioned into four even distances, and speeds for these sections had to be compared. For the final task the children had to count while a toy car rolled down an incline, at certain intervals a point along the incline was marked, and they had then to compare these intervals in terms of length and speeds. The results show a developmental change in giving correct responses – albeit across the comparatively small age range. A higher proportion of children solved each task correctly as age increased, although it was only at 11 years that all four tasks were solved at a consistently high level. At 11 years, the lowest percentage of correct responses was 67 per cent, compared with 40 per cent of correct responses at 10 years of age. Overcoming the critique that Piaget (1970a) seemingly never tested the same children on multiple tasks, Raven's (1972) results nonetheless concur with Stages IIIa to IV identified above.

The complexity of the term acceleration, however, becomes obvious when finding that there is no clear distinction between speed and acceleration, and acceleration is simply seen as 'speeding up'. Solving the Piagetian acceleration task in research by Trowbridge and McDermott (1980) merely relied on undergraduate students' *qualitative* predictions of the relationship between distance travelled and elapsed time for a ball rolling down an incline, that is, that distance travelled simply becomes less with time. Successful completion did not require consideration of any ratios; a primitive intuition of speeding up appeared to be adequate. The task posed no overall problem for any of the students. Trowbridge and McDermott (1981) therefore modified this task into a semi quantitative extension. A ball rolled from rest down an incline, and the motion over a particular distance was timed. The participants were then asked to predict approximately how much time the ball would require in order to cover twice the distance from the starting point. Most students were able to complete the task successfully. In a further task, a ball

travelled at a constant speed, that is, with no acceleration. A second ball started at a later time from a point behind the first ball, at an initially higher speed and then decelerated. Students were asked to judge whether these two balls ever had the same acceleration. A successful comparison did not require any quantitative understanding of acceleration, yet only students who recognised that acceleration implies a change in speed over time were able to complete the task correctly; correct completion of such a task therefore implies that the relationship between speed and acceleration is understood. However, there was not necessarily an understanding of the involvement of time.

This led to the development of a third task. In two channels, two balls travelled from rest until, at the end of the incline, the same speed had been reached. The balls were not released from the same point or at the same time, and did not travel equal distances but reached their respective endpoints simultaneously. They did have the same average and the same final speed, but one ball reached that final speed faster than the other, therefore having a greater acceleration. The students were then asked if these balls had the same or different accelerations. To obtain the correct answer, it was essential to recognise either that since the first ball is already moving when the other is released, the change in speed for that second ball must be greater in order for them to reach their endpoints simultaneously, or that they reach the same final speed in different amounts of time, therefore the second ball requires less time to change speed. Although this was a qualitative task, explicit consideration of change in speed and change in time to determine acceleration was required. From the results of these tasks, ten different approaches to compare accelerations were identified; one being a non-kinematical approach, one being a confusion between position and acceleration, four involving confusion between speed and acceleration – these first six all lead to wrong answers –, two showing a discrimination between speed and acceleration but neglecting any impact of time, and two showing the correct qualitative understanding of acceleration. There is a shift from perceptual (first six approaches) to conceptual (final four approaches) component usage. Overall, performance was poor; even in the group of introductory physics students

only about 40 per cent showed some understanding of acceleration and used one of the last four approaches, even though they were aware of the theoretical concept.

6.5 Assessment of tacit knowledge of object motion

6.5.1 Infancy studies

As mentioned earlier in Chapter 3 on the explicit-tacit distinction, a wealth of research has shown that young infants display a rich yet tacit understanding of the physical world. And as is the case for many areas in developmental cognition, the study of speed and acceleration, too, has turned to infancy. This area of research is still limited but the few studies that exist are nonetheless crucial for current purposes.

Kim and Spelke (1992), for instance, habituated 5- and 7-month-old infants to one of two possible events, a ball either accelerating down an incline or decelerating up an incline. In the test phase the infants were then shown two novel events where the direction of the incline had been changed; one of the novel events was possible, the other impossible. Those infants who had been habituated to the acceleration scene were tested with the ball moving up the incline, accelerating in the impossible trial and decelerating in the possible trial. Those who had seen the decelerating ball during habituation then saw the ball moving down the incline during testing, accelerating in the possible event and decelerating in the impossible event. Additionally, sometimes the direction of motion changed as well. The main result was that the 5-month-olds looked longer at those novel test trials where both acceleration or deceleration *and* direction changed than when only one changed. However, the possibility of the scenario did not affect their behaviour. This would appear to imply that the impossible test event did not violate any expectations, and infants instead reacted on the basis of the amount of perceptual deviance from the familiar habituation event. The 7-month-olds, on the other hand, looked longer at the impossible event, even though less perceptual changes had taken place. Kim and

Spelke (1992) conclude from this that the sensitivity to changes in speed in relation to gravitational constraints develops early but gradually.

A similar study by Kannass et al. (1999) assessed 10- and 16-month-old infants' perceptions of events involving a computer-generated ball rolling up or down an incline. The first experiment, showing the infants either a ball accelerating up or down, or decelerating up or down the incline, revealed that there appear to be no a priori expectations within these age groups about how objects should behave when in motion; all four events were regarded with similar interest. However, this similarity in interest need not be a response to the possibility or the impossibility of events, but may merely be a learning reaction – especially considering infants were given only six trials – where all events were treated as novel. In a second experiment, the infants were habituated to the ball either accelerating or decelerating down the incline, and in a third experiment they were habituated to the ball accelerating or decelerating up the incline. In both cases, test events consisted of all four scenarios tested in Experiment 1. In the case of downward motion, only the 16-month-olds reacted to the change in possibility; the 10-month-olds merely reacted to change in direction. In the case of upward motion, the 16-month-olds responded to featural changes, direction in particular, and 10-month-olds did not differentiate between any of the scenarios.

Overall, Kannass et al. (1999) conclude, in consensus with Kim and Spelke (1992), that there is a developmental trend: Over time, infants become more sophisticated in their responses to tasks where object speed and acceleration are of primary concern, though Kannass et al.'s (1999) results imply slightly slower development than might be inferred from Kim and Spelke (1992). But despite this difference, both studies clearly point out that even if there is developmental change it must take place much earlier than the work on young children's erroneous reaching behaviour in search tasks, which was described in Chapter 3, would account for.

It might seem reasonable to say that Piaget and all those who have followed since have drawn sufficiently similar conclusions to rule out further research when it

comes to children's basic understanding of object speed and acceleration. However, while there is not much research specifically related to infants' understanding of speed and acceleration in object motion, the described studies already show that even in young infants there appears to be at least some rudimentary understanding of these concepts. Regardless of the difference between the two studies, that is, the difference in speed of development, what is important to note is that from the results of both studies it can be ascertained that development takes place from a very young age. And it is this issue that highlights the need to include means of assessing tacit knowledge in children – particularly with younger children who typically cannot solve speed or acceleration tasks satisfactorily, attempting to explore their tacit knowledge may reveal that they know more about these concepts than they, or researchers so far, may be explicitly aware of.

6.5.2 Tacit knowledge of motion beyond infancy

As has been pointed out in Chapter 3 on the explicit-tacit distinction, a case can be made for assessing tacit knowledge and making use of that knowledge in facilitating conceptual change. Some attempts have already been made in assessing dissociations between explicit knowledge of object motion and tacit understanding thereof. Although not specifically looking at speed and acceleration, a study by Kaiser, Proffitt, Whelan and Hecht (1992) assessed the dissociation between motion predictions and judgements of naturalness of motion. Students were first asked to draw animations of motion if an aeroplane were to release a keg of beer during flight. The trajectories drawn were generally not consistent with physical principles. Conversely, when the students were shown animations of this motion, more than 80 per cent of students tended to express a preference for the trajectories that were, in fact, more natural.

Specifically looking at speed and acceleration, Shanon (1976) presented undergraduate students with predictive tasks where they were required to respond to a series of questions regarding speed and acceleration in free fall. The consensus was that between a third and a half of the responses were Aristotelian in nature. But

when presented with video recordings of motion, the recordings of movement with constant acceleration were identified by all students as being natural, rather than the recordings of movement with constant velocity. Shanon (1976) concluded that people are able to perceive kinematic phenomena correctly, despite their incorrect predictions.

Both these crucial studies have been concerned with the understanding expressed by adults. However, the results, on a larger scale, do not differ from those obtained with young children (or even with infants). Kim and Spelke (1999), for instance, had 2-year-old children predict landing positions of an object that was to be launched off a cliff. The children tended to choose a straight-down motion path rather than a parabolic path. Yet when viewing objects being launched, where the children were shown the possible and impossible falling trajectories, the results indicate that the children judged the impossible trajectories – where the object fell straight down – as looking strange to them, but not when the object correctly followed a parabolic path. Quite similarly, in a study by Howe, Taylor Tavares and Devine (2010b) an attempt has been made to assess young children's explicit and tacit reasoning of object fall in a computer-presented task with a hot air balloon and a girl in the balloon releasing balls of different sizes. Their predictive reasoning results show that throughout the age range of 6 to 10 years children were generally unaware of the influence of acceleration due to gravity in free fall. Their tacit reasoning task, on the other hand, implied that the same children do display a reasonably good tacit understanding that objects accelerate through air.

All four studies mentioned above looked at motion in free fall. However, what about the understanding of naturalness of motion in other dimensions? Kaiser and Proffitt (1984), for one, found that both college students and children aged 6 to 10 years could judge video recordings of dynamic collision events in horizontal motion as natural or anomalous above chance levels, with only little improvement as age increased. In an additional computer-presented study on the understanding of horizontal motion, Howe et al. (2010a) presented 6- to 10-year-olds with scenarios involving billiard balls on a billiard table. The children were required to make

predictions about the motion patterns, and to then observe their choices. Their predictions seem to suggest that friction is only slowly taken into account, as children get older, yet their judgements of motion imply they do acknowledge the role of friction in motion.

Interestingly, a study by Kozhevnikov and Hegarty (2001) on the understanding of upward motion suggests something rather opposite. Whilst undergraduate students' explicit knowledge was generally good, implicit knowledge was more likely to match medieval impetus theories. When the participants were shown an *apparent* motion display with an ascending object, they were able to make correct explicit judgements about the motion, if they had had some form of physics training beforehand. But their implicit knowledge did not differ significantly from that of their novice counterparts. However, Kozhevnikov and Hegarty (2001) do acknowledge several crucial faults in their work. A lack of realism in their displays may certainly have affected the results, as participants merely saw a series of static frames rather than videos of continuous motion like in Shanon (1976), and Kozhevnikov and Hegarty (2001) appreciate that more realistic displays could have elicited more correct implicit knowledge. In addition, they also suggest that there might be different situations where implicit knowledge could be expected to be inaccurate. This could happen when witnessing events that do not occur very often in everyday life, as was the case in their study, and they stress that it might be plausible for people to develop correct implicit knowledge if they have had specific experiences.

6.6 Summary

The literature covered here has shown that children's (and adults') explicit understanding of speed and acceleration – fundamental concepts in physics – are rarely understood correctly or in all entirety. Tacit knowledge assessment attempts have shown first fruitful signs of underlying notions about the correctness of motion. In combination with the wealth of infancy studies there is certainly a good case for continuing this thread of work. What is important to note about the work reviewed here is that despite quite an array of studies on individual dimensions, that is,

motion along a horizontal, motion down inclines, and motion in free fall, no studies appear to have assessed the same children's understanding of motion in more than one dimension, and certainly not all three dimensions. While tacit judgement tasks are generally sparse, the ones discussed here, too, do not consider more than one dimension, and incline motion judgement tasks do not appear to have been done at all. Yet the interaction of dimensions in tasks could provide useful information on children's reasoning about individual dimensions and show how the individual dimension reasoning processes, if at all, affect each other.

"[…] every student of elementary physics has to struggle with the same errors and misconceptions which then had to be overcome, and on a reduced scale, […] history repeats itself every year." (E. J. Dijksterhuis, 1961, p. 30)

CHAPTER 7:

SUMMARY, RATIONALE AND OVERVIEW OF THE CURRENT WORK

At the very beginning of this thesis, two questions were asked. What do we know about the physical world we live in? And what do we *really* know about the world we live in? Motion is certainly only one aspect of the physical world, so why consider this topic? Speed and acceleration are important everyday concepts; they happen all around us. Also, they are fairly stable concepts – a moving object either has constant speed or changes its speed. Furthermore, whenever there is motion there automatically is speed, and in naturally induced motion there is usually acceleration or deceleration[5], so the proposed research is looking at variables that are connected with every single moving object. Additionally, given the frequency with which speed and acceleration are relevant because of their everyday occurrence, they provide an interesting concept to investigate in terms of what children know about them.

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[5] Unless, as described in previous chapters, terminal velocity, barriers or too much friction interfere, which will either cause inertia or motion at a constant speed.

7.1 Summary of the introductory chapters

7.1.1 Naïve physics and the problem with prior conceptions

It emerged quite quickly that there is a problem. Despite extensive experiences with the everyday physical world, Chapter 1 illustrated that many children and adults hold naïve theories of motion that do not correspond to scientific views. Chapter 1 continued by highlighting the obvious fact that children do not come to the classroom as tabula rasa, but instead that there is a plethora of conceptions about the everyday world that children bring with them. They construct these naïve beliefs from their observations of and interactions with events and objects. Furthermore, while the educator's role should be to facilitate a change in conceptions, children's prior beliefs bring with them the issue of being resistant to change. In fact, specific studies on speed and acceleration, which were introduced in Chapter 6 (e.g. Baker et al., 2009; Gunstone & White, 1981), suggest that confirmation biases with regard to observations of events establish themselves early and gradually become more manifest, even within a short timeframe of only two years. This argues for early intervention.

Chapter 2 on conceptual change reflected on the theories of how knowledge is organised and how conceptual change can be brought about. Key mechanisms of mental modelling, model-based reasoning and thought experiments were introduced in this chapter. The conclusion from these is that despite the range of theories and processes in conceptual change research resistance to change remains, particularly in the area of physics. How can this be remedied?

7.1.2 The role of tacit knowledge

An alternative form of knowledge was then introduced in Chapter 3 – tacit knowledge. The idea of some form of knowledge about the everyday physical world ties in well with the findings from infancy research. The specific studies on infants' understanding of speed and acceleration described in Chapter 3 and later in Chapter

6 imply the idea of relevant tacit knowledge existing in infancy, and the notion of core knowledge or cognition suggests that this tacit knowledge remains unchanged throughout the lifetime. This promotes the idea of assessing tacit knowledge in childhood. However, while the approaches used with infants may not be appropriate with older children, Chapter 3 has suggested the usefulness of judgements as a method to tap tacit understanding of object motion. The use of ICT in early science education has also briefly been reviewed. In combination with the review of infancy research and the judgement methodology this suggests an effective tool for assessing tacit knowledge in childhood. This can be done by creating and presenting correct and false scenarios to activate tacit knowledge, which can then hopefully be used in facilitating conceptual change within early science education by designing instructional programmes.

One final point to make here is that in explicit reasoning tasks there appear to be two particular difficulties in examining the beliefs of young children (Tytler, 2000). Firstly, there is the issue of communication. Children might not necessarily understand what the researcher expects from them, or if they do understand the purpose they might not be able to articulate their views. Secondly, the act of probing might cause children to create conceptions in order to respond, even if perhaps they have not had any conceptions up to that point. This seems to be a particular concern with younger children who may have had less experience and therefore may have less settled beliefs. The assessment of tacit knowledge might be able to overcome these issues. Given the difficulty of expressing intuition, the crucial question that now remains is how, if at all, can tacit knowledge be assessed? And is there really anything to assess?

7.1.3 Understanding of speed and acceleration

The theoretical chapters on prior conceptions, conceptual change and mental models were succeeded by an interim summary of physical laws governing motion in Chapter 4. This, in turn, gave way to a literature review on children's general understanding of speed in Chapter 5. The resulting suggestions are that Piagetian

and alternative methods seem to show a somewhat consistent explicit understanding of general speed. Given this consistency it might seem reasonable to conclude that further research could be ruled out in this area. However, other than assessing the understanding of the meaning of these concepts these studies provide no information about the relevant issue at stake, that of naïve theories of motion and the understanding of how speed and acceleration function in dynamic everyday life events.

So what about specific everyday-related object motion? The currently available literature was reviewed in the subsequent Chapter 6, too, looking at the understanding of object motion. While the literature on motion along a horizontal and motion down an incline is somewhat limited, the studies on free fall make it particularly clear that inconsistencies between naïve beliefs and accepted scientific notions exist, persisting into adulthood. The importance of weight in reasoning about object motion supports this view. One particular issue that arose was that none of the work covered in Chapter 6 (also see Table A1 in the appendix, pp. 338-342, for a summary of studies) has assessed the same children's understanding of motion in more than one dimension. Yet "vertical gravity is a constant fact of life, so vertical dimensions should be treated differently from horizontal dimensions" (Hayes, 1979, p. 256). This claim would suggest that events involving downward motion are differentiated psychologically from horizontal motion (Howe, 1998). But what about motion in diagonal dimensions, that is, motion down inclines? If horizontal and vertical dimensions are distinguished from each other, does either one of them inform understanding of incline motion? Or do both? Or is incline motion treated independently from horizontal motion and from vertical motion?

7.2 Key research questions

In Chapter 1, this thesis proposed to examine three main objectives. Firstly, the question was raised of what could be said on the topic of children's general *explicit* beliefs about object motion, which variables are important to children in their reasoning, and how these variables affect their predictions of dynamic events.

Secondly, the question emerged of what could be said about children's ideas as to how motion types inform each other, if they do so at all; how reasoning about horizontal motion, reasoning about motion in fall and reasoning about incline motion interact, and how this information might assist in developing a single model of young children's conceptions of motion. And thirdly, given that one might anticipate young children to have limited or incorrect beliefs about motion, considering the literature, the question was raised of whether children have alternative *tacit* knowledge about dynamic events available to them that could potentially be integrated into early science education and utilised in modifying their limited or incorrect beliefs more effectively.

The more specific research questions thus asked within the frame of research are as follows:

1. What are the common conceptions of object speed and acceleration; do young children have a common *explicit* belief of object speed and acceleration?
2. What are the primary factors that affect explicit decision-making when it comes to assessing object speed and acceleration; does weight feature as predominantly as the literature suggests?
3. How do motion types interact in children's understanding of vertical, horizontal and diagonal dimensions? In particular, do horizontal and vertical dimensions inform reasoning about incline motion?
4. Can explicit knowledge be assessed via a computer in a comparable manner as via real-life object tasks?
5. Is *tacit* knowledge about object speed and acceleration accessible?
6. If tacit knowledge can be assessed, how correct are young children's tacit conceptions and how do they compare to explicit knowledge?

Four studies, covered in Chapters 8 to 11, sought to address these questions. Question 1 is addressed by the first three studies. Question 2 is specifically addressed by the first study in Chapter 8. Young children's general beliefs as to what

variables influence object motion are explored here. Question 3 is looked at in the first study, but is primarily tackled by the second study in Chapter 9. Here, a more detailed real-object reasoning task assessed how object weight impacts upon young children's beliefs about motion, and how the three motion dimensions horizontal, fall and incline may inform each other. Question 4 is covered by the third study in Chapter 10, where a computer-presented task of the second study is used to investigate how computers can assist in exploring young children's explicit beliefs about motion. Finally, questions 5 and 6 are addressed in the fourth study in Chapter 11 by assessing young children's tacit judgements of dynamic events.

7.3 An overview of the work

7.3.1 Ethical considerations

Ethical approval for the studies described hereafter was sought from and granted by the Faculty of Education, University of Cambridge. Written consent for the participation of all children was obtained from their parents. The main experimental procedures were described to the participating children immediately before the experiments and to their parents in advance through the consent forms, and it was made clear that the children's participation was voluntary. All children were told that they could discontinue the studies if and whenever they wished to do so. It was made clear that the children were not obliged to answer any of the questions. The children as well as their parents were made aware that any collected data would be treated with full confidentiality and that, if published, the data would not be identifiable as theirs. Following the research, the children and their parents were debriefed via written summaries in which the research was explained. The participating children were not deliberately misled in any manner, and there was no realistic risk of any children experiencing physical or psychological distress or discomfort. Enhanced disclosure from the Criminal Records Bureau had been obtained prior to any data collection.

<u>7.3.2 Participants</u>

Participants were recruited from a state primary school located in a suburban area of Cambridge, United Kingdom. In agreement with the school, the opt-out method was used to exclude children for whom parental consent was not granted. From the remaining group of potential participants, class teachers were asked to select children in order to be able to exclude cases where, for example, language was known to be an issue, as this could have interfered with understanding research instructions. The resulting sample then comprised of 144 children from four age groups, and the same children participated in all four studies. An additional 17 children formed the piloting sample for all four studies. The studies aimed to test children from Year 1 (around 5 years of age), Year 2 (around 6 years of age), Year 4 (around 8 years of age) and Year 6 (around 10 years of age). Piloting for the first study was carried out before the school summer holidays of 2008, and in order to continue working with the same children after the summer holidays, the piloting for Study 1 was carried out with children who were then in Reception, Year 1, Year 3 and Year 5 respectively. They were also tested in approximately the same order for each study in order to maintain a similar time difference between studies for each child, thereby reducing effects of time as much as possible.

7.3.2.1 Choice of participant age bands

The particular age groups were selected for two principal reasons. Firstly, they reflect the general trend of age groups covered in the literature reviewed in the previous chapters, where children were assessed (see the overview of relevant studies laid out in Table A1 in the appendix, pp. 338-342). By using a similar age range a better overall comparison of results was anticipated, to see if the explicit task results would be consistent with any previous research, and if so how additional explicit task results and the tacit task results would compare and fit into the overall picture. Secondly, the young age, as opposed to working with adults, stems from Isaacs' (1930) notion introduced earlier, that remedying disjunctions between science and the everyday world is best tackled as early as possible.

7.3.2.2 Repeated testing of same sample and order of tasks

For practical reasons, due to research time availability as well as to the designing of the computer programs, the children could not be tested in different order of tasks, that is, some children beginning with the tacit reasoning task and some with the explicit reasoning task. However, similarly structured research by Howe et al. (2010a, b), for instance, found no order effects when assessing explicit and tacit reasoning in primary school children and counter-balancing the order of the explicit and tacit tasks. In addition, as no motion took place during any of the explicit prediction tasks, it was not anticipated that any learning effects regarding motion could occur before reaching the tacit task. It was felt that by repeatedly testing the same children on all tasks, this would allow a more sensible comparison of performances among tasks.

Despite similarly structured research suggesting no such effects, to ensure that order effects had not occurred in the present work either, a small sample of 16 additional children was subsequently tested. The children were recruited from the same school as those in the main studies, and they were from the same four age groups, four children per age band. None of these children had participated in any of the four pilot studies or any of the four main studies, and they did not receive the tasks outlined in Studies 1 and 2. One set of eight of the children received the task outlined in Study 3 first, then the task outlined in Study 4 a few days later. The second set of eight children received the Study 4 task first, then the Study 3 task (see the appendix, pp. 350-353, for details).

The additionally collected data indicate the same patterns observed in the main data presented in the research chapters here (see the appendix, pp. 350-353, for details regarding data analysis). Analyses of the data revealed no significant differences in performance between the two sets of additional children, suggesting no order effect in this additional sample. At the same time, the additional data collected for the Study 3 task do not differ significantly from that of the main Study 3 sample. This suggests that the main Study 2 performance presumably had no effect on the main Study 3 performance. Finally, the additional Study 4 data do not differ significantly

from that of the main Study 4 sample. This indicates that even if children had done the tacit judgement task first (or only the tacit judgement task), their judgements would have still been comparable to those of children who had already had considerable exposure to explicit prediction tasks, implying no problem with assessing the same children on a number of explicit tasks prior to assessing their tacit judgements of related dynamic events. And this is not particularly surprising, since the children were not given any feedback in any of the tasks, that is, they were never told whether their predictions or their judgements were correct or incorrect.

7.3.2.3 Science education levels

The National Curriculum for England specifies what primary school children should be taught in science (Department for Education and Employment, 1999). In terms of the present work, they are certainly expected to know several important elements by the end of primary school. For instance, already in Key Stage 1 (ages 5 to 7 years) children are to be taught how to scientifically investigate about materials and physical processes, by planning and asking questions, obtaining evidence, presenting and evaluating it, and include the use of ICT. Children are expected to be taught how to use their senses to explore materials (such as solidity and texture) and to compare objects. Finally, the National Curriculum also requires that children be taught to find out about and describe motions of familiar things, including changes in speed and causal relations. In Key Stage 2 (ages 7 to 11 years), children are expected to extend their investigation skills from Key Stage 1. In addition, they are required to be taught to compare materials and objects on the basis of their properties. They are also required to be taught about downward motion and gravity, friction and air resistance.

7.3.3 Timeline of data collection

A timeline, beginning in May 2008 and ending in July 2009, is shown in Figure 7.1 below. It illustrates the process of data collection for the four studies presented in the subsequent Chapters 8 to 11.
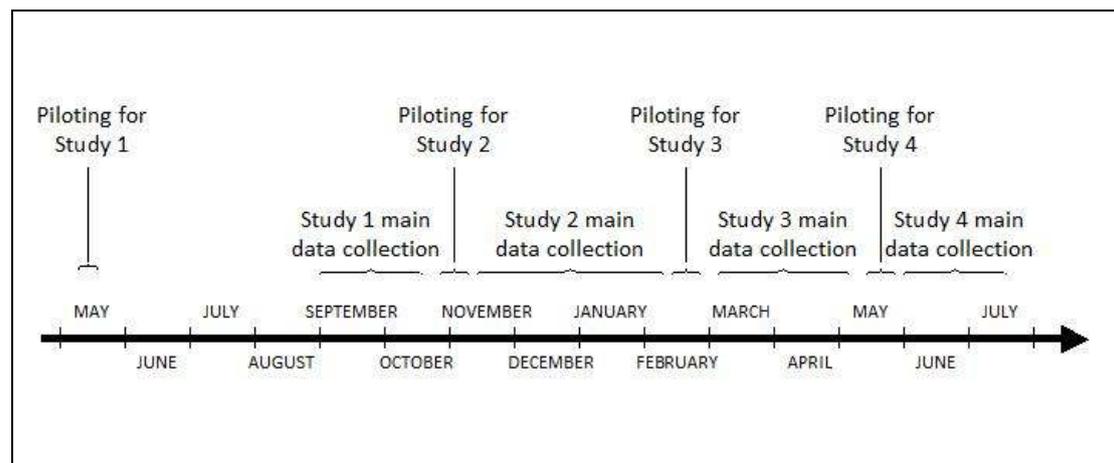
Figure 7.1   A timeline of the thesis data collection

7.3.4 Use of computers

In terms of the current topic of object speed and acceleration, it has been noted that motion is a particularly well-suited topic for computer tasks in general due to its essential structure being visual, geometric and dynamic (diSessa, 1986). However, despite the claim that computer simulations can, in fact, be credible representations of reality, at least where diagnosis and remediation of alternative conceptions of velocity is concerned (Zietsman & Hewson, 1986), the naturalness of such simulations has been questioned (e.g. Hennessy & O'Shea, 1993). However, it cannot escape notice that many of these simulations have rather strange scenarios, such as shops on Mars – while these may, of course, be entertaining, it is no surprise that the naturalness is criticised. The criticism does not, on the other hand, include real scenarios, that is, video recordings of actual events. Whether this factor is equally dubious remains to be seen.

The two infancy studies on speed and acceleration (Kannass et al., 1999; Kim & Spelke, 1992) described in Chapter 6, and related studies exploring infants' knowledge of the physical world by Baillargeon and colleagues (Baillargeon, 1994; Baillargeon & Hanko-Summers, 1990; Baillargeon et al., 1992; Needham & Baillargeon, 1993; also see Baillargeon, Kotovsky, & Needham, 1995) described in Chapter 3 provide an excellent opportunity to continue where explicit reasoning tasks stopped in the 1980s. With infant studies having made successful use of computers to create false scenarios and to tap into tacit knowledge of the physical world, the suggested research attempts to bridge the gap between different research methods (real-life object tasks and computer tasks) as well as between research and primary education teaching, by making use of research methods to investigate knowledge, which can then hopefully be applied within education.

So how can computer methods be integrated into children's assessment of their understanding of motion in the everyday world? How can tacit knowledge be tapped into? The methods used in specifically related infancy research (Kannass et al., 1999; Kim & Spelke, 1992) could perhaps also be used with children. By creating false scenarios that conflict with expectations about the real world, demands could be placed on underlying tacit knowledge, similar to that expressed in violation-of-expectation paradigms. Howe et al. (2010a, b) and Kim and Spelke (1999) show first tentative uses of this approach, and related work with adults lends support as well (Kaiser & Proffitt, 1984; Kaiser et al., 1992; Shanon, 1976). To avoid issues of naturalness as much as possible, real scenarios can be used and altered in such ways that false scenarios can be created without the introduction of alternative or surreal environments. Furthermore, if successful, this would bear implications for designing educational computer programs, and the above-established use of ICT in early education certainly provides support for this notion as well.

7.3.4.1 Specific use of ICT at the recruited school

As two of the studies relied on computer-presented tasks, it was crucial to establish the extent of the children's experience with computers. The use of ICT in primary

schools in England in general has been covered earlier. A brief questionnaire was distributed among the class teachers at the school involved in the current research, of those year groups that contributed to the data. They were asked to provide information about the use of ICT in their classrooms and their children's hands-on experience with ICT. A summary of this information is shown in Table 7.1 below. Across the age range, the children are under regular exposure to a range of ICT techniques when being taught (ranging from 40 per cent to 85 per cent of teaching time), and in addition they have personal experience using some of them in the classroom. Even the youngest children are already equipped with basic experience of using computers. This is important to be aware of when considering the methodologies applied and the results obtained from those studies that involve computer-presented tasks.

Table 7.1   Summary of the use of ICT at the recruited school

Age group	Hours of general teaching with ICT per week	Hours of science teaching with ICT per week	ICT equipment used in teaching	Children's ICT hands-on experience
Year 1	15 out of 25 (60%)	1 out of 2 (50%)	Interactive whiteboard, laptop, PCs, CD player, programmable toys.	PCs, programmable toys.
Year 2	10 out of 25 (40%)	½ out of 1 (50%)	Interactive whiteboard, paint programs, talking books, ICT games, word processing, internet.	Interactive whiteboard, paint programs, talking books, ICT games, word processing, internet.
Year 4	22 out of 26 (85%)	1½ out of 2 (75%)	Interactive whiteboard, image-processing programs, interactive maths programs.	Interactive whiteboard, image-processing programs, interactive maths programs.
Year 6	20 out of 30 (67%)	2 out of 4 (50%)	Interactive whiteboard, PCs, DVDs, videos, internet.	Interactive whiteboard, PCs, internet.

7.4 Contributions of the research to the literature

Studies 1 to 4 each offer unique contributions to the existing literature. Study 1 provides information about how a range of everyday objects – which children have considerable experience with in general, and which would have an effect on naïve explicit knowledge formation – inform views of motion, and what variables play a crucial role in their predictions. This may help to understand more clearly where children's alternative conceptions of motion originate from, particularly as a parallel to Aristotelian physics based on the everyday world, and their ability to reason about motion by using objects they are familiar with. It also provides initial information on children's understanding of motion dimension interaction, which is examined in more detail in the following studies. Study 2 then provides a detailed account of how motion dimensions interact in children's reasoning; prior work has only focused on individual dimensions. The study particularly provides information about children's conceptions of incline motion in relation to horizontal and vertical dimensions, as the question of how motion down an incline is perceived in relation to either still remains open. This study will further the understanding of explicit motion models in childhood. Study 3 provides information on motion dimension interaction (i.e. horizontal, vertical, incline) as well as a more direct means to compare explicit with tacit knowledge – do children consider relevant real-object tasks in the same way as computer-presented tasks? It thus provides a point of comparison and adds to the literature on the use of ICT in learning, thereby contributing information to educational practice. Finally, Study 4 provides information on the underlying judgements that children hold of dynamic events. Again, while prior literature may have focussed on judgements of events, none has compared all three motion dimensions. Given that much of the prior literature indicates incorrect explicit beliefs of motion, it is hoped that more can be learned about any underlying tacit conceptions of motion in order to contribute to designing conceptual change programmes for educational practice.

CHAPTER 8:

YOUNG CHILDREN'S EXPLICIT BELIEFS ABOUT MOTION USING EVERYDAY OBJECTS (STUDY 1)

8.1 Overview

It has been noted in Chapter 1 of this thesis that the problem of learning lies with what knowledge children possess rather than what knowledge they do not have (Carey, 2000a), that is, prior conceptions about the world that are inconsistent with science. In fact, many children and adults hold beliefs that reflect incorrect Aristotelian ideas of object motion in the physical world. As facilitating conceptual change seems to be difficult, as shown in Chapter 2, it seems worthwhile to investigate children's explicit beliefs about motion using everyday objects. The first objective of this thesis was to see what can be said on the topic of children's general beliefs about object motion, to see which variables are important to children in their reasoning, and how these variables affect their predictions of dynamic events.

Much of the research that has been covered in the introductory Chapter 6 addressed children's explicit beliefs about object motion using a limited array of objects, usually two objects only (Baker et al., 2009; Champagne et al., 1980, as cited in McDermott, 1984; Chinn & Malhotra, 2002; Nachtigall, 1982; Sequeira & Leite, 1991; Trowbridge & McDermott, 1981; van Hise, 1988). However, how consistent are these beliefs across a range of objects, particularly objects that occur in everyday life? This study aimed to establish what general basic beliefs children hold about speeds of different objects following different kinds of motion paths, using everyday objects that most children would probably have seen or held before and perhaps even experienced in particular motions before. While the actual choice of object was not important, the study aimed to examine which object variables feature predominantly in primary school children's justifications of their beliefs, and how these variables affect their predictions – do particular features mean faster motion, or slower motion?

In particular light of Galili's (2001) notion, which was first introduced in Chapter 6, that weight is one of the more crucial variables in reasoning about the physical world, this study aimed to see if weight was, indeed, a predominant justification in children's explanations. But not only was the study concerned with whether weight is a predominant feature as such, but also with the direction of justifications – does, for instance, object heaviness facilitate or inhibit motion as compared to object lightness in children's reasoning? Although reliance on weight and the direction of justification has been reasonably well established in reasoning about free fall motion (e.g. Baker et al., 2009; Chinn & Malhotra, 2004; Nachtigall, 1982; Sequeira & Leite, 1992), less is known about how strongly weight features in reasoning about motion along a horizontal or down inclines, and in what direction it features: Do young children predominantly associate faster horizontal motion and motion down inclines with heavy objects or with light objects? Furthermore, what about other variables that children might use in their predictions about motion? Do children perhaps rely on other object features as well, possibly incorporating different variables in different motion dimensions?

Finally, despite a not unreasonable amount of research on children's explicit beliefs about object speed, this literature appears to have concentrated primarily on motion in free fall or on motion down an incline (see Chapter 6, and the summary in Table A1 in the appendix, pp. 338-342). There do not appear to be any studies that have examined the same children's reasoning about object motion along a horizontal, object motion in free fall *and* object motion down an incline. Given the view that horizontal motion and free fall motion should be differentiated psychologically from each other (Hayes, 1979; Howe, 1998) – do children associate motion down inclines more with motion along horizontals, or with motion in free fall in terms of their predictions and justifications, or do they even treat it as completely separate from either of them? This study was an attempt to close this gap.

In addition, children engage with everyday objects – as the name implies – very frequently, so they are very familiar with them. Much of naïve scientific knowledge, similar to Aristotle's experiences that led him to writing *Physics*, is based on

observations of the everyday world. These observations presumably play a crucial role in the development of explicit motion knowledge. So in order to increase understanding of children's abilities to reason about motion as it occurs in the everyday world, where most of their experience of object motion ultimately derives from, the use of everyday objects will enable to help them engage with objects and events they can relate to. With regard to the above-mentioned aspect of motion dimension interaction, using everyday objects may also provide information about children's reasoning about different motion dimensions on the basis of what they are already familiar with.

8.2 Research questions

1. Which variables do primary school children predominantly use when they reason about motion of *everyday* objects?
2. In which direction are variables associated with faster motion; is, if taking weight as an example, heaviness associated with faster motion, or lightness?
3. How does the use of variables compare between motion dimensions, that is, do children use the same or different variables when reasoning about motion along horizontals, motion down inclines and motion in free fall?

8.3 Method

8.3.1 Pilot study

8.3.1.1 Participants

As noted in Chapter 7, the pilot sample for the study consisted of 17 children (nine boys). The sample included three Reception children (two boys; age M = 5.20 years, SD = 0.38), six Year 1 children (four boys; age M = 6.19 years, SD = 0.26), five Year 3 children (three girls; age M = 7.90, SD = 0.13) and three Year 5 children (two girls; age M = 10.31, SD = 0.51).

8.3.1.2 Materials

The materials consisted of 12 objects (see Figure 8.1, p. 133). The objects were a yellow glass marble (approximately 1.5 cm in diameter), a red billiard ball (approximately 5 cm in diameter), a red toy car (approximately 7 cm length x 3 cm width x 2 cm height), an orange toy truck (approximately 8 cm length x 3 cm width x 4 cm height), a standard golf ball (approximately 4 cm in diameter), a standard squash ball (approximately 4 cm in diameter), a standard tennis ball (approximately 7 cm in diameter), an orange (approximately 7 cm in diameter), a hammer (approximately 32 cm length x 13.5 cm head width), a rock (approximately 5 cm diameter x 3.5 cm height), a feather (approximately 13 cm length x 3 cm width), and a leaf (approximately 13 cm length x 9 cm width). Due to the orange and leaf being perishable they needed to be exchanged every few days, but care was taken to match old and new objects by size and shape as much as possible. In addition to the 12 objects, a questionnaire was used to guide the task and for the researcher to note children's responses to questions.

Figure 8.1   Objects used in Study 1

8.3.1.3 Design

There were questions relating to three different motion types within the assessment – one set of questions on motion along a horizontal, one set of questions on motion down an incline, and one set of questions on motion in free fall. The 12 objects listed above were separated into three groups, one group per motion type, with four objects in each group. The horizontal motion objects were the glass marble, the billiard ball, the toy car and the toy truck. The incline motion objects were the golf ball, the squash ball, the tennis ball and the orange. The free fall objects were the hammer, the rock, the feather and the leaf. The objects were paired with each other within each group, giving six pairs per group and 18 pairs overall, giving 18 comparisons. Each child was assessed on all comparisons.

8.3.1.4 Procedure

The interviews took place outside of the classrooms but in an open and publicly accessible area of the school. Upon arrival, the child was given general information about the study – that the researcher had brought some toys and that there were going to be some questions about them. It was made clear to the child that participation was voluntary and that completion of individual items or the study as a whole was not compulsory. The child was then asked to provide name, gender, year group and date of birth. Although this information was already made available to the researcher by the school, it was hoped that making the children contribute it might put them more at ease. The information was noted on the questionnaire by the researcher, with the exception of the child's name for which only initials were used. Where the child was not able to provide complete information, usually the date of birth, this was retrieved from lists provided to the researcher by the school.

To begin with, the child was introduced to all 12 objects. The child was allowed to handle the objects and was asked to notify the researcher when an unknown object was encountered. Whenever this was the case the researcher briefly explained what the unknown object was. The objects could be handled at any time but the child was asked not to carry out any relevant motions with the objects when having to respond to the questionnaire items, that is, not to roll them across the table or deliberately let them fall. Two of the objects were then selected, in accordance with the first question on the questionnaire.

For the horizontal motion objects, the child was given the following first instruction (object pairs are examples; italics were stressed by the researcher in speech): "Imagine you are playing on the floor, you are holding the car with one hand and the truck with the other hand *right next* to each other, like this [researcher demonstrated this action with hands]. If you push them both *as hard as each other* across the floor at the *same time*, do you think one of the two will roll faster, or do you think they will both roll as fast as each other?" Depending on the child's choice, the researcher then asked, "*Why* do you think the truck (or the car) will roll faster?"

or "*Why* do you think they will roll as fast as each other?" For the incline motion objects, the child was given the following first instruction: "Imagine you are on a hill, you are holding the tennis ball with one hand and the orange with the other hand *right next* to each other, like this [researcher demonstrated this action with hands]. If you let both of them go at the *same time*, do you think one of the two will roll down the hill faster, or do you think they will both roll as fast as each other?" Depending on the child's choice, the researcher then asked, "*Why* do you think the tennis ball (or the orange) will roll faster?" or "*Why* do you think they will roll as fast as each other?" And for the free fall motion objects, the child was given the following first instruction: "Imagine you are standing up, you are holding your arms out at the *same height*, like this [researcher demonstrated this action with hands] and you have the hammer in one hand and the feather in the other hand. If you let both of them drop at the *same time*, do you think one of the two will fall faster, or do you think they will both fall as fast as each other?" Depending on the child's choice, the researcher then asked, "*Why* do you think the hammer (or the feather) will fall down faster?" or "*Why* do you think they will fall down as fast as each other?"

For half of the comparisons the questions were directly about speed and the child was asked whether one of the two would be faster, for the other half the questions were about time taken and the child was asked whether one of the two would take more time, such that for each object category there were three questions of each type. Furthermore, the two sets of questions represented an inverse relationship with each other, that is, more speed (which requires less time over the same distance) and more time (which results in less speed over the same distance). For each question, there was thus a choice between three response possibilities: The child could select one of the two objects over another, or state that both would behave the same. In addition, the child was asked to provide justifications, that is, state why they had made their choices. The child's responses were noted on the questionnaire by the researcher. Each interview lasted approximately 20 to 25 minutes for each child.

8.3.1.5 Outcomes of the pilot study

The structure of the questionnaires was put to the test in two piloting sessions. In the first session, all 12 objects had been made available to the children at the same time, and all questions had been placed in a random order, irrespective of motion type. As a variation, in the second session the questions were then grouped by motion type, and it seemed that this structure bore two advantages. Firstly, having changes on fewer levels (changing object pairs alone versus changing object pairs *and* motion type) appeared to be less confusing for the children. Also, by having to change objects twice during a session it not only gave the children a chance to take a short break if they needed one, but it also appeared to have raised their interest level each time a new array of objects was presented. This latter point seemed particularly crucial with the youngest children. Finally, an initial concern had been that 18 questions in one session might not be entirely feasible, but the piloting revealed no complications with having that many questions within a single session.

In the first session of the pilot study, some of the Year 1, Year 3 and Year 5 children had been assessed in small groups, respective of their age bands. In the second session, children from Reception and the remainder of the Year 1 and Year 3 children had been assessed individually. It was initially thought that the older children, given their reading and writing skills, could have been assessed in groups, so as to facilitate the process of data collection. However, the problems that arose from this procedure were twofold. Firstly, it appeared that bar those from the oldest age group most of the children did not have adequate writing skills in order to write the justifications for their responses, or that their writing required too much time. Secondly, having the children in groups, even though it had been made clear to them that they should not discuss their answers with each other or say them out loud, made it unclear how individual responses might have been influenced by what had been said by other children in the group. Thus it appeared necessary to conduct the interviews on a one-to-one basis for all children, and the second session from the piloting showed this to be much more effective.

8.3.2 Main study

8.3.2.1 Participants

As noted in Chapter 7, the Study 1 main sample consisted of 144 children (80 girls). The sample included 36 Year 1 children (20 girls; age M = 5.47 years, SD = 0.33), 36 Year 2 children (21 girls; age M = 6.48 years, SD = 0.29), 36 Year 4 children (21 girls; age M = 8.34, SD = 0.35) and 36 Year 6 children (18 girls; age M = 10.51, SD = 0.23).

8.3.2.2. Materials

The materials were the same as used in the pilot study. In addition, instead of one questionnaire three different questionnaires were used to guide the tasks and for the researcher to note children's responses to questions (see the appendix, pp. 346-347, for a sample questionnaire). Only one questionnaire was used per child and the random selection of questionnaire determined the test condition for each child (as outlined below).

8.3.2.3 Design

The 12 objects listed in the materials were separated into three groups in the same way as in the pilot study, again resulting in 18 comparisons. The comparisons were distributed over three blocks – one block on motion along a horizontal, one block on motion down an incline, and one block on motion in free fall. The order of blocks and the order of comparisons within each block were randomised, giving three different conditions, such that the questionnaires either began with the questions about objects rolling horizontally, about objects rolling down an incline, or about objects in free fall (see Table 8.1, p. 138, and the appendix, pp. 346-347, for a sample questionnaire). Each child contributed to all three blocks. For each justification type that was made, each child thus scored between 0 and 18 (for each block the score was between 0 and 6). In those cases where children made same-speed decisions, they were given a score of 0.5 for each of the two directions of the justification they

used. Equal numbers of children per age group were selected for each condition, that is, 12 children per age group were selected for each condition.

Table 8.1   Conditions in Study 1

	Condition 1	**Condition 2**	**Condition 3**
Block 1	Horizontal motion questions	Incline motion questions	Free fall motion questions
Block 2	Incline motion questions	Free fall motion questions	Horizontal motion questions
Block 3	Free fall motion questions	Horizontal motion questions	Incline motion questions

8.3.2.4 Procedure

The general procedure and the instructions were the same as in the pilot study, but with the following changes. As three different questionnaires were now to be used in the assessment, prior to a child joining, a questionnaire was selected at random, and only one questionnaire was used per child. Children were tested on an individual basis as the piloting had revealed difficulties in assessing the children in groups, notably lack of sufficient writing skills, and discussion amongst the group. The latter aspect in particular would have made it difficult to conclude whether responses given were those of individual children, or whether the other children in the group had influenced them. The objects were presented four at a time only, relevant to the testing block, that is, only objects for the horizontal motion task or the incline motion task or the free fall task. This was because during the piloting it had become apparent that having only four objects at a time instead of all 12 made the task easier for the children to follow due to less scenario-switching, and having intermittent breaks where objects were changed allowed maintaining higher interest levels throughout, especially for the younger children. During each block, the initial description of the situation was only given with the first comparison and not repeated in subsequent items, only the two questions using the new object pairs.

Finally, at the end of each block the four objects were removed and the child was given the option either to take a short break or to continue with the next block of questions. The procedure for the remaining two blocks was then the same as for the first block.

8.4 Results

8.4.1 Methods of analysis

Five main justification types were identified from the responses. These included references to the objects' weight, size, shape or texture, or any other justifications. Data were collected in the form of justifications (see 8.3.2.3); multiple justifications could be given for each questionnaire item. With the exception of the final group of responses, each of the justification types was broken down into two 'directions' – when children used a justification type to indicate faster or slower speed, they referred to either one of the two. Thus, weight was separated into 'heavy' and 'light', size was separated into 'big' and 'small', shape was separated into 'round' and 'uneven', and texture was separated into 'smooth' and 'rough'. Other reasons were not separable into directions and were thus not considered for directional analyses.

Kolmogorov-Smirnov tests on the normality of distribution of the data showed that all distributions deviated significantly from normality. Therefore assumptions for parametric tests were not met. Wilcoxon signed-rank tests showed no significant differences between scores for questions asking about time taken and scores for questions asking about speed. Therefore the scores of the two sets were merged, that is, scores for 'faster' and 'less time' were grouped, to avoid reporting similar results twice. Analyses of mean scores involved Friedman's ANOVAs and post hoc Wilcoxon signed-rank tests, with Bonferroni corrections applied (all significance thresholds $p \leq .0125$). Effects of gender were analysed with Mann-Whitney tests, and effects of age and effects of conditions were analysed with Kruskal-Wallis tests and post hoc Jonckheere-Terpstra tests. No significant gender or condition effects were

found, therefore these are not considered further. All data were analysed using PASW (Predictive Analytics Software, formerly SPSS) Statistics version 18.

8.4.2 Justification types

Figure 8.2 below shows the mean scores for overall faster motion justification types. For each justification type used by children in their predictions of faster motion, a maximum score of 18 was obtainable. There was significant variation in mean scores for justification types, $\chi^2(4, N = 144) = 219.15$, $p < .001$. Object weight ($M = 6.62$, $SD = 3.61$) was used as a justification significantly more often than size $(M = 3.70$, $SD = 2.25)$, $T = 7$, $r = -.55$. Mean scores for size and shape did not differ significantly. Shape ($M = 3.20$, $SD = 2.08$) was used significantly more often than texture ($M = 2.56$, $SD = 1.95$), $T = 3$, $r = -.02$. Texture was used significantly more often than other reasons ($M = 0.97$, $SD = 1.49$), $T = 6$, $r = -.05$.
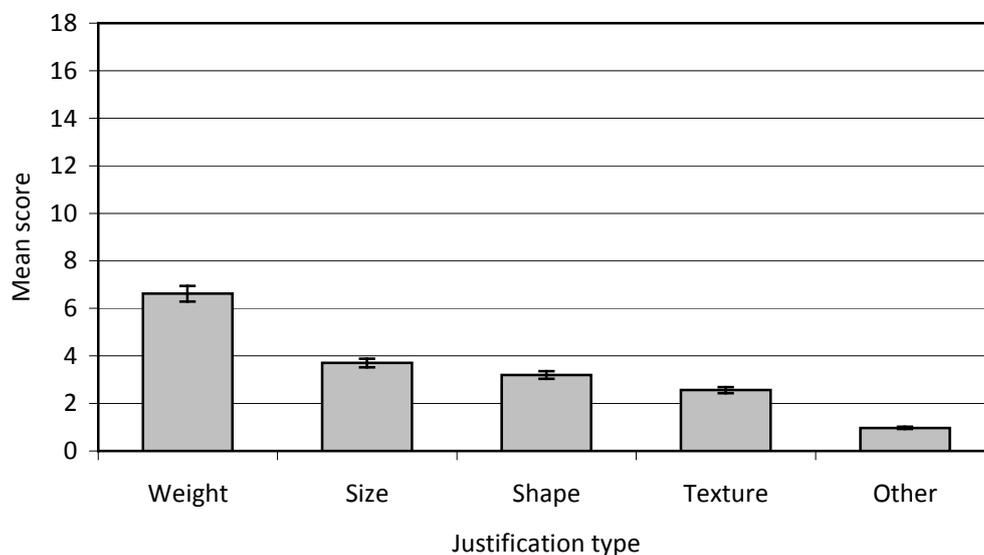
Figure 8.2   Mean scores for overall faster motion justification types (Maximum possible score = 18)

Figure 8.3 (p. 141) shows the mean scores for overall faster motion justification types by age groups. There was a significant interaction of age with the use of weight

as a justification, $H(3) = 77.37$, $p < .001$, usage increasing with age, $J = 6118$, $z = 8.01$, $r = .67$. There was a significant interaction of age with the use of size as a justification, $H(3) = 15.57$, $p < .001$, usage decreasing with age, $J = 3125$, $z = -2.75$, $r = -.23$. There was a significant interaction of age with the use of shape as a justification, $H(3) = 32.71$, $p < .001$, usage increasing with age, $J = 5344$, $z = 5.26$, $r = .44$. There was also a significant interaction of age with the use of texture as a justification, $H(3) = 36.59$, $p < .001$, usage increasing with age, $J = 5165$, $z = 4.63$, $r = .39$. However, there was no significant interaction of age with the use of other justifications.
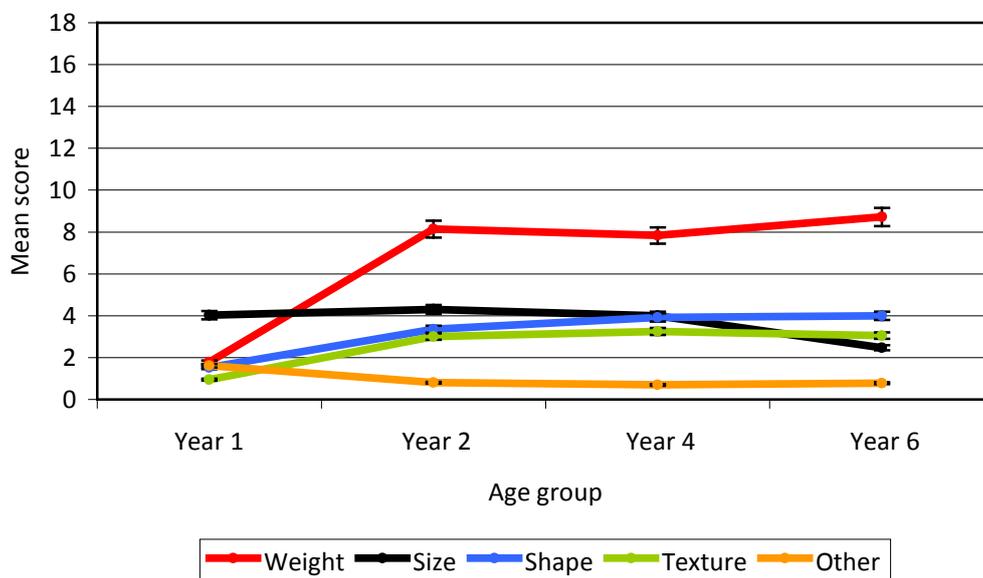
Figure 8.3   Mean scores for overall justification types by age groups (Maximum possible score = 18)

8.4.2.1 Motion along a horizontal

Figure 8.4 (p. 142) shows the mean scores for overall faster motion justification types for motion along a horizontal. For each justification type used by children in their predictions of faster motion, a maximum score of 6 was obtainable. There was significant variation in mean scores for justification types in horizontal motion predictions, $\chi^2(4, N = 144) = 237.80$, $p < .001$. The mean scores for size and shape did

not differ significantly. Both size (M = 2.13, SD = 1.40), T = 4, r = -.35, and shape (M = 2.13, SD = 1.45), T = 4, r = -.37, were used significantly more often than weight (M = 1.33, SD = 1.38). Weight was used significantly more often than other reasons (M = 0.51, SD = 1.16), T = 5, r = -.43. Other reasons were used significantly more often than texture (M = 0.14, SD = 0.57), T = 3, r = -.26.
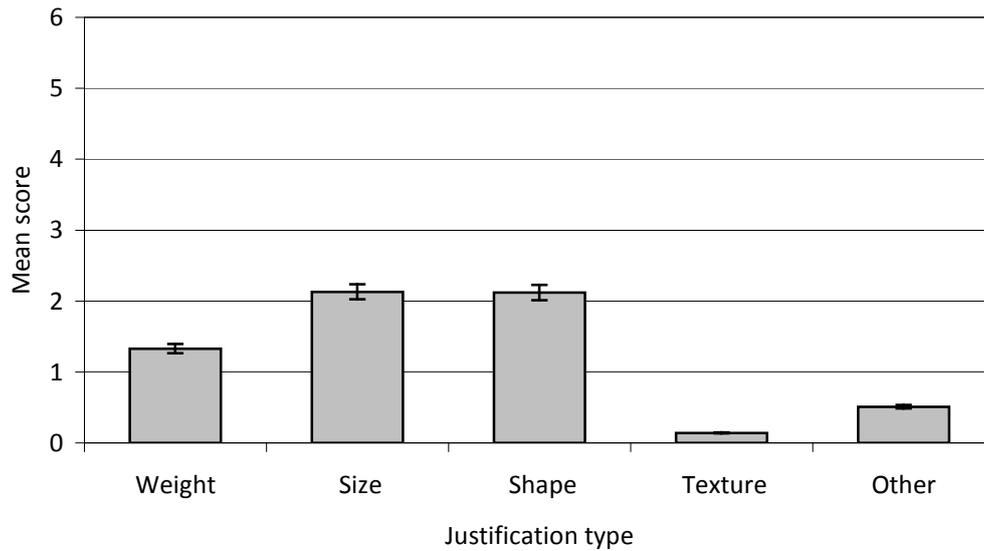
Figure 8.4   Mean scores for overall justification types in horizontal motion (Maximum possible score = 6)

Figure 8.5 (p. 143) shows the distribution of scores by age group. The same general age effect pattern as for overall justifications was found. Use of weight increased with age, J = 5110, z = 4.56, r = .38, use of shape increased with age, J = 4953, z = 3.91, r = .33, and use of texture increased with age, J = 4230, z = 2.91, r = .24. Size and other reasons did not vary significantly with age.
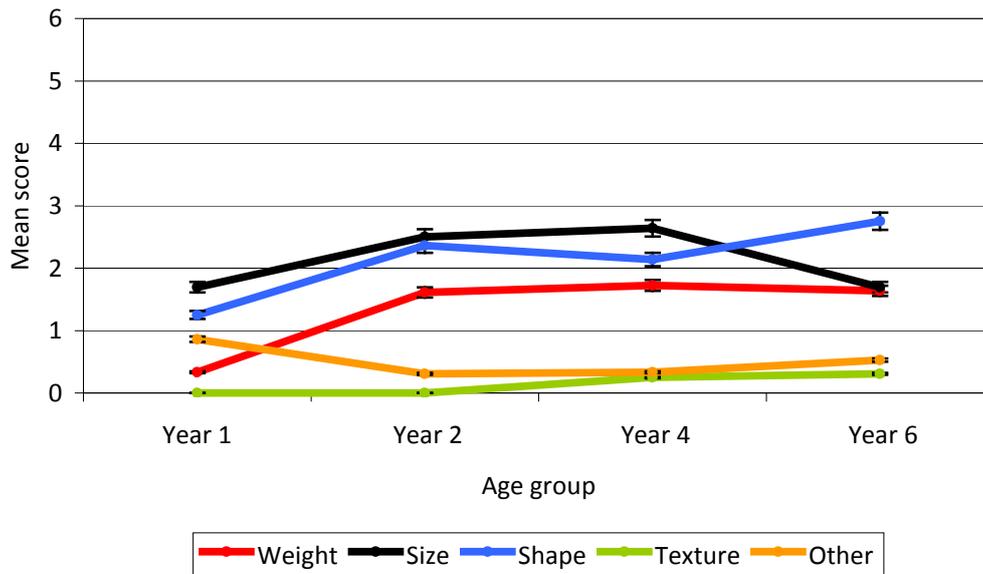
Figure 8.5 Mean scores for justification types in horizontal motion by age groups (Maximum possible score = 6)

8.4.2.2 Motion down an incline

Figure 8.6 (p. 144) shows the mean scores for overall faster motion justification types for motion down an incline. For each justification type used by children in their predictions of faster motion, a maximum score of 6 was obtainable. There was significant variation in mean scores for justification types in incline motion predictions, χ^2(4, N = 144) = 188.78, p < .001. Object texture (M = 2.33, SD = 1.74) was used as a justification significantly more often than shape (M = 1.02, SD = 1.09), T = 6, r = -.53. There were no significant differences among shape, size and weight, but all three were used significantly more often than other reasons (all p < .001).
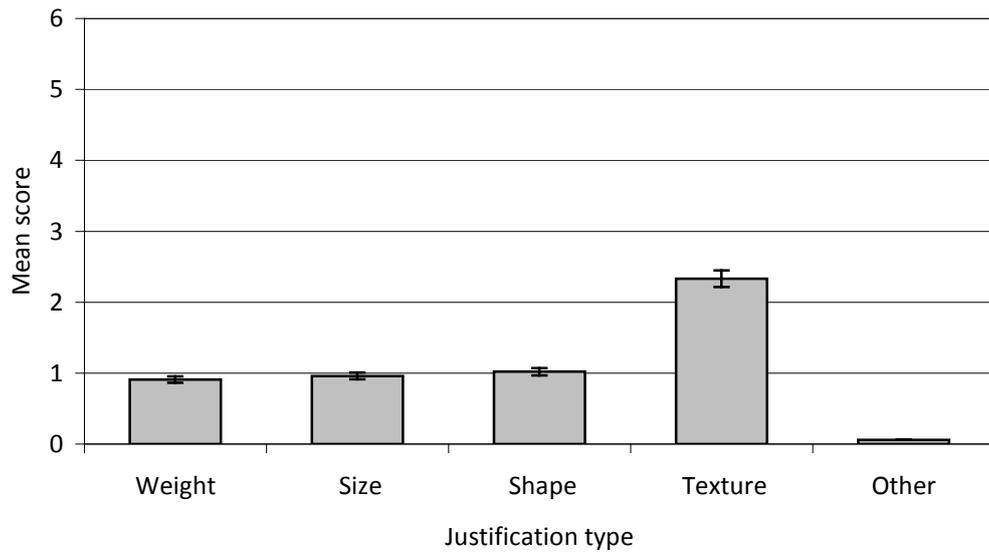
Figure 8.6   Mean scores for overall justification types in incline motion (Maximum possible score = 6)

Figure 8.7 (p. 145) shows the distribution of scores by age group. The same general age effect pattern as for overall justifications was found. Use of weight increased with age, J = 5401, z = 5.83, r = .49, use of shape increased with age, J = 5221, z = 5.04, r = .42, and use of texture increased with age, J = 4955, z = 3.88, r = .24. Size and other reasons did not vary significantly with age.
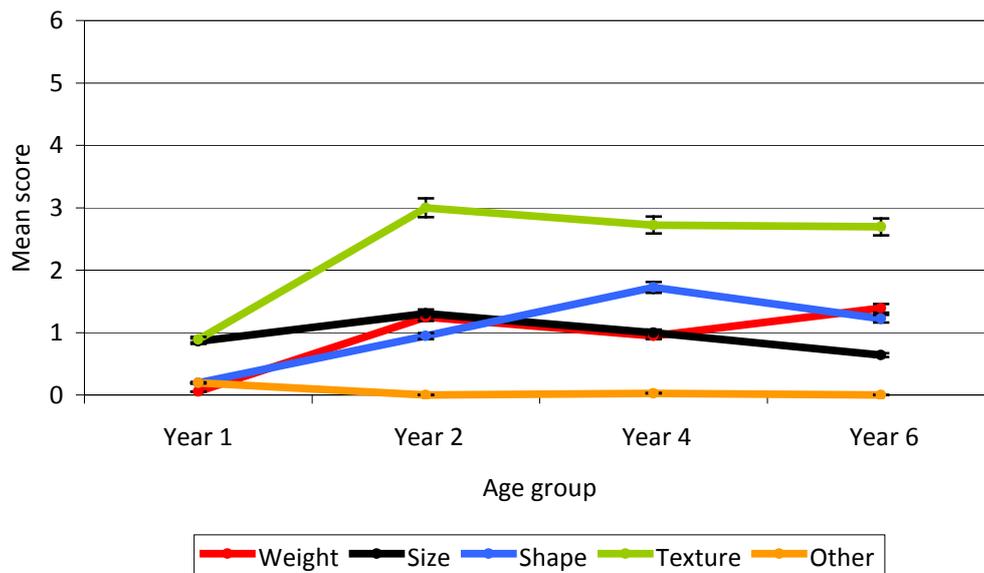
Figure 8.7 Mean scores for justification types in incline motion by age groups (Maximum possible score = 6)

8.4.2.3 Motion in free fall

Figure 8.8 (p. 146) shows the mean scores for overall faster motion justification types for motion in free fall. For each justification type used by children in their predictions of faster motion, a maximum score of 6 was obtainable. There was significant variation in mean scores for justification types in free fall motion predictions, χ^2(4, *N* = 144) = 338.99, *p* < .001. Object weight (*M* = 4.38, *SD* = 2.02) was used as a justification significantly more often than size (*M* = 0.57, *SD* = 0.87), *T* = 10, *r* = -.81. Mean scores for size and other reasons did not differ significantly. Other reasons (*M* = 0.41, *SD* = 0.82) were used more often than texture (*M* = 0.10, *SD* = 0.34), *T* = 4, *r* = -.35. Mean scores for texture and shape did not differ significantly.

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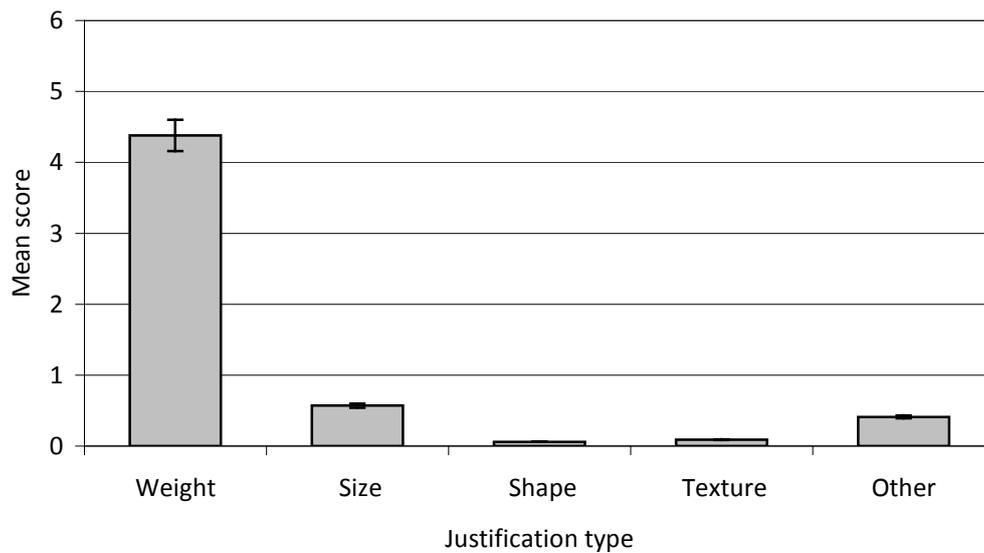
Figure 8.8   Mean scores for overall justification types in free fall motion (Maximum possible score = 6)

Figure 8.9 (p. 147) shows the distribution of scores by age group. The same general age effect pattern as for overall justifications was found. Use of weight increased with age, $J = 6049$, $z = 8.12$, $r = .68$, and use of size decreased with age, $J = 2617$, $z = -5.27$, $r = -.44$. Shape, texture and other reasons did not vary significantly with age.
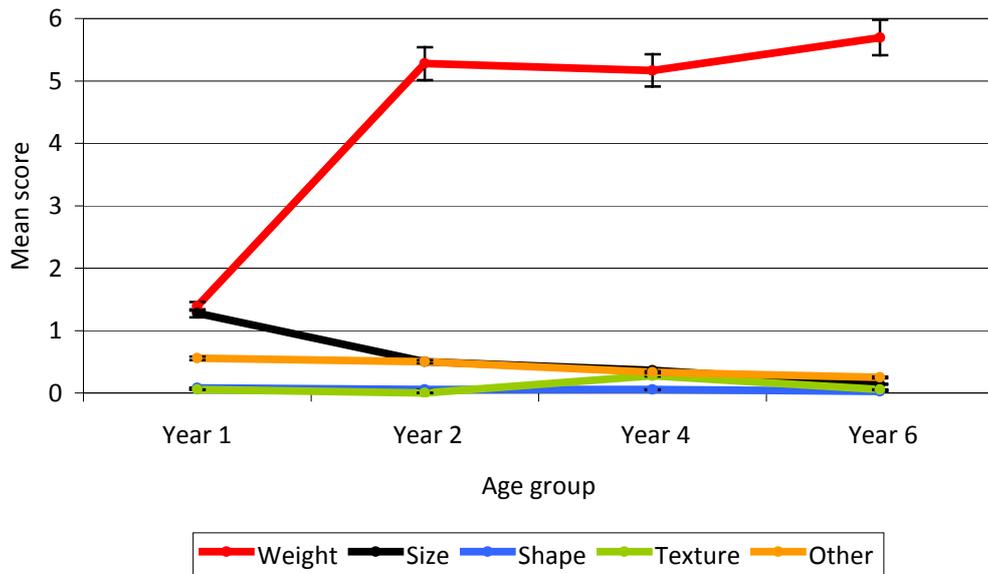
Figure 8.9   Mean scores for justification types in free fall motion by age groups (Maximum possible score = 6)

8.4.3 Directions of justifications

Figure 8.10 (p. 148) shows the mean scores for overall faster motion justification directions. For each justification direction used by children in their predictions of faster motion, a maximum score of 18 was obtainable. Faster motion was significantly associated with heaviness (M = 4.72, SD = 2.60) over lightness (M = 1.90, SD = 2.29), T = 8, p < .001, r = -.68, roundness (M = 3.18, SD = 2.09) over unevenness (M = 0.02, SD = 0.11), T = 10, p < .001, r = -.80, and smoothness (M = 2.21, SD = 1.80) over roughness (M = 0.35, SD = 0.75), T = 8, p < .001, r = -.67. No significant effect of justification direction was found for size.

147
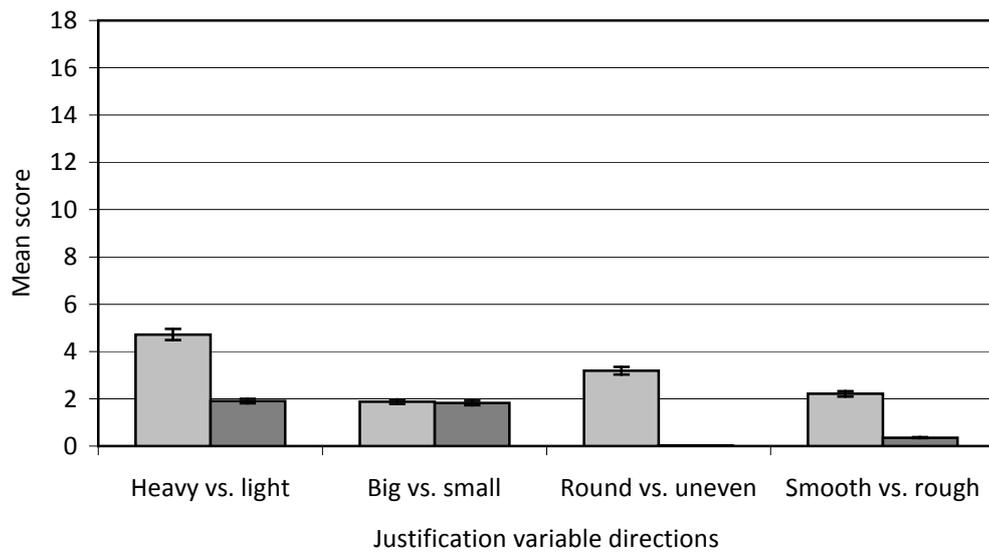
Figure 8.10   Mean scores for overall directions of justification variables (Maximum possible score = 18)

8.4.4 Motion along a horizontal

Figure 8.11 (p. 149) shows the mean scores for overall faster motion justification directions for motion along a horizontal. For each justification direction, a maximum score of 6 was obtainable.
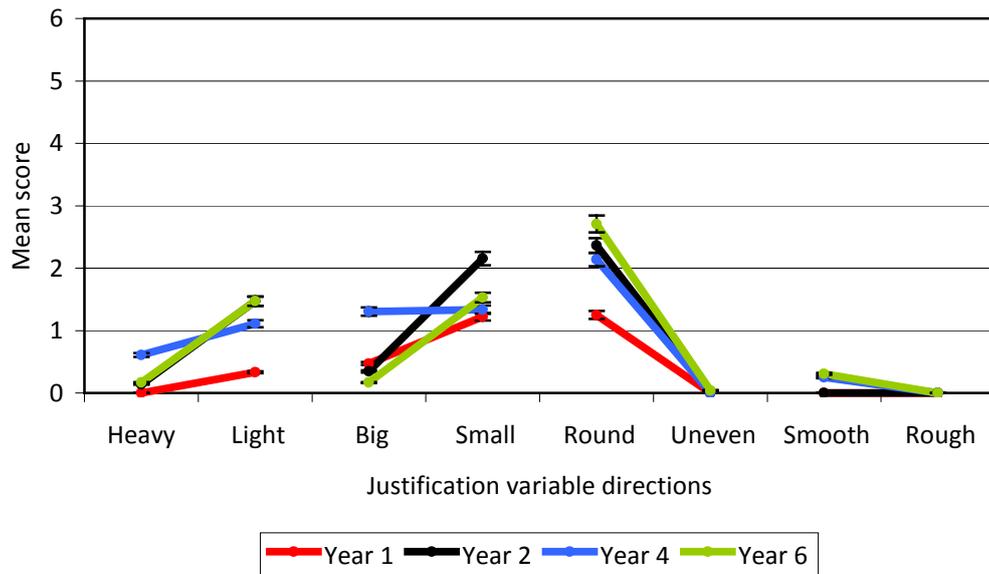
Figure 8.11   Mean scores for directions of justification variables in horizontal motion (Maximum possible score = 6)

8.4.4.1 Object weight

Overall, faster horizontal motion was significantly associated with lightness (*M* = 1.10, *SD* = 1.30) over heaviness (*M* = 0.23, *SD* = 0.60), *T* = 6, *p* < .001, *r* = -.50. Among Year 1, Year 2 and Year 6 children, the same difference (all *p* < .05) was observed, and among Year 4 children there was no significant difference.

8.4.4.2 Object size

Overall, faster horizontal motion was significantly associated with smallness (*M* = 1.56, *SD* = 1.30) over bigness (*M* = 0.57, *SD* = 1.00), *T* = 6, *p* < .001, *r* = -.48. Among Year 1, Year 2 and Year 6 children, the same difference (all *p* < .05) was observed, and among Year 4 children there was no significant difference.

8.4.4.3 Object shape

Overall, faster horizontal motion was significantly associated with roundness (M = 2.11, SD = 1.46) over unevenness (M = 0.01, SD = 0.07), T = 9, p < .001, r = -.77. Among all four age groups, the same difference (all p < .001) was observed.

8.4.4.4 Object texture

Overall, faster horizontal motion was significantly associated with smoothness (M = 0.14, SD = 0.57) over roughness (M = 0.00, SD = 0.00), T = 2, p < .05, r = -.17. Among Year 6 children, faster motion was significantly associated with smoothness (M = 0.31, SD = 0.82) over roughness (M = 0.00, SD = 0.00), T = -2, p < .05, r = -.34. Year 1, Year 2 and Year 4 children made no reference to texture.

<u>8.4.5 Motion down an incline</u>

Figure 8.12 (p. 151) shows the mean scores for overall faster motion justification directions for motion down an incline. For each justification direction, a maximum score of 6 was obtainable.
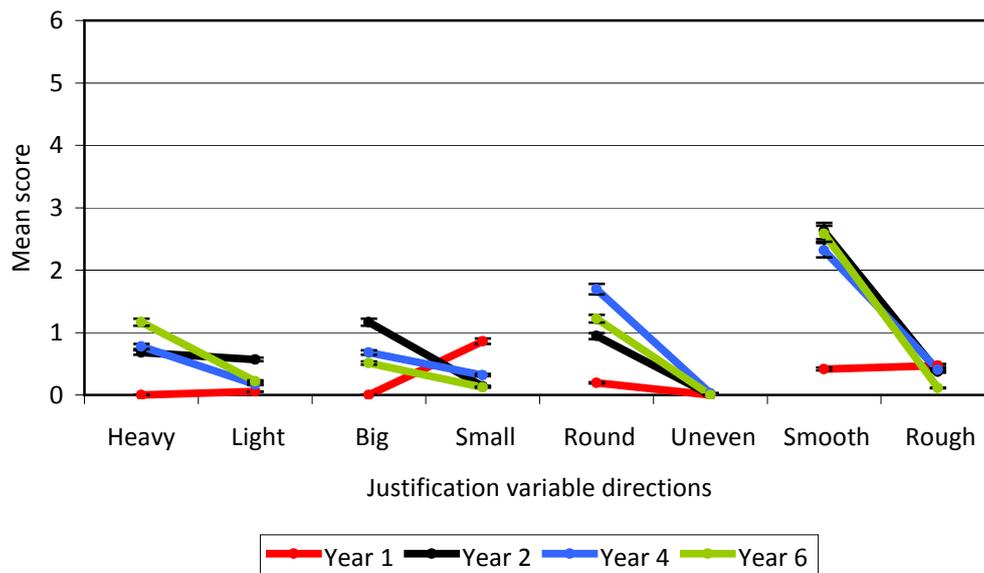
Figure 8.12   Mean scores for directions of justification variables in incline motion (Maximum possible score = 6)

8.4.5.1 Object weight

Overall, faster motion down an incline was significantly associated with heaviness (M = 0.66, SD = 0.92) over lightness (M = 0.25, SD = 0.92), T = 5, p < .001, r = -.41. Among Year 4 and Year 6 children, the same difference (all p < .05) was observed, and among Year 1 and Year 2 children there was no significant difference.

8.4.5.2 Object size

Overall, faster motion down an incline was significantly associated with bigness (M = 0.59, SD = 0.99) over smallness (M = 0.36, SD = 0.75), T = 6, p < .001, r = -.54. Year 1 children showed a preference for smaller objects moving faster, T = 4, p < .001, r = -.60, but among the three older age groups, the preference was for big objects moving faster (all p < .05).

8.4.5.3 Object shape

Overall, faster motion down an incline was significantly associated with roundness (M = 1.01, SD = 1.08) over unevenness (M = 0.01, SD = 0.08), T = 8, p < .001, r = -.66. Among all four age groups, the same difference (all p < .05) was observed.

8.4.5.4 Object texture

Overall, faster motion down an incline was significantly associated with smoothness (M = 1.99, SD = 1.65) over roughness (M = 0.34, SD = 0.75), T = 8, p < .001, r = -.65. Among Year 2, Year 4 and Year 6 children, the same difference (all p < .001) was observed, and among Year 1 children there was no significant difference.

<u>8.4.6 Motion in free fall</u>

Figure 8.13 (p. 153) shows the mean scores for overall faster motion justification directions for motion in free fall. For each justification direction, a maximum score of 6 was obtainable.
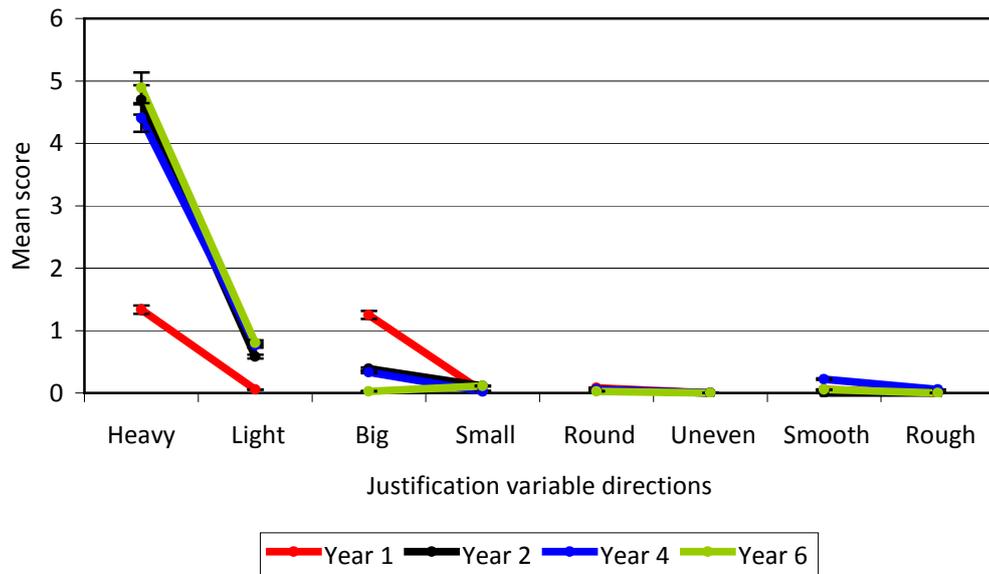
Figure 8.13   Mean scores for directions of justification variables in free fall motion

(Maximum possible score = 6)

8.4.6.1 Object weight

Overall, faster motion in free fall was significantly associated with heaviness (M = 3.83, SD = 1.95) over lightness (M = 0.55, SD = 0.91), T = 9, p < .001, r = -.77. Among all four age groups, the same difference (all p < .001) was observed.

8.4.6.2 Object size

Overall, faster motion in free fall was significantly associated with bigness (M = 0.50, SD = 0.86) over smallness (M = 0.07, SD = 0.26), T = 5, p < .001, r = -.43. Among Year 1, Year 2 and Year 4 children, the same difference (all p < .05) was observed, and among Year 6 children there was no significant difference.

8.4.6.3 Object shape

Overall, faster motion in free fall was significantly associated with roundness (M = 0.06, SD = 0.23) over unevenness (M = 0.00, SD = 0.00), T = 3, p < .05, r = -.24. No

significant differences were found for any of the four age groups when they were considered separately.

8.4.6.4 Object texture

Overall, faster motion in free fall was significantly associated with smoothness (M = 0.08, SD = 0.31) over roughness (M = 0.01, SD = 0.08), T = 3, p < .05, r = -.22. Year 2 children made no reference to texture, and the other three age groups showed no significant preference for either.

8.5 Discussion

This study was an attempt to establish what general beliefs children hold about speed of different everyday objects following three different kinds of motion paths. It was not concerned with whether primary school children's predictions about object motion were consistent with accepted scientific views or not, but instead it addressed the variables that affect children's predictions about object motion, and how predictions and variable use compare across different motion types.

8.5.1 Variables used in children's justifications of object motion

Children's justifications about object motion could be grouped into five categories. Predictions were either made on the basis of object weight, object size, object shape, object texture, or other reasons. The last group included a range of reasons referring to attributes of the objects that did not fit into any of the other categories, such as "the truck will be faster than the car because it has more wheels than the car", or reasons that were not necessarily attributes of the objects themselves, such as "the car will be faster than the truck because cars are faster than trucks in real life". Overall, it would, at least at first glance, appear that the results are in concordance with Galili's (2001) idea of weight being a rather important variable in reasoning about the physical world. Almost 40 per cent of all justifications in this study were weight-based. Where motion in free fall was concerned, weight

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accounted for over 85 per cent of justifications. However, in horizontal motion weight only accounted for a quarter of justifications, and in incline motion for less than 20 per cent. Instead, horizontal motion justifications were dominated by size and shape (almost 40 per cent each), and incline motion justifications by texture (45 per cent), with size and shape being used in about one fifth of cases, just like weight.

Of course, the objects used in each of the motion types were different, thereby making cross-motion-type comparisons a little difficult. If the incline motion objects had been used to make predictions for horizontal motion and for free fall, perhaps texture would have outweighed the other variables as well (although it would seem unlikely for motion in free fall). In fact, the objects used for horizontal motion predictions do not really offer much obvious variation in texture. Younger children appeared to rely more on size than older children, and less on weight; it seems that only when visual aspects, that is, size or shape, could not account for any predicted differences in motion did they turn to the intrinsic variable (although this was only shown to be true for free fall motion – while the use of weight increased over age in all three motion types, size did not change over age in horizontal motion and incline motion).

8.5.2 Directions of variables

Not only was the study interested in what variables are used in children's reasoning, but also with the directions of these variables in relation to object motion. The use of shape and texture as means of justification may be interesting per se, but the directions associated with faster speed are less so. When used as a justification, faster speed was, perhaps not unsurprisingly, almost always associated with roundness and smoothness of objects, no matter which motion type was concerned. However, where object weight and size are concerned, a different picture emerges from the results. Given the literature on understanding of object motion in free fall, it does not come as a surprise that here, too, children mainly associated faster motion with heavier objects across all ages, though children in the youngest age group also referred to size reasonably often, almost as frequently as to weight, and

faster motion was associated with bigger objects. Horizontal motion, on the other hand, was associated with lighter and smaller objects, again fairly consistently across all ages. This observation is in concordance with previous work suggesting that in horizontal scenarios children under the age of 12 years associate heavy objects with higher resistance to motion (Howe, 1991, as cited in Howe, 1998). There was, however, less consistency for incline motion. While younger children predicted faster motion for lighter and smaller objects, there was a clear shift in conceptions, with older children predicting faster motion for heavier and bigger objects. This, too, is consistent with prior work by Howe et al. (1992, as cited in Howe, 1998).

8.5.3 Interaction of motion dimensions

A final aspect the study was trying to investigate was how the three motion types are connected in terms of children's reasoning about motion taking place. It might seem fair to conclude that motion in horizontal and motion in vertical dimensions are not considered in the same way, at least as far as justification directions are concerned. In fact, inverse pictures emerged for the two motion types – while faster motion along a horizontal was generally associated with small and light objects, faster motion in free fall was associated with big and heavy objects, and both views were held consistently over age. So indeed, the two motion types do seem to be differentiated psychologically from each other at least to some degree, lending support to previous ideas (Hayes, 1979; Howe, 1998).

However, what about motion down an incline? Is it perceived to be an integration of horizontal and vertical dimensions, or do children treat it as a third, independent, dimension that bears no significant relation to either horizontal or vertical paths? This is a difficult question to answer on the basis of the present results. As mentioned already, object variable use in predictions varied among motion types, and this could of course suggest that children consider each motion type independently from the other. At the same time, however, the possibility of incline motion being an integration of horizontal and vertical motion cannot be refuted on the basis of the results either. In fact, the variance in justifications among motion

types was possibly more due to the difference in objects used and less due to the difference in motion dimensions per se. So children may indeed consider the three motion types as interrelated, but no answer can be provided at this point, only speculation.

8.6 Summary

Primary children are able to use a variety of variables when reasoning about motion of everyday objects. Five main justification variables were identified in this study. Although object shape and texture were always associated with faster motion in one variable direction only, that is, roundness and smoothness, weight and size varied somewhat in their directional associations with faster motion. Faster horizontal motion was consistently associated with lightness and smallness of objects, and faster vertical motion consistently with heaviness and bigness. Motion down an incline, on the other hand, was associated with lightness and smallness in younger children and with heaviness and bigness in older children. This would seem to be an indicator of conceptual change and thus supports the notion of early intervention.

CHAPTER 9:

YOUNG CHILDREN'S EXPLICIT BELIEFS ABOUT MOTION USING A 'SCIENTIFIC' APPARATUS (STUDY 2)

9.1 Overview

Clearly, a variety of variables are available to and used by children when predicting object motion, as shown in Study 1. The first chapter of this thesis showed, however, that the particular variable creating dissonance between Aristotelian and Newtonian physics is object weight. To further the first objective of this thesis – how variables affect children's predictions of dynamic events – a more controlled study is presented here, which focuses on weight.

The task of mental modelling, which was introduced in Chapter 2, is made easier when the object in question is in front of the reasoner acting to support the structure in imagination (e.g. Nersessian, 2002a). So if an entire apparatus is provided, rather than just the individual objects and having to imagine the environment in which they are supposedly moving, model-based reasoning should be facilitated. However, does it cause differences in results when children are provided with all information bar the dynamics, or is children's understanding of motion sufficiently robust that they would not necessarily require any prompts in form of an apparatus? Also, as established in Study 1, object weight may indeed seem to be an important variable in children's reasoning, consistent with Galili's (2001) view. It was noted, however, that when reasoning about horizontal motion and about motion down an incline object texture, object shape and object size played important roles as well. If object shape and object size are kept constant in comparisons and texture differences are minimal, will predictions be made based on object weight, and if so, what direction will justifications take?

In order to appreciate naturalness of motion, changes in speed often need to be registered, that is, children need to show an understanding of acceleration or

deceleration, or at least an appreciation of their occurrence without necessarily needing to understand the details involved. As for the understanding of speed, explicit understanding of acceleration and deceleration, too, has been covered by some researchers (Champagne et al., 1980, as cited in McDermott, 1984; Kim & Spelke, 1992; Nachtigall, 1982; Piaget, 1970a; Raven, 1972; Trowbridge & McDermott, 1981). But there is no consistent age range among these studies; studies with children, for example, do not seem to have looked at speed changes in motion along a horizontal. And again, none of the studies integrated different motion dimensions. The current study was therefore an attempt to fill this gap in the literature.

The second objective noted at the beginning of this thesis was addressing what can be said about children's ideas as to how motion types inform each other, if they do so at all. While Study 1 was able to provide information on how children reason about object motion along different paths, a viable conclusion as to how these inform each other could not be drawn. Although differences in justifications emerged, these were quite possibly due to a different set of objects being used for each motion type, where there was no commonality in object variables across the three blocks. The previous literature, too, cannot provide an ultimate answer because there is a range of weight-related outcomes emerging from the research. In free fall, the research is relatively consistent, finding that faster motion is largely associated with heavy objects (Baker et al., 2009; Chinn & Malhotra, 2004; Nachtigall, 1982; Sequeira & Leite, 1992), and Study 1 confirmed this observation. In horizontal dimensions, however, faster motion sometimes seems to be associated with lighter objects (Maloney, 1988) and sometimes with heavier objects (Howe, 1991, as cited in Howe, 1998). In incline motion, too, there appears to be no consistency, but here it is an issue within tasks rather than between studies (Howe et al., 1992, as cited in Howe, 1998; Inhelder & Piaget, 1958), with associations changing across age.

With the exception of free fall, where one might expect to find faster motion to be associated with heavier objects in general, will faster motion in the other two

dimensions be associated more with heaviness or more with lightness of objects, given the same objects are used and the same children reason about all three dimensions? In the present study, therefore, the number of objects to be considered for comparison was reduced to two balls, and the same balls were used for predictions across all three motion types. Balls are useful objects in the present context, as they do not have high friction coefficients. This means that object friction does not play a crucial role, and comparisons between the three motion types and between two different incline heights could be established more easily.

Furthermore, the current study attempted to investigate how children understand the interaction of incline height and motion changes. Do young children appreciate that when inclines are raised objects roll down faster and when inclines are lowered objects roll down slower? And do children make the same predictions regardless of object weight, or are different balls associated with different changes? The importance of this lies in the fact that changes in incline height cause changes in motion, even when the objects do not change their weight. Children's beliefs about how object motion is affected by incline changes may contribute to appreciating how, if at all, horizontal and vertical dimensions affect children's understanding of object motion in incline situations, or whether incline motion is treated as an independent dimension, much in the same way as horizontal and vertical dimensions are differentiated from each other (Hayes, 1979; Howe, 1998). Given the variances in reasoning observed within studies on incline motion (Howe et al., 1992, as cited in Howe, 1998; Inhelder & Piaget, 1958), can this be expected here, too, and if so, could this provide more information about how children reason about motion down inclines?

9.2 Research questions

1. If other variables are kept as constant as possible, how does weight affect primary school children's predictions of motion in all three dimensions, that is, horizontal motion, motion down an incline, and motion in free fall?
2. What is primary school children's understanding of speed change?

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3. How do motion dimensions compare, that is, do children hold the same beliefs about speed and speed change if they use the same objects when reasoning about motion along horizontals, motion down inclines and motion in free fall, or do the beliefs differ among dimensions?

4. How do children reason about incline height changes and its effects on object speed, and how might this inform their reasoning about incline motion in general?

9.3 Method

9.3.1 Pilot study

9.3.1.1 Participants

As noted in Chapter 7, the pilot sample for the study consisted of 17 children (nine boys), which included three Year 1 children (two boys; age M = 5.57 years, SD = 0.38), six Year 2 children (four boys; age M = 6.56 years, SD = 0.26), five Year 4 children (three girls; age M = 8.30, SD = 0.13) and three Year 6 children (two girls; age M = 10.71, SD = 0.51).

9.3.1.2 Materials

Two test balls were used; one was a bright pink standard table tennis ball and one was a dark green solid glass marble similar in size to the table tennis ball (both approximately 4 cm in diameter, the table tennis ball weighing approximately 3 g and the marble weighing approximately 75 g). In addition, one practice ball was used as well, a standard squash ball (approximately 4 cm in diameter). The materials further consisted of a transparent acrylic tube of 101.5 cm length and with an internal diameter of 6.5 cm. The tube was marked at equal distances of 50 cm, beginning from the end point (referred to as Point A at 100 cm, Point B at 50 cm and Point C at 0 cm from the end), thus placing the starting point of motion at 1.5 cm inside the tube. A wooden frame allowed the tube to be placed at inclines of two

different angles such that the starting point of motion inside the tube could be at either 15 cm or 30 cm height. A paper track of 101 cm length and 10 cm width was placed underneath the opening of the tube when placed at an incline. The paper track was marked at equal distances of 50 cm, beginning from the tube exit (referred to as Point A at 0 cm, Point B at 50 cm and Point C at 100 cm from the end – Point A on the paper track was therefore at the same location as Point C along the tube), thus placing the opening of the tube, that is, the starting point of horizontal motion, at 1 cm into the paper track. The apparatus, without the paper track and set up as for the incline motion tasks, can be seen in Figure 9.1 (p. 163). In addition to the apparatus and objects, eight different questionnaires were used to guide the tasks and for the researcher to note children's responses to questions (see the appendix, pp. 348-349, for a sample questionnaire). Only one questionnaire was used per child and the random selection of questionnaire determined the test condition for each child (as outlined below).
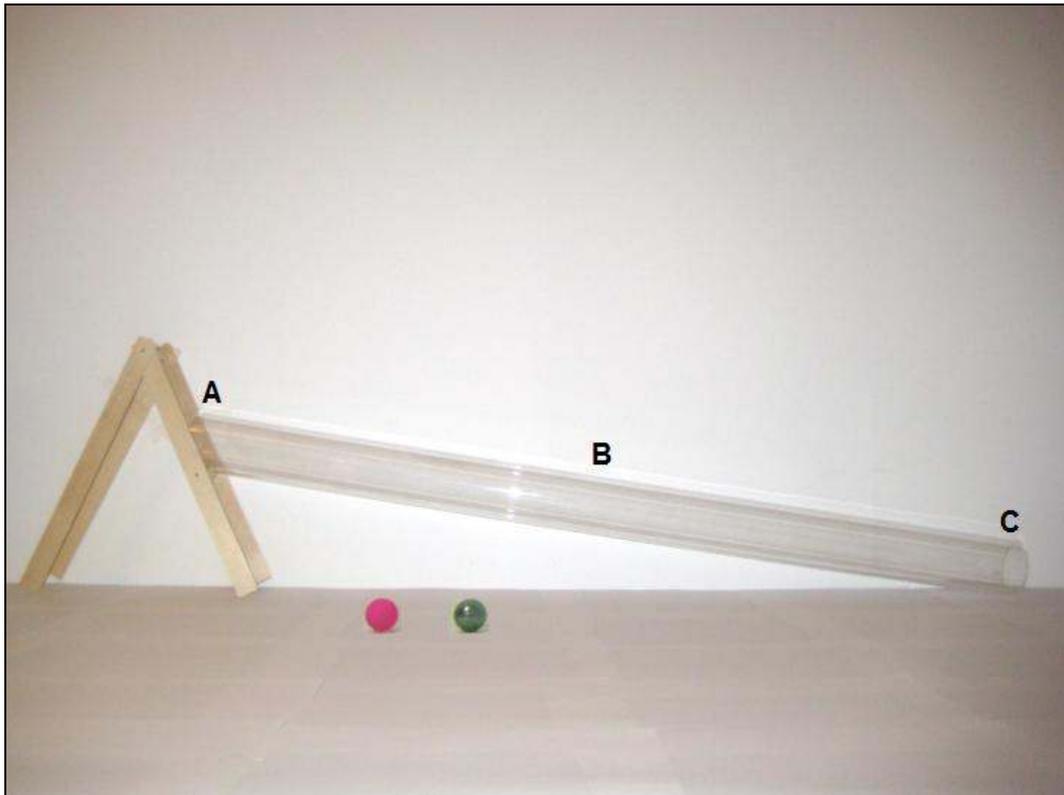
Figure 9.1   Apparatus and test balls used in Study 2, as set up for incline motion tasks with indications of the three points A, B and C relevant for the speed change questions

9.3.1.3 Design

There were four separate blocks within the assessment – two blocks on motion down an incline, one block on motion along a horizontal, and one block on motion in free fall. The horizontal motion blocks always came after the incline motion blocks because horizontal motion, in this case, followed on from motion down the incline, that is, because the objects needed to be in motion without the help of external factors such as having to push them. Incline comparisons were also paired together to facilitate instructions. For each condition there were altogether three control questions and 20 test questions. In four cases – in the second incline block and in the speed change tasks – comparisons needed to be made, that is, motion down a low height incline versus motion down a high height incline, or speed at different points along a path. These comparisons needed to be made for one ball only, either the

glass marble ('heavy') or the table tennis ball ('light'). All comparisons within each condition were made with the same ball.

9.3.1.4 Procedure

The interviews took place outside of the classrooms but in an open and publicly accessible area of the school. Prior to a child joining, a questionnaire was selected at random. Upon arrival, the child was given general information about the study – that the researcher had brought a fun science experiment and that there were going to be some questions about it. It was made clear to the child that participation was voluntary and that completion of individual items or the study as a whole was not compulsory. Information regarding the child's name, gender, year group and date of birth was already available from Study 1 and was not requested again.

At the beginning of the first block the child was introduced to the apparatus, which was set up according to the first block in the respective condition, and was introduced to the three balls, which could be handled at any time, but the child was asked not to carry out any relevant motions with the objects when having to respond to the questionnaire items, that is, not to roll them across the table or deliberately let them fall. At the beginning of each block (with exception of the second incline block in each condition; the incline comparison block) the child was given a control question. This control question only required some general statement about what would happen to the practice ball if it were held into the tube and then released, that is that the ball would roll or fall down the tube. The same question was asked for the horizontal motion block but emphasis was placed on the ball's behaviour along the track rather than the tube. This control question was asked to ensure the child understood the apparatus and was familiar with the general concepts of object motion involved.

For the first incline motion block, regardless of incline height, the child was given the following first instruction (italics were stressed by the researcher in speech): "Imagine you have *two* tubes like this one next to each other, and they are *exactly*

the same. Then imagine you are holding both balls with your hands in the tube, like this [researcher demonstrated this action with hands]. If you let both of them go at the *same time*, do you think one of the two will roll down to the end of the tube faster, or do you think they will both roll as fast as each other?" For the free fall motion block, the child was given the following first instruction: "Imagine you have *two* tubes like this one next to each other, and they are *exactly the same*. Then imagine you are holding both balls with your hands in the tube, like this [researcher demonstrated this action with hands]. If you let both of them go at the *same time*, do you think one of the two will fall down to the bottom of the tube faster, or do you think they will both fall as fast as each other?" In subsequent questions within each block, only the question, not the description, was repeated using the new object pairs. For the second incline, the child was given the following first instruction: "Now watch this. If I put the tube here [researcher changes tube from high to low incline or vice versa], and you let *this* ball [researcher points out comparison ball] roll down the tube, do you think it will roll faster than before, or slower than before, or do you think it will roll as fast as it did before?" In the subsequent item within each block, only the question, not the description, was repeated.

Horizontal motion was always considered to occur following the incline height used in the first incline block, and the apparatus was changed back to how it was set up in the first block. For the horizontal motion block, the child was given the following first instruction (italics were stressed by the researcher in speech): "Remember how we just pretended the two balls were rolling down at the same time? Imagine you have *two* tubes like this one next to each other again, and they are *exactly the same*. Now imagine you are holding the two balls into the tube, like this [researcher demonstrated this action with hands] and you let them go and they reach the bottom of the tube [researcher points out the tube exit] at the *same time* and the balls roll out along here, all the way to the end [researcher points along the paper track]. Do you think one of the two will roll to the end faster, or do you think they will both roll as fast as each other?" In the subsequent item within each block, only the question, not the description, was repeated.

Questions were asked about speed, time taken and distance travelled. In addition, each block, with the exception of the incline comparison block, comprised three questions relating to speed change, which succeeded the speed questions. The child was assured that the distances between Points A and B, between Points A and C, and between Points B and C, which were pointed out by the researcher, were the same before having to respond to the questions. Speed change questions only referred to speed and required a comparison of speeds for only one test ball, choice of ball depending on the condition, at Points A, B and C along the tube or the track. For each item in the block the child was given the following instruction: "If the ball rolls [or falls] from here to here [researcher points out the two Points in question], do you think it will be faster here [researcher points out first Point], or here [researcher points out second Point], or do you think it will be just as fast?"

For each question on speed, there was a choice between three response possibilities: The child could select one of the two objects over another, or state that both would behave the same. In addition, the child was asked to provide justifications, that is, state why they had made their choices. For each question on speed change, there was also a choice between three response possibilities: The child could choose an increase in speed, a decrease in speed, or no change in speed. Justifications were not required. The child's responses were noted on the questionnaire by the researcher. At the end of each block the child was given the option either to take a short break or to continue with the next block of questions. The apparatus was then modified as necessary. The procedure for the remaining three blocks was then the same as for the first block. Each interview lasted approximately 40 to 50 minutes for each child.

9.3.1.5 Outcomes of the pilot study

Due to the difficulties with group administration encountered in the piloting for Study 1, all of the children in Study 2 were assessed individually rather than in groups. No particular problems in the general structure of the sessions were revealed during the piloting. All children took an active interest in the apparatus and

the materials. Having the practice ball increased the children's involvement and interest in the task in general, as well as their interaction with the apparatus.

During the pilot study, questions were asked about speed, time and distance travelled. However, one particular difficulty was noted with this. This was with understanding questions referring to distance, where the children were asked, for example, whether one of the balls would fall or roll *farther* down the incline, or whether they would cover the same distance. It had been intended to function as a control question to suggest to the children that one variable, that is, distance, did not vary throughout the entire task. It became apparent, though, that this question was easily misunderstood. In the horizontal and incline motion scenarios it was not clear whether the children really understood that distance referred to motion up to the end point of the tube or the paper track only, rather than up to the point where the balls would stop moving, even though they had been asked the distance questions after the speed and time questions, for which the end points had been identified to the child by the researcher.

It seems that in this case their decisions about speed and time affected their decisions about distance. However, placing the distance questions before the speed and time questions did not make a difference either. This miscomprehension was particularly noticeable in the free fall scenarios, though, where children claimed that the heavy ball (which was the one selected as being faster and taking less time by all the children in the pilot study) would fall a greater distance – despite neither ball being physically able to fall beyond the table on which the tube stood. The questions relating to distance were thus removed from the interviews during Study 2, and in each block there were therefore only two questions relating to speed, with one question referring to differences in speed and one question referring to differences in time taken.

9.3.2 Main study

9.3.2.1 Participants

As noted in Chapter 7, the Study 2 main sample consisted of 144 children (80 girls), which included 36 Year 1 children (20 girls; age M = 5.70 years, SD = 0.32), 36 Year 2 children (21 girls; age M = 6.68 years, SD = 0.26), 36 Year 4 children (21 girls; age M = 8.64, SD = 0.33) and 36 Year 6 children (18 girls; age M = 10.77, SD = 0.25).

9.3.2.2 Materials

The materials were the same as used in the pilot study.

9.3.2.3 Design

The general design was the same as in the pilot study. With the exception of the horizontal-incline order and the two incline blocks being together, the order of blocks and the order of comparisons within each block were randomised, giving eight different conditions, such that the questionnaires either began with the questions about objects rolling down one of the two inclines, or about objects in free fall (see Table 9., p. 169). Because of removing questions on distance travelled, for each condition there were altogether only three control questions and 17 test questions. Each child contributed to all four blocks. For each direction, that is, whenever the heavy ball and whenever the light ball was chosen to be faster, each child thus scored between 0 and 6 for the speed questions (for each block the score was between 0 and 2), between 0 and 2 for the incline comparison questions, and between 0 and 9 for the speed change questions (for each block the score was between 0 and 3). Equal numbers of children per age group were selected for each condition, that is, 12 children per age group were selected for each condition.

Table 9.1   Conditions in Study 2

	Condition							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Incline comparisons[6]	Heavy ball	Light ball	Heavy ball	Light ball	Heavy ball	Light ball	Heavy ball	Light ball
Block 1	Incline at 15 cm (both balls)		Incline at 30 cm (both balls)		Free fall (both balls)		Free fall (both balls)	
Block 2	Incline at 30 cm (one ball)		Incline at 15 cm (one ball)		Incline at 15 cm (both balls)		Incline at 30 cm (both balls)	
Block 3	Horizontal (both balls)		Horizontal (both balls)		Incline at 30 cm (one ball)		Incline at 15 cm (one ball)	
Block 4	Free fall (both balls)		Free fall (both balls)		Horizontal (both balls)		Horizontal (both balls)	

9.3.2.4 Procedure

The general procedure was the same as in the pilot study but with distance-related questions removed. During the piloting, questions had been asked about speed, time and distance travelled, and it was noted that questions referring to distance travelled, where the children were asked, for example, whether one of the balls would fall or roll farther down the incline, or whether they would cover the same distance, appeared to be rather confusing. While it had only been intended as a control question to suggest that one variable, distance, did not vary throughout the task, it became apparent that the children easily misunderstood the question. In the horizontal and incline motion scenarios it was not clear whether the children really understood that distance referred to motion up to the end point of the tube or the paper track only, rather than up to the point where the balls would stop moving. This

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[6] Incline comparisons (either in Block 2 – Conditions 1 to 4 – or in Block 3 – Conditions 5 to 8 – only needed to be made for two inclines with the same ball; the condition determines whether this was the heavy ball or the light ball.

miscomprehension was particularly noticeable with the free fall scenarios, where children claimed that one of the balls would fall a greater distance – despite neither ball being physically able to fall beyond the table on which the tube stood. The questions relating to distance were thus removed from the interviews during Study 2, and in each block there were therefore only two questions relating to speed, with one question referring to differences in speed and one question referring to differences in time taken. The removal of the distance questions meant that each interview now lasted approximately 30 to 40 minutes for each child.

9.4 Results

9.4.1 Methods of analysis

All children passed all control questions (where predictions had to be made for the practice ball), so data for all children qualified for analysis. Two justification types were identified from the responses. These were references to the objects' weight or texture. Where justifications were made, reference was always made to weight. Very rarely was any reference made to texture of the balls, and where this was the case it was always in conjunction with weight. Weight was broken down into its two directions, 'heavy' and 'light'. No misattribution of weight was observed, that is, no child stated the table tennis ball was heavier than the glass marble or vice versa. Data were collected in the form of response choices (see 9.3.2.3). In line with the physics of object motion (see Chapter 4) speed change was analysed in terms of acceleration, that is, speeding up, for free fall motion and for incline motion, and as deceleration, that is, slowing down, for motion along the horizontal.

Kolmogorov-Smirnov tests on the normality of distribution of data showed that all distributions deviated significantly from normality. Therefore assumptions for parametric tests were not met. Wilcoxon signed-rank tests showed no significant differences between scores for questions asking about time taken and scores for questions asking about speed. Therefore the scores of the two sets were merged, that is, scores for 'faster' and 'less time' were grouped, to avoid reporting similar

results twice. Mean scores were analysed using Friedman's ANOVAs and post hoc Wilcoxon signed-rank tests, with Bonferroni corrections applied (all significance thresholds $p \leq .025$). Effects of gender and effects of ball type were analysed with Mann-Whitney tests. Effects of age and effects of conditions were analysed with Kruskal-Wallis tests and post hoc Jonckheere-Terpstra tests. No significant gender or condition effects were found, therefore these are not considered further. All data were analysed using PASW (Predictive Analytics Software, formerly SPSS) Statistics version 18.

9.4.2 Speed

Figure 9.2 (p. 172) shows the mean scores for overall faster motion response options, whether the heavy ball or the light ball would be faster, or whether the two would be the same. A maximum score of 6 was obtainable. There was significant variation among mean scores for response options, $\chi^2(2, N = 144) = 208.80$, $p < .001$. Different-speed options ($M = 5.81$, $SD = 0.47$) were chosen significantly more often than same-speed options ($M = 0.19$, $SD = 0.47$), $T = 11$, $r = -.94$. But there was no overall significant difference between choosing the heavy or the light ball as being faster.
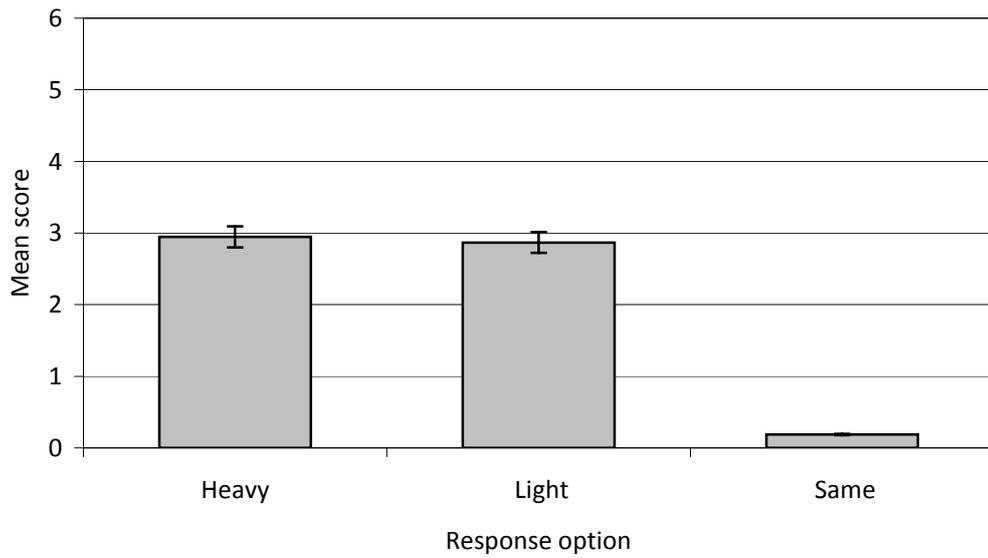
Figure 9.2   Mean scores for overall response options (Maximum possible score = 6)

Figure 9.3 (p. 173) shows the mean scores for overall justification types by age groups. There was a significant interaction of age with mean scores for choosing the heavy ball as faster, $H(3) = 28.22$, $p < .001$. Mean scores increased with age, $J = 5188$, $z = 4.84$, $r = .40$. There was also a significant interaction of age with mean scores for choosing the light ball as faster, $H(3) = 31.46$, $p < .001$. Mean scores decreased with age, $J = 2433$, $z = -5.38$, $r = -.45$. There was no significant interaction of age with mean scores for same-speed options.
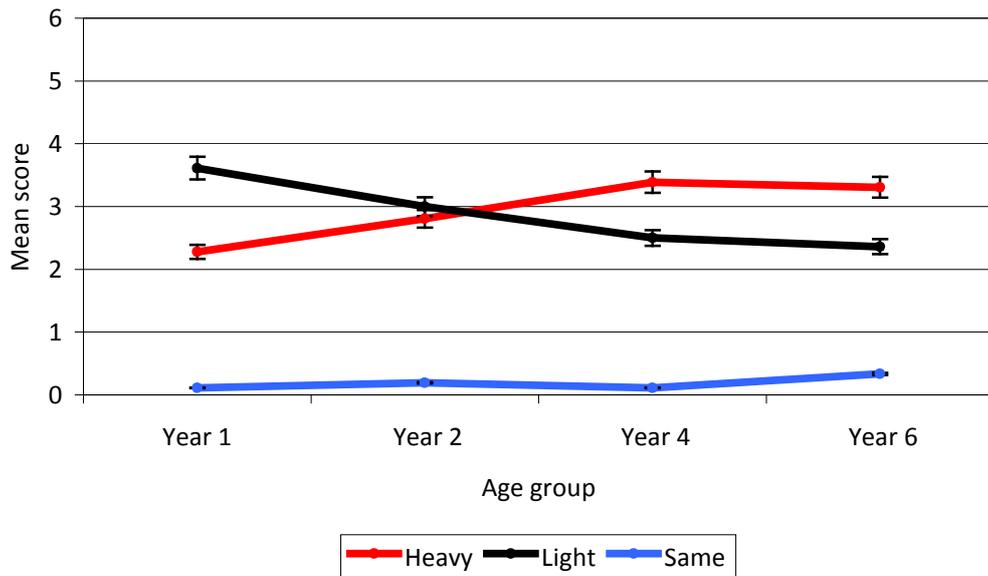
Figure 9.3   Mean scores for overall justification types by age groups (Maximum possible score = 6)

9.4.2.1 Motion along a horizontal

Figure 9.4 (p. 174) shows the mean scores for overall faster motion response options in the horizontal motion block, whether the heavy ball or the light ball would be faster, or whether the two would be the same. A maximum score of 2 was obtainable. There was significant variation among mean scores for horizontal motion response options, χ^2(2, *N* = 144) = 191.85, *p* < .001. The light ball (*M* = 1.66, *SD* = 0.57) was predicted significantly more often to be faster than the heavy ball (*M* = 0.28, *SD* = 0.52), *T* = 9, *r* = -.78. The heavy ball being faster was predicted more frequently than making a same-speed prediction (*M* = 0.06, *SD* = 0.23), *T* = 11, *r* = -.88.
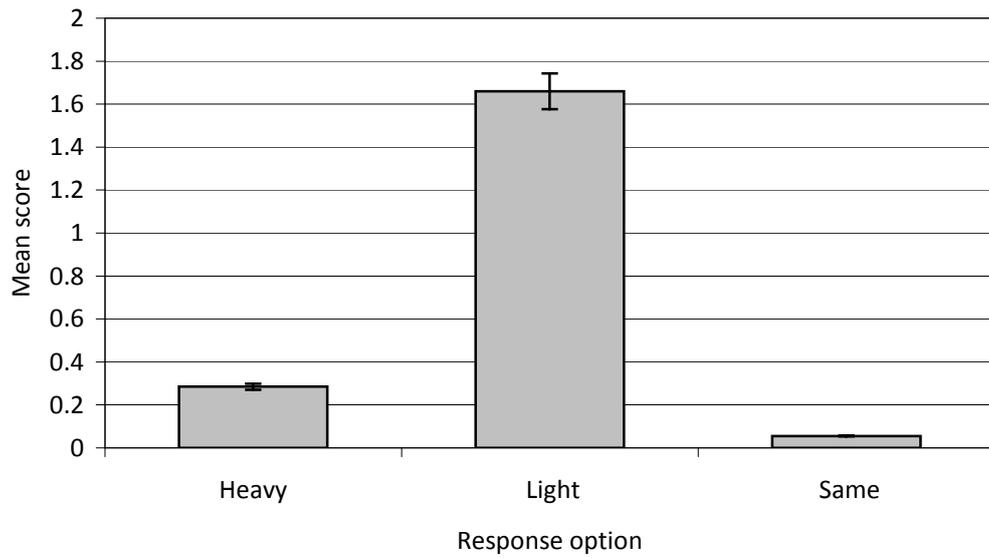
Figure 9.4   Mean scores for response options in horizontal motion (Maximum possible score = 2)

Figure 9.5 (p. 175) shows the mean scores for horizontal motion predictions by age groups. Age did not interact significantly with mean scores. Regardless of age, children consistently predicted the light ball to be faster.
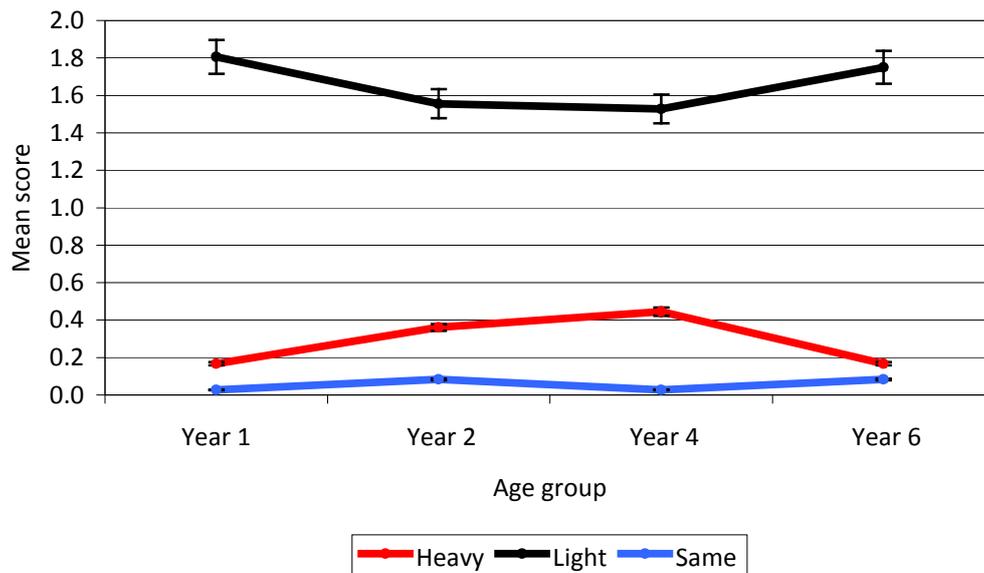
Figure 9.5   Mean scores for predictions in horizontal motion by age groups (Maximum possible score = 2)

9.4.2.2 Motion down an incline

Figure 9.6 (p. 176) shows the mean scores for overall faster motion response options in the incline motion block, whether the heavy ball or the light ball would be faster, or whether the two would be the same. A maximum score of 2 was obtainable. There was significant variation among mean scores for response options, χ^2(2, N = 144) = 93.76, p < .001. There was no significant preference for predicting either of the balls as being faster. But both predicting the heavy ball to be faster (M = 1.00, SD = 0.84), T = 8, r = -.68, and predicting the light ball to be faster (M = 0.94, SD = 0.85), T = 8, r = -.65, was done significantly more often than choosing the same-speed option (M = 0.06, SD = 0.27).
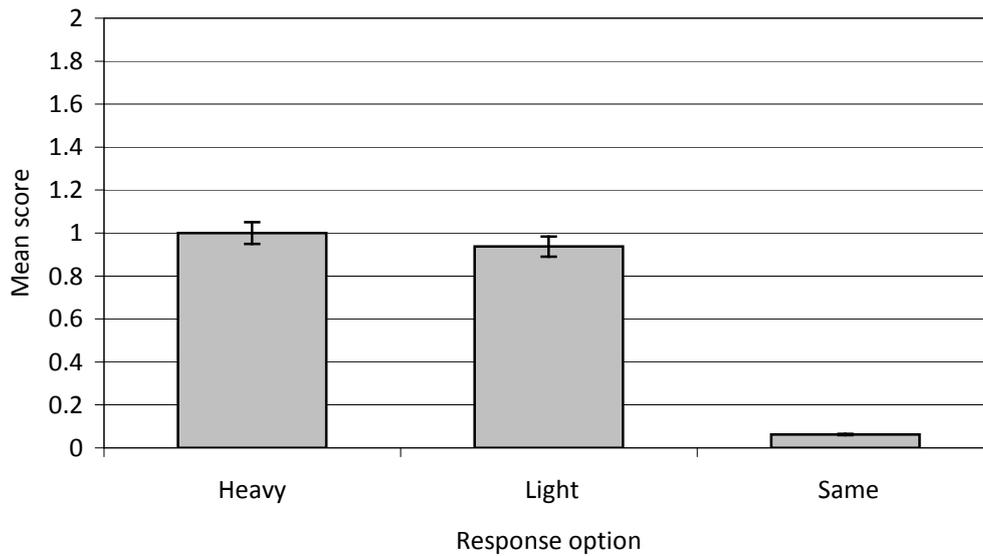
Figure 9.6   Mean scores for response options in incline motion (Maximum possible score = 2)

Figure 9.7 (p. 177) shows the mean scores for incline motion predictions by age groups. There was significant variation with age for predicting the heavy ball to be faster, $H(3) = 54.91$, $p < .001$, with mean scores increasing with age, $J = 5875$, $z =7.54$, $r = .63$. There was significant age variation for predicting the light ball to be faster, $H(3) = 54.91$, $p < .001$, with mean scores decreasing with age, $J = 1908$, $z = -7.54$, $r = -.63$. There was no significant interaction of age with mean scores for same-speed options.
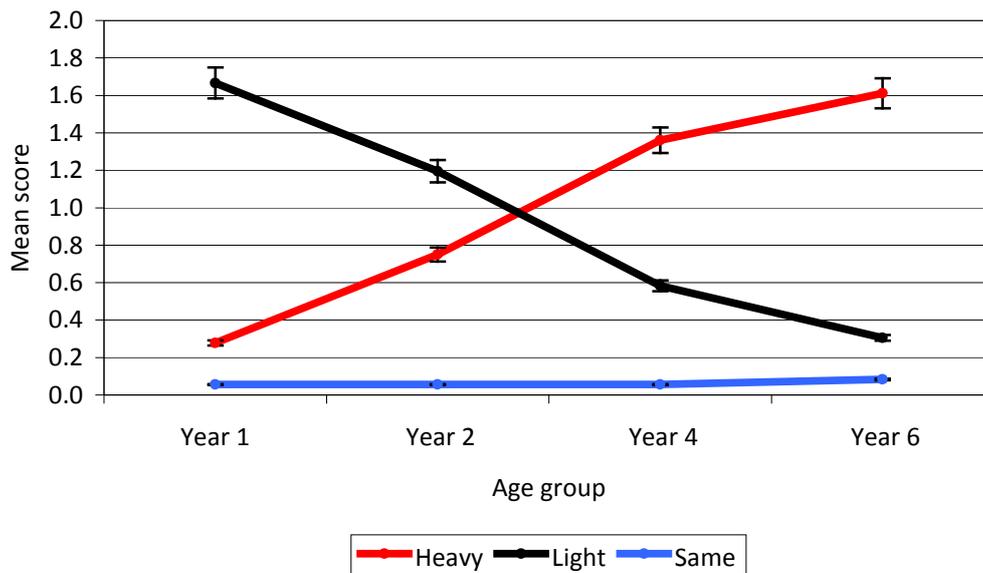
Figure 9.7   Mean scores for predictions in incline motion by age groups (Maximum possible score = 2)

9.4.2.3 Motion in free fall

Figure 9.8 (p. 178) shows the mean scores for overall faster motion response options in the free fall motion block, whether the heavy ball or the light ball would be faster, or whether the two would be the same. A maximum score of 2 was obtainable. There was significant variation among mean scores for free fall motion response options, χ^2(2, *N* = 144) = 197.26, *p* < .001. The heavy ball (*M* = 1.66, *SD* = 0.56) was predicted significantly more often to be faster than the light ball (*M* = 0.27, *SD* = 0.49), *T* = 10, *r* = -.80. The light ball being faster was predicted more frequently than making a same-speed prediction (*M* = 0.06, *SD* = 0.23), *T* = 4, *r* = -.30.
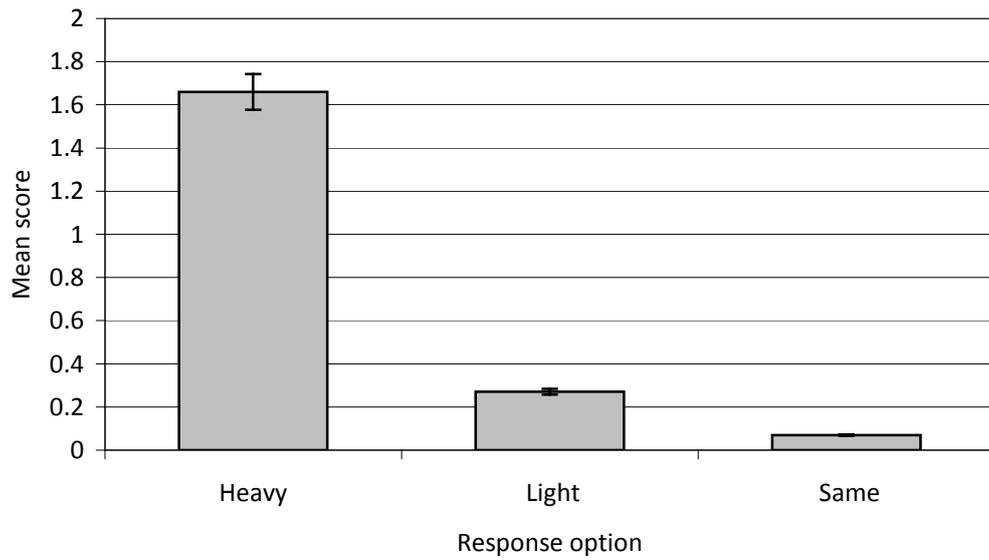
Figure 9.8   Mean scores for response options in free fall motion (Maximum possible score = 2)

Figure 9.9 (p. 179) shows the mean scores for free fall motion predictions by age groups. Age did not interact significantly with mean scores. Regardless of age, children consistently predicted the heavy ball to be faster.
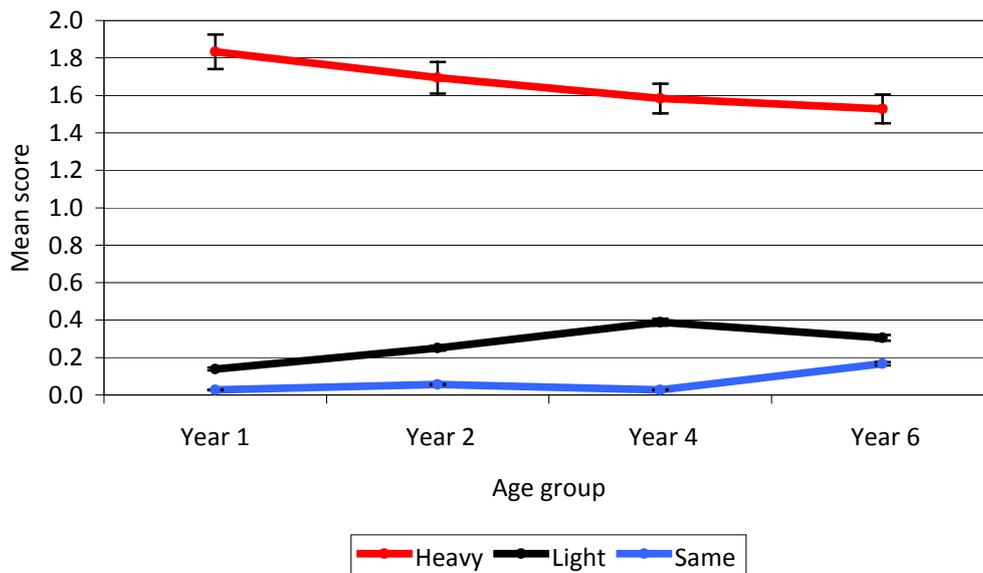
Figure 9.9   Mean scores for predictions in free fall motion by age groups (Maximum possible score = 2)

9.4.3 Incline height comparisons

Figure 9.10 (p. 180) shows the mean scores for faster motion response options in incline comparisons, that is, where children had to compare motion down a high incline with the same ball's motion down a low incline. A maximum score of 2 was obtainable. There was a significant interaction of incline change with mean scores, χ^2(2, *N* = 144) = 50.01, *p* < .001. There was no overall significant preference for faster or slower motion as the incline changed, but both faster motion (*M* = 0.89, *SD* = 1.01), *T* = 7, *r* = -.58, and slower motion (*M* = 1.00, *SD* = 1.01), *T* = 6, *r* = -.53, were significantly preferred over no change at all (*M* = 0.11, *SD* = 0.46). There was no overall age variation. There were no significant differences between the heavy ball and the light ball conditions for faster or slower motion, but there was a significant difference for same-speed choices, where the light ball (*M* = 0.25, *SD* = 0.64) was more likely to be attributed no change in speed than the heavy ball (*M* = 0.01, *SD* = 0.11) as the incline changed, *U* = 2264, *p* < .05, *r* = -.24.
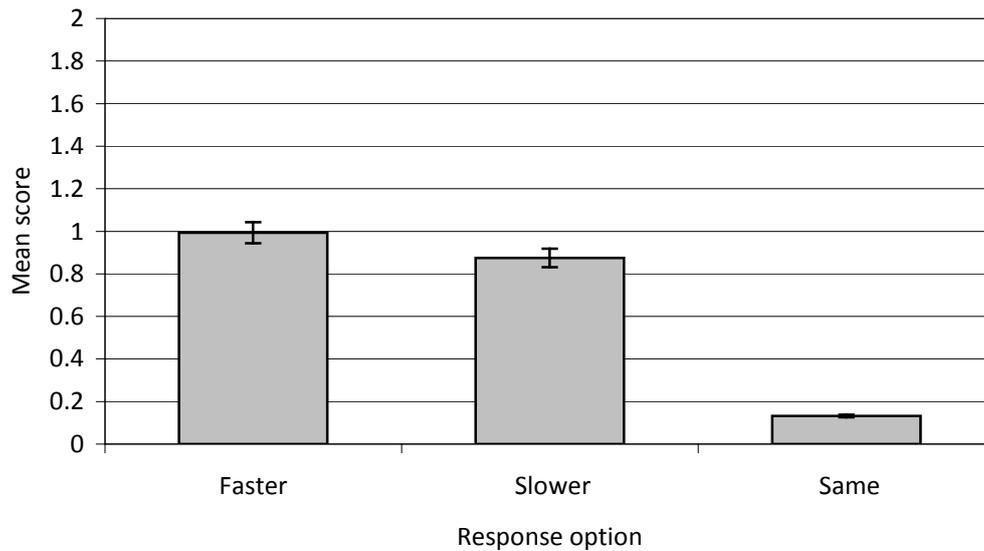
Figure 9.10   Mean scores for response options in incline height comparisons (Maximum possible score = 2)

9.4.3.1 Incline height

Figure 9.11 (p. 181) shows the mean scores for response options in incline comparisons by incline height change. A maximum score of 2 was obtainable. There was a significant difference in speed attribution for direction of incline height change. The balls were predicted to be faster (M = 1.69, SD = 0.68) rather than slower (M = 0.18, SD = 0.54) when the incline height was raised, T = 7, p < .001, r = -.80. There was no significant difference between predicting them to be slower or unchanged. The balls were predicted to be slower (M = 1.57, SD = 0.80) rather than faster (M = 0.29, SD = 0.68) when the incline height was lowered, T = 6, p < .001, r = -.68. There was no significant difference between predicting them to be faster or unchanged. Ball type had no significant effect on either of the incline height changes.
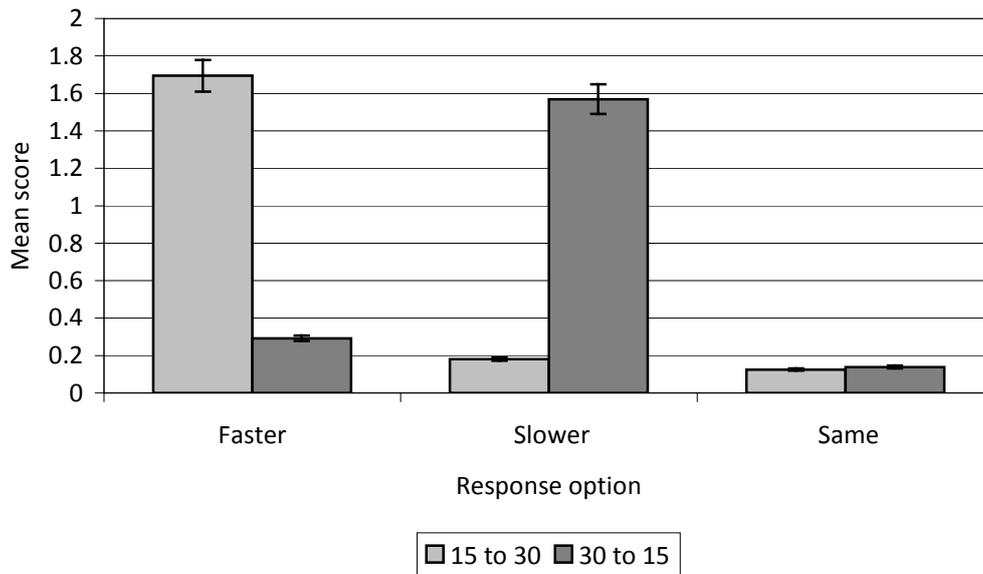
Figure 9.11   Mean scores for response options in incline height comparisons by incline height change (Maximum possible score = 2)

9.4.4 Changes in speed

For speed change, the children were required to compare speeds of one ball at Points A, B and C, which were indicated on the tube and along the horizontal. Figure 9.12 (p. 182) shows mean scores for attributions of changes in speed, that is, whether speed changed or not. A maximum score of 3 was obtainable for each distance AB, AC and BC. Response scores varied significantly, χ^2(2, *N* = 144) = 118.77, *p* < .001. While attribution scores for AB and AC did not differ significantly, both AB (*M* = 2.51, *SD* = 0.88), *T* = 8, *r* = -.67, and AC (*M* = 2.60, *SD* = 0.76), *T* = 8, *r* = -.64, received significantly more correct attributions than BC (*M* = 1.23, *SD* = 1.27).
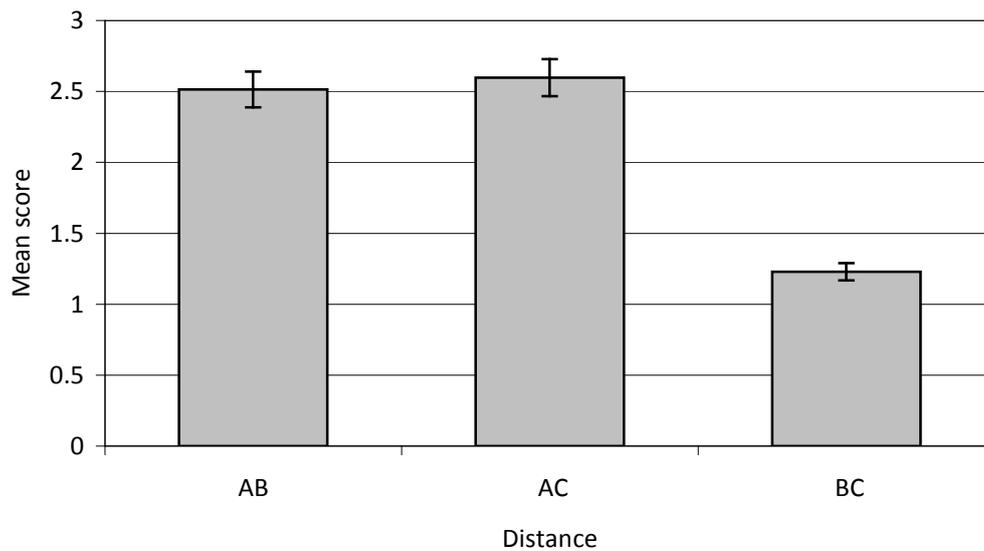
Figure 9.12   Mean scores for attributions of speed change (Maximum possible score = 3)

Figure 9.13 (p. 183) shows the mean speed change attribution scores by age groups. A maximum score of 3 was obtainable for each distance AB, AC and BC. Age interacted significantly with total attribution score, $H(3) = 57.27$, $p < .001$, with speed change attributions increasing with age, $J = 5926$, $z = 7.39$, $r = .62$. Similar age-score interactions were observed for attribution scores to all three distances (all $p < .05$).
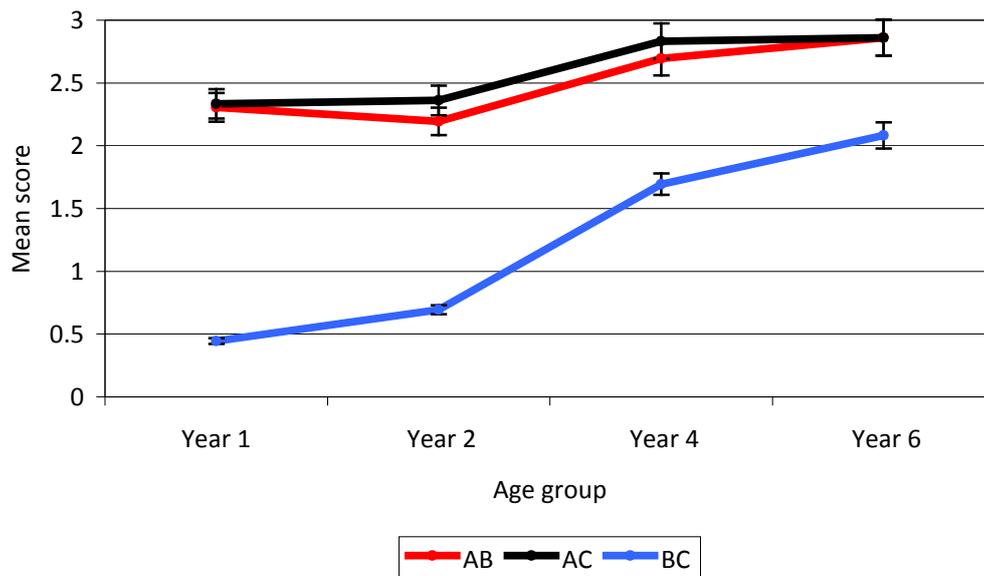
Figure 9.13   Mean scores for attributions of speed change by age groups (Maximum possible score = 3)

Figure 9.14 (p. 184) shows the mean speed change attribution scores by ball weight. A maximum score of 3 was obtainable for each distance AB, AC and BC. The weight of the ball interacted significantly with total attribution score, with more attribution of speed changes to the heavy ball (*M* = 6.73, *SD* = 1.91) rather than the light ball (*M* = 5.94, *SD* = 1.88), *U* = 2000, *p* < .05, *r* = -.20. This difference was significant for AB, *U* = 2074, *p* < .05, *r* = -.22, but not for AC or BC.
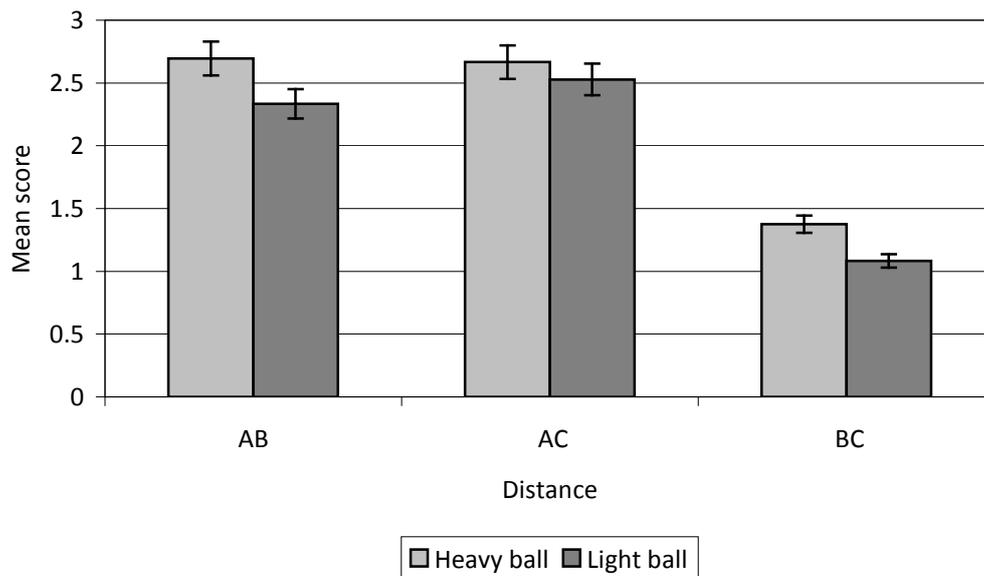
Figure 9.14   Mean scores for attributions of speed change by ball weight (Maximum possible score = 3)

Figure 9.15 (p. 185) shows the distribution of mean scores for attributions of speed changes by motion type. A maximum score of 1 was obtainable for each distance AB, AC and BC in each of the three motion dimensions. Motion type interacted significantly with attributions, χ^2(2, *N* = 144) = 65.00, *p* < .001. Incline scenarios did not receive significantly more attributions than free fall scenarios, but both incline scenarios (*M* = 2.28, *SD* = 0.73), *T* = 7, *r* = -.57, and free fall scenarios (*M* = 2.23, *SD* = 0.69), *T* = 6, *r* = -.48, received significantly more attributions than horizontal scenarios (*M* = 1.83, *SD* = 0.85). For all three motion types, the attribution pattern was the same: Speed change was attributed to AB and AC significantly more often than to AB (all *p* < .025), but there were no differences in attribution between AB and AC.
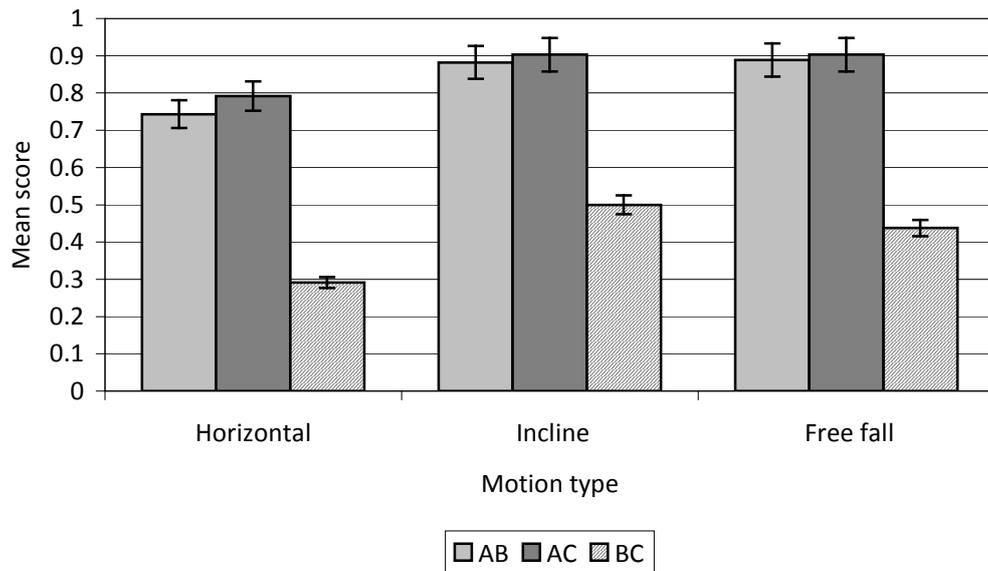
Figure 9.15   Mean scores for attributions of speed change by motion type (Maximum possible score = 1)

Figure 9.16 (p. 186) shows the distribution of mean scores for attributions of speed changes by motion type and by ball weight. A maximum score of 3 was obtainable for each motion dimension. Motion type and object weight interacted significantly. For motion along a horizontal, the heavy ball (*M* = 2.07, *SD* = 0.76) received more attributions of speed change than the light ball (*M* = 1.58, *SD* = 0.87), *U* = 1821, *p* < .05, *r* = -.27, meaning children were more likely to attribute a slowing down to the heavy ball. For motion in free fall, too, the heavy ball (*M* = 2.33, *SD* = 0.71) received more attributions of speed change than the light ball (*M* = 2.13, *SD* = 0.65), *U* = 2123, *p* < .05, *r* = -.17, meaning children were more likely to attribute a speeding up to the heavy ball. For motion down an incline, there was no significant difference between the two balls.
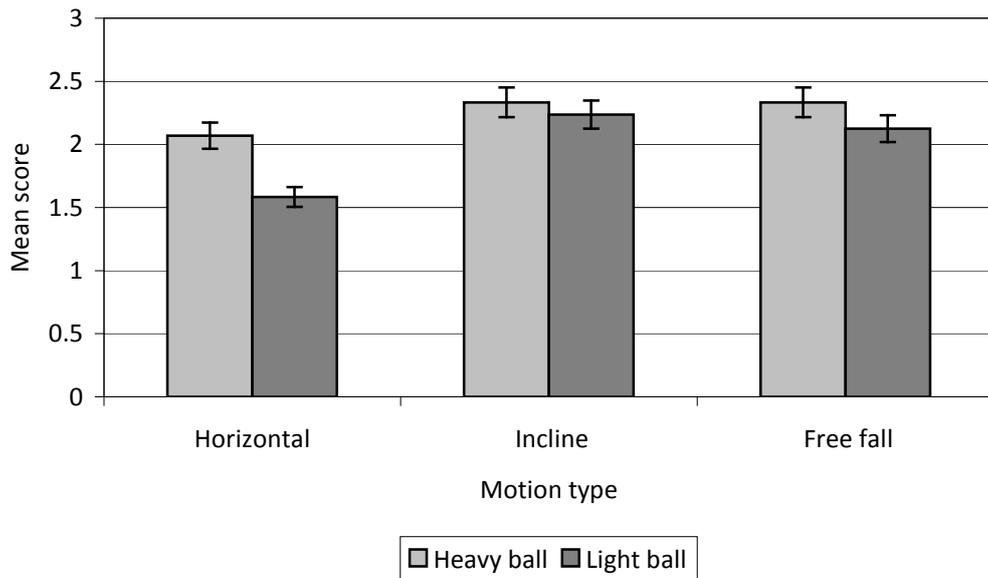
Figure 9.16   Mean scores for attributions of speed change by motion type and by ball weight (Maximum possible score = 3)

9.5 Discussion

This study aimed to further investigate findings from Study 1 but within a more controlled environment, also looking at whether children's conceptions regarding object motion are consistent with accepted scientific views or not. Additionally, children's appreciation of speed changes during motion was investigated, as speed changes occur frequently and are thus important in the appreciation of naturalness of motion. Finally, given that no conclusion could be drawn from Study 1 regarding the interrelation of the three motion types, this study aimed to provide more information towards how children might understand motion down an incline in terms of vertical and horizontal dimension interaction, if this does indeed inform incline motion.

9.5.1 Directions of variables

Using the two test balls enabled the control of a number of variables that emerged from children's reasoning about object motion in Study 1. Size and shape were held

constant, and differences in texture were so minimal that almost no reference was made, and none of the children made any reference to texture on its own. Instead, with the exception of those children who made same-speed predictions, the children's predictions were always made on the basis of the balls' weights. Overall, there were no differences in predictions of faster motion between the two balls. However, there were differences across the motion type blocks. Consistent with Study 1 and previous work (e.g. Howe, 1991, as cited in Howe, 1998), faster horizontal motion was usually associated with the lighter ball. Also consistent with Study 1 and extensive previous research (e.g. Baker et al., 2009; Champagne et al., 1980, as cited in McDermott, 1984; Chinn & Malhotra, 2002; Nachtigall, 1982; Sequeira & Leite, 1991; van Hise, 1988), faster motion in free fall was usually associated with the heavier ball, in both cases accounting for over 80 per cent of predictions. The frequency of these predictions for both dimensions was constant across all four age groups.

Faster incline motion predictions, on the other hand, changed with age. Whilst younger children predicted faster motion for the lighter ball, older children predicted it for the heavier ball. It seems that there was not a particular age point where children suddenly switched from associating faster incline motion with lightness to associating it with heaviness. Instead, it seems to be a gradual process of change. This suggests that even though the changes go from one incorrect view to another incorrect view, without affecting same-speed predictions at all, there is little resistance to change in conceptions within the total age range, at least where motion down an incline is concerned. This is a crucial observation and lends much support to the notion that conceptual change should be tackled in the early years. Given the extensive literature on children's prior conceptions and the mismatch between these and accepted scientific views, not only concerning children's understanding of motion, it may come as no particular surprise that here, too, children held views about object speed that were incompatible with science. Regardless of direction of the responses, a staggering 97 per cent of speed task responses were in favour of differences in motion between the two balls.

9.5.2 Attribution of changes in speed

Concerning attribution of changes in speed, children seem to appreciate that there must be a change in speed between a starting point and any subsequent point. Both attributions of speed change to AB and attributions of speed change to AC were made in over 80 per cent of cases each, but attributions of speed change to BC only in 40 per cent of cases. The rather high attribution rate for AB and AC could presumably be explained by the simple fact that at Point A in incline motion and motion in free fall motion did not take place, so at any subsequent point speed would be more than it was at Point A. This is rather similar to Piaget's (1970a) observation of children initially perceiving acceleration in incline motion as a short and intensive effort, or Nachtigall's (1982) similar findings in children's understanding of speed changes in free fall motion. In horizontal motion, children probably hold the beliefs in a similar way, only inversely: As soon as a ball rolls along a horizontal upon leaving a diagonal dimension, it instantly slows down for a short while, therefore being slower at any point after leaving the tube, and then continues at a constant speed.

The observation that the heavier ball was expected to slow down more often than the lighter ball can quite possibly be explained by children believing that light objects roll faster along a horizontal and weight being a hindrance to motion (cf. Howe, 1991, as cited in Howe, 1998). Moreover, the change in speed from the diagonal to the horizontal dimension may suggest that children believe that objects have to slow down once there is no downward element of motion anymore – to the extent that incline motion can be considered in terms of downward motion. This would imply that children perceive incline motion to be affected by vertical dimensions, although as children get older, they may hold this association more strongly, given their predictions that the relationship between heavy and light objects rolling down inclines become more similar to their predictions than the relationship between the two when in free fall.

9.5.3 Interrelation of motion types

Again, as in Study 1, it appears that for young children motion along a horizontal and motion in free fall do indeed seem to be distinguished from each other, as they affect the same objects in different ways, lending support to previous ideas (Hayes, 1979; Howe, 1998). However as opposed to Study 1, where it was difficult to interpret children's understanding of motion down an incline in terms of horizontal and vertical dimensions, it seems to be somewhat clearer from this study's results. The same objects were used to assess understanding of all three motion types, enabling a better comparison. It would appear that, at least in terms of the objects used here, younger children associate motion down an incline more with motion along a horizontal than with motion in free fall, and that as age increases this association crosses over, such that as children get older they associate motion down an incline more with motion in free fall and less with motion along a horizontal. As with the directions of variables, even though the changes go from one incorrect view to another incorrect view, there is little resistance to change in conceptions. Therefore support is added to the notion that conceptual change should be engaged with early on.

9.5.4 Incline comparisons

One aspect that may contribute to understanding how the motion types interact is by looking at incline comparisons. Over 80 per cent of incline comparison predictions were consistent with accepted scientific views. Even the youngest children appreciated that an increase in the height of the incline would results in faster speed, regardless of the weight of the ball, or that a decrease in the height would result in slower speed. This is an interesting finding, as a change in incline has the same effect on any object, regardless of weight, as long as friction is overcome. Similar to Baillargeon and colleagues' observation of a décalage in infant's understanding of object support (cf. Baillargeon & Hanko-Summers, 1990; Baillargeon et al., 1992; Needham & Baillargeon, 1993), it would appear that there is a shift in conceptions of what incline motion entails in relation to the degree of

support it offers the objects. As aforementioned, the younger children associated faster incline motion with lightness, and older children associated it with heaviness. However, regardless of age the children seemed to understand that the interaction of horizontal and vertical dimensions and its effect on object motion changes with the degree of incline. It would thus seem reasonable to suggest that children's notion of diagonal dimensions is informed both by horizontal and by vertical dimensions, but that the salience of dimensions changes with age – while younger children associate incline motion more with supported horizontal motion and therefore reason similarly about motion in those two dimensions, older children integrate elements of free fall more frequently into their conception of inclines, thereby reasoning similarly about those two dimensions.

9.6 Summary

Consistent with previous work, primary school children associate faster horizontal motion with lightness and faster free fall with heaviness of objects. What the literature could not provide was information on children's understanding of motion down inclines, and the present study has begun to close this gap by showing that conceptions of incline motion vary with age. The children's understanding of speed change appears to be limited and rarely goes beyond the simple intuitive notion of speed change happening as a short and intensive 'spurt' to begin with. However, attributions of speed change increased with age and would seem to have become more sophisticated in the sense that attributions not involving the starting point of motion were made *much* more frequently by older children. Varying incline heights has helped to further the understanding of how children understand diagonal dimensions and how supported horizontal motion and unsupported free fall motion may affect their understanding of incline motion.

CHAPTER 10:

ASSESSING YOUNG CHILDREN'S EXPLICIT BELIEFS ABOUT MOTION USING A COMPUTER-PRESENTED TASK (STUDY 3)

10.1 Overview

The third objective mentioned at the beginning of this thesis was to see whether alternative knowledge sources might be accessible that could facilitate conceptual change, as Chapter 2 indicated that the current approaches bear limited success. The results from Study 2 have suggested that children's *explicit* verbalised conceptions of object motion are somewhat limited and bear a striking resemblance to naïve Aristotelian views, as noted in Chapter 1. Earlier in this thesis, in Chapter 3, it was questioned whether alternative knowledge sources might be available to tap, and it emerged that tacit understanding might indeed be present. However, to enable a better comparison between explicit prediction tasks and tacit judgement tasks, for which computers are deemed to be extremely helpful (see Chapter 3), it is crucial to establish whether explicit beliefs about motion can be assessed by using computers as well, and to see how these results compare with those of real-object tasks, as was done in Study 1 and Study 2.

ICT is being used increasingly within schools in the United Kingdom, and the National Curriculum for England (Department for Education and Employment, 1999) emphasises the need for teachers to incorporate ICT in their teaching, even at the primary school level. The benefit and potential of computer-based teaching have been recognised in a range of recent publications, as laid out in the introductory Chapter 3 (e.g. Barton, 2004; Glover et al., 2005; Holliman & Scanlon, 2004; Murphy, 2003; L. R. Newton & Rogers, 2001; Smith et al., 2005). At the school involved in the present research, too, almost two thirds of teaching is aided by ICT, and the children have considerable hands-on experience with a variety of the equipment used, even in the youngest age group (see Table 7.1, p. 127). This experience ought to be made use of.

The key question asked in the present study was thus whether children's explicit knowledge could be assessed via computers in a comparable manner to assessing it via real-life object tasks, as was done in Study 1 and Study 2, by essentially replicating Study 2, and whether the results would be comparable to those of Study 2. Regardless of the results that emerge, it seems that using computers as a medium to assess young children's explicit understanding of object motion might bear at least three advantages over real-life object tasks within the current research framework. Two of these advantages are theoretical in their nature, and the third advantage is of a more practical nature.

One theoretical advantage in the current work is that in addition to providing information about children's beliefs, computers can also enable the recording of accurate measures of response times. Response times could contribute to furthering understanding of young children's explicit conceptions of object speed and acceleration. For example, are some tasks perhaps easier for children than others; do they find it easier to reason about motion in one particular dimension than in others? If so, then – whilst keeping the tasks as constant as possible across the motion types – children should spend more time on tasks they find difficult and that require more thinking.

The second theoretical advantage of using computers to assess explicit knowledge is that the findings about explicit beliefs can be related more readily to children's possible tacit understanding about the same phenomena by assessing both kinds of knowledge using the same medium, that is, computers. As has been established in the introductory chapters, computers could be useful tools in the investigation of tacit knowledge. This second advantage leads on to the practical advantage of using computers, which is the application of the work to the classroom. The use of ICT in schools has already been mentioned above. In light of the fact that the current research as a whole is concerned with being able to provide information contributing towards the possible establishment of conceptual change programmes within early science education, it was hoped that this study could provide data about the effect, if any, of computers on explicit knowledge assessment.

10.2 Research questions

1. Can primary school children's explicit beliefs about object speed and speed change be assessed using computer-presented tasks resulting in similar outcomes to real-object tasks?
2. Can computers provide more information about children's explicit beliefs by considering response time data?

10.3 Method

<u>10.3.1 Pilot study</u>

10.3.1.1 Participants

As noted in Chapter 7, the pilot sample for the study consisted of 17 children (nine boys), which included three Year 1 children (two boys; age *M* = 5.96 years, *SD* = 0.38), six Year 2 children (four boys; age *M* = 6.94 years, *SD* = 0.26), five Year 4 children (three girls; age *M* = 8.65, *SD* = 0.13) and three Year 6 children (two girls; age *M* = 11.05, *SD* = 0.51).

10.3.1.2 Materials

The scenarios were created using PowerPoint. The speed scenarios and incline comparison scenarios each consisted of two pictures, A and B, which showed the apparatus used in Study 2. The test balls used in Study 2 – a bright pink table tennis ball and a dark green solid glass marble – could be seen in the scenarios. Below the pictures were three brief possible ball motion comparison outcomes written in large font against coloured backgrounds. The options read "A is faster", "B is faster" and "Same speed" for speed question scenarios, and "A takes longer", "B takes longer", and "Same time" for time question scenarios. Background colours always remained in the same order but the same options were in different locations in different trials, that is, the response-colour combinations varied. An example of a scenario is shown

in Figure 10.1 below. Furthermore, the apparatus and test balls from Study 2 were also used in this study (see Figure 9.1, p. 163).
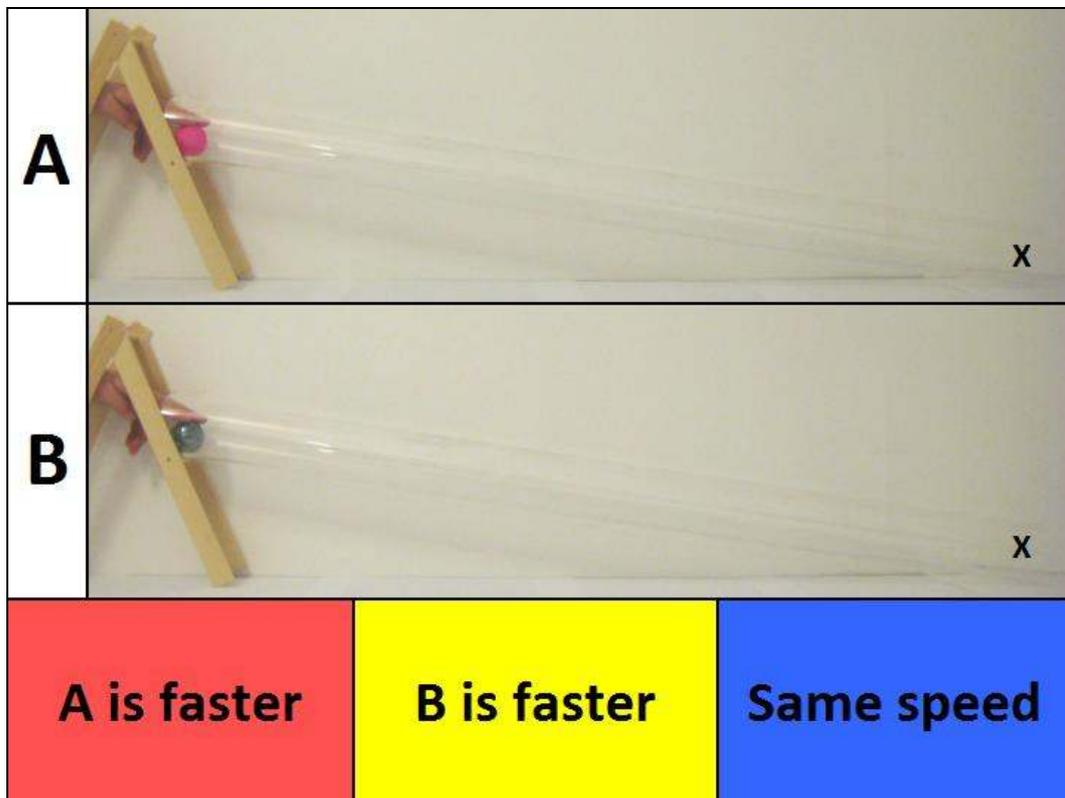
Figure 10.1   Example scenario of speed task in Study 3; comparisons have to be made between Ball A and Ball B in their speed to reach point X at the end of the tube if released simultaneously

The speed change scenarios each consisted of one picture, which showed the apparatus used in Study 2, and one test ball – either the table tennis ball or the glass marble. Along the tube or the horizontal three points, A, B and C, were pointed out. Below the picture were again three brief possible ball motion comparison outcomes written in large font against coloured background. The options read "Faster at A", "Faster at B" and "Same speed" for speed question scenarios where speed change for the distance AB needed to be considered. Equivalent options were prepared for the distance AC and for the distance BC. An example of a scenario is shown in Figure 10.2 (p. 195).
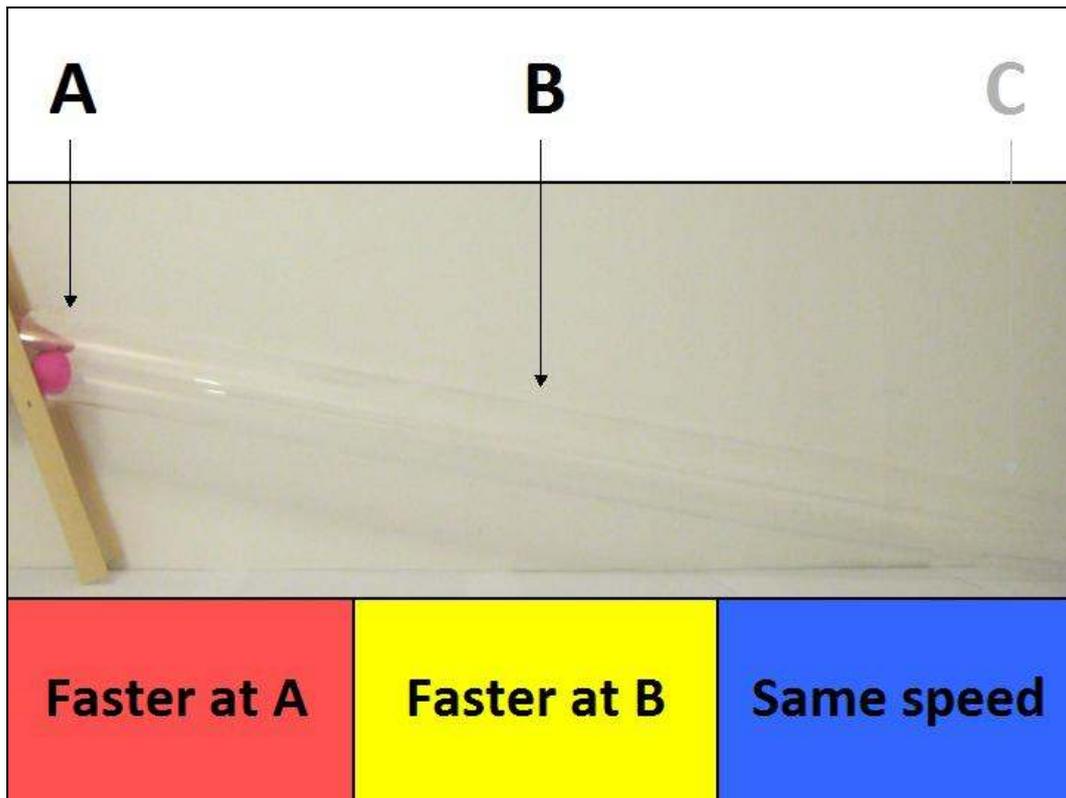
Figure 10.2   Example scenario of speed change task in Study 3; comparisons need to be made between the ball's speeds at Point A and at Point B

In addition to the test scenarios, there were practice scenarios consisting of PowerPoint slides on which small and large squares were shown, again with three options to choose from ("A is bigger", "B is bigger", "Same size"). An example of a practice scenario is shown in Figure 10.3 (p. 196).

Figure 10.3   Example scenario of practice trials in Study 3

The trials were presented using DMDX (Forster & Forster, 2003), a computer program that allows the recording of response choices as well as response times. The software was run on a Sony VAIO VGN-NR21J laptop. Connected to the laptop was an external 15" LCD colour monitor via which the scenarios were presented to the participants. An external KeySonic[TM] Nano Keyboard ACK-3400U, also connected to the laptop, was used for responses to the scenarios. The keyboard was masked to reduce distractions from unnecessary keys. Three keys were indicated by colour on the masking. The DMDX programme was set up to only allow these three keys to function, the other keys were disabled. One key was on the centre of the keyboard (the yellow key), the other two were on the left (the red key) and on the right (the blue key) end of the keyboard, in the same row as the centre key (see Figure 10.4, p. 197).

Figure 10.4   Computer screen and keyboard used in Study 3

The three key colours referred to the three response options given in the scenarios. Each response had a different background colour; the response on the left had a red background, the response in the middle had a yellow background, and the response on the right had a blue background. To choose the left response with the red background the red key had to be pressed, to choose the middle response with the yellow background the yellow key had to be pressed, and to choose the right response with the blue background the blue key had to be pressed. Each trial could be set so that it could only be seen for up to 60 seconds, after which a new trial would start without recording a response if none was made within the 60 seconds.

10.3.1.3 Design

There were eight separate blocks within the assessment – one practice block, five blocks on speed, and three blocks on speed change. Of the speed blocks, two were on motion down an incline, one was on motion along a horizontal, and one was on motion in free fall. Of the speed change blocks, there was one for each of the three motion dimensions. As in Study 2, the horizontal motion blocks always came after the incline motion blocks because horizontal motion, in this case, followed on from motion down the incline, that is, because the objects needed to be in motion without the help of external factors such as having to push them. Incline comparisons were also paired together. Conditions all had the practice block first, then the speed blocks and then the speed change blocks. All blocks consisted of six trials each, with each individual trial appearing twice within a block. The order of blocks was known to the researcher, but the order of trials was not. For each condition there were altogether six practice questions and 42 test questions. Like in Study 2, in four cases – in the second incline block and in the speed change tasks – comparisons needed to be made, that is, motion down a low height incline versus motion down a high height incline, or speed at different points along a path. These comparisons needed to be made for one ball only, either the glass marble ('heavy') or the table tennis ball ('light'). All comparisons within each condition were made with the same ball.

10.3.1.4 Procedure

Children were assessed on an individual basis. The task was carried out outside of the classrooms but in an open and publicly accessible area of the school. The apparatus of transparent tube and incline frame used in Study 2 and shown in the trials was present at all times and was set up as for the incline tasks (see Figure 9.1, p. 163). Prior to a child joining, the computer program was set up and a condition was selected at random. The necessary information for each child was entered at this point. Upon arrival, the child was reminded about the previous task in Study 2 and was shown the apparatus used, and was told that this time there would be a

computer where they would see pictures of the apparatus and hands holding the test balls into the tube, and that the child would have to answer questions about the pictures. The two test balls used in Study 2 and shown in the computer-presented scenarios – the table tennis ball and the glass marble – were made available to the child at this point, and the child could handle them at any time but was asked not to carry out any relevant motions with the objects when having to respond to the computer scenario items, that is, not to roll them across the table or deliberately let them fall. It was made clear to the child that participation was voluntary and that completion of individual items or the study as a whole was not compulsory.

The child first saw a blank screen, and the researcher familiarised the child with the monitor and the keyboard. The researcher asked the child to point out each key according to its colour. The child was then asked to press the yellow key. This elicited an introduction to the materials. The child saw a series of diagrams of the monitor and keyboard. The researcher used the diagrams to explain the procedure to the child, showing the link between response choices and keys to press. At the end of the introduction, the child was told that there would be some very easy trials to practice the use of the keyboard. This practice block consisted of six simple questions, where the sizes of two squares had to be compared, that is, whether one square was bigger or smaller than the other, or if they were the same size.

If children were unable to read the options, the researcher followed the trials and for each trial gave the child instructions. The instruction given by the researcher always corresponded to the particular trial on the screen; response-colour combinations varied (that is, while background colours remained in the same order, response options varied in their location across trials) but responses were always read out from left to right. To avoid any top-bottom or left-right confusion, the researcher pointed to the picture in question and the corresponding response option each time. In the practice trials the researcher would say to the child: "If you think the square on the top [researcher points at picture A] is bigger, press the red key. If you think the square on the bottom [researcher points at picture B] is bigger, press the yellow

key. If you think they are both [researcher points at pictures A and B] the same size, press the blue key."

Each of the test blocks consisted of six questions, three relating to speed predictions and three relating to time predictions. All six questions required a comparison of the two test balls, that is, whether one of the two would be faster or take less time than the other to reach the end of the tube or the end of the track, or if speed or time taken would be the same for both. The incline comparison block consisted of questions where a comparison had to be made for only one test ball, that is, whether after raising or lowering the incline height the ball would change its speed, or whether there would be a change in time taken to reach the end of the tube or track. For this, the scenarios showed both the low height incline and the high height incline with the same ball. If required, the child was given the following instructions: "If you think the ball on the top [researcher points at picture A] will roll faster, press the red key. If you think the ball on the bottom [researcher points at picture B] will roll faster, press the yellow key. If you think they will both [researcher points at pictures A and B] roll at the same speed, press the blue key." In the case of free fall trials, a left/right rather than top/bottom distinction was made. The speed change trials required a comparison of speeds for again only one test ball, the same ball as used for the incline comparison block, choice of ball depending on the condition. If required, the child was given the following instructions: "If you think the ball will be faster at Point A [researcher points at Point A], press the red key. If you think the ball will be faster at Point B [researcher points at Point B], press the yellow key. If you think the ball will have the same speed at both points [researcher points at Points A and B], press the blue key."

At the end of the block, the child was given the option to either take a short break or continue with the next block. Before each block the child was told which scenario type to expect, that is, motion down an incline, motion along a horizontal or motion in free fall. When horizontal motion trials were to come, the child was told that the balls had rolled down the inclines such that they reached the end of the tube at the same time. The task lasted approximately 20 to 25 minutes for each child.

10.3.1.5 Outcomes of the pilot study

During the first session of the pilot study the children were asked to explain how they would respond to the questions, that is, state which key they would press and why they would press it. This was to ensure that the prediction statements were clear enough for the children, and that the process of matching statement backgrounds with key colours was understood. As the piloting was not concerned with collecting data or information about response times, it was not crucial that the children responded as quickly or even accurately as they would in the main study. Trials were therefore set to last until a response was made, giving the children time to explain their choices. No difficulties in understanding instructions or the computer apparatus were registered. The second set of children received the task without having to explain their response processes. Here, the trial length was put to the test, and each trial was set to last for 60 seconds only.

One problem that had been considered likely to arise was the children's ability, or lack thereof, to read the prediction statements, due to age and reading levels rather than font size or simplicity of the statements. This was a particular concern with the children from the youngest age group. However, the pilot study showed that having the researcher read out the responses to the children, where necessary, did not seem to have an impact on the children's ability to understand the statements or on making decisions. In addition to explaining choices in the first session, the children were also asked to read out the statements, where possible, and where children were able to read, no difficulties in understanding the statements were apparent. Hence during the practice trials in the main study it became clear whether a child's reading ability was sufficient for the child to complete the blocks alone, or whether the researcher needed to read out the replies.

10.3.2.1 Participants

The Study 3 main sample consisted of 127 children (69 girls) from the sample noted in Chapter 7, which included 27 Year 1 children (14 girls; age M = 6.14 years, SD = 0.33), 32 Year 2 children (18 girls; age M = 7.03 years, SD = 0.26), 34 Year 4 children (20 girls; age M = 9.02, SD = 0.30) and 34 Year 6 children (17 girls; age M = 11.00, SD = 0.24). An additional 16 children participated but were excluded from data analysis due to insufficient completion of the practice trials, not completing the study, or technical errors, and one child left the school between Study 2 and Study 3 and could therefore not take part anymore.

10.3.2.2 Materials

The materials were the same as used in the pilot study, but the trial length was set to last for 60 seconds only for all children.

10.3.2.3 Design

The general design was the same as in the pilot study. With the exception of the horizontal-incline order and the two incline blocks being together, as well as separating practice, speed and speed change blocks, the order of blocks and the order of comparisons within each block were randomised, giving altogether eight different conditions (see Table 10.1, p. 203). Altogether there were eight conditions with eight blocks in each condition. Each child contributed to all eight blocks. In each trial there were always three options to choose from. For the speed task choices each child scored between 0 and 18 (for each block the score was between 0 and 6), for the incline comparison task block choices each child scored between 0 and 6, and for the speed change task choices each child scored between 0 and 18 (for each block the score was between 0 and 6). Approximately equal numbers of children per age group were selected for each condition. Overall, there were 17 children per

condition, with the exception of Condition 5 for which only 16 children were selected. From each age group, four children were selected for each condition, and the remaining seven children were distributed over the eight conditions at random, one child per condition – Condition 5 was not allocated an additional child.

Table 10.1   Conditions in Study 3

	Condition							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Motion direction	Left to right		Right to left		Right to left		Left to right	
Comparisons[7]	Heavy ball	Light ball	Heavy ball	Light ball	Heavy ball	Light ball	Heavy ball	Light ball
Block 1	Practice trials							
Block 2	Incline at 15 cm (both balls)		Incline at 30 cm (both balls)		Free fall (both balls)		Free fall (both balls)	
Block 3	Incline comparison (one ball)		Incline comparison (one ball)		Incline at 15 cm (both balls)		Incline at 30 cm (both balls)	
Block 4	Horizontal (both balls)		Horizontal (both balls)		Incline comparison (one ball)		Incline comparison (one ball)	
Block 5	Free fall (both balls)		Free fall (both balls)		Horizontal (both balls)		Horizontal (both balls)	
Block 6	Incline speed change (one ball)				Free fall speed change (one ball)			
Block 7	Horizontal speed change (one ball)				Incline speed change (one ball)			
Block 8	Free fall speed change (one ball)				Horizontal speed change (one ball)			

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[7] Incline comparisons (either in Block 3 – Conditions 1 to 4 – or in Block 4 – Conditions 5 to 8 – only needed to be made for two inclines with the same ball. Speed change comparisons between Points A, B and C (Blocks 6 to 8) also only needed to be made with one ball. The condition determines whether this was the heavy ball or the light ball.

10.3.2.4 Procedure

The general procedure was the same as in the pilot study; the piloting revealed no inadequacies in the procedure that needed to be addressed.

10.4 Results

<u>10.4.1 Method of analysis</u>

In order for data to be considered for analysis, children had to correctly complete at least 4 out of the 6 practice trials and had to complete the study. 127 of the 143 children who participated were able to fulfil these requirements, so their data qualified for analysis. Data were collected in the form of response choices (see 10.3.2.3). In line with the physics of object motion (see Chapter 4) and with the analysis procedure of Study 2, speed change was analysed in terms of acceleration, that is, speeding up, for free fall motion and for incline motion, and as deceleration, that is, slowing down, for motion along the horizontal. Data were also collected in form of response times. Age differences were not considered for analysis in the case of response times because of the differences in methodology (reading out to children or not). It would have been too difficult to take into account individual reading times.

Kolmogorov-Smirnov tests on the normality of distribution of data showed that all distributions deviated significantly from normality. Therefore assumptions for parametric tests were not met. Wilcoxon signed-rank tests showed no significant differences between scores for questions asking about time taken and scores for questions asking about speed. Therefore the scores of the two sets were merged, that is, scores for 'faster' and 'less time' were grouped, to avoid reporting similar results twice. Mean scores and mean response times were analysed using Friedman's ANOVAs and post hoc Wilcoxon signed-rank tests, with Bonferroni corrections applied (all significance thresholds $p \leq .025$ except where specified otherwise). Correlations were analysed using Kendall's tau tests. Effects of gender,

effects of handedness and effects of ball type were analysed with Mann-Whitney tests. Effects of age and effects of condition were analysed with Kruskal-Wallis tests and post hoc Jonckheere-Terpstra tests. No significant gender, handedness or condition effects were found, therefore these are not considered further. All data were analysed using PASW (Predictive Analytics Software, formerly SPSS) Statistics version 18.

10.4.2 Speed

Figure 10.5 (p. 206) shows the mean scores for overall faster motion response options, whether the heavy ball or the light ball would be faster, or whether the two would be the same. A maximum score of 18 was obtainable. There was a significant interaction of prediction statement choice with mean scores, $\chi^2(2, N = 127) = 156.88$, $p < .001$. Different-speed statements ($M = 17.02$, $SD = 1.74$) were chosen significantly more often than same-speed statements ($M = 0.98$, $SD = 1.74$), $T = 10$, $r = .90$. There was an overall significant preference to choose statements where the heavy ball ($M = 9.33$, $SD = 3.85$) was faster than the light ball ($M = 7.69$, $SD = 3.69$), $T = 3$, r = .26.
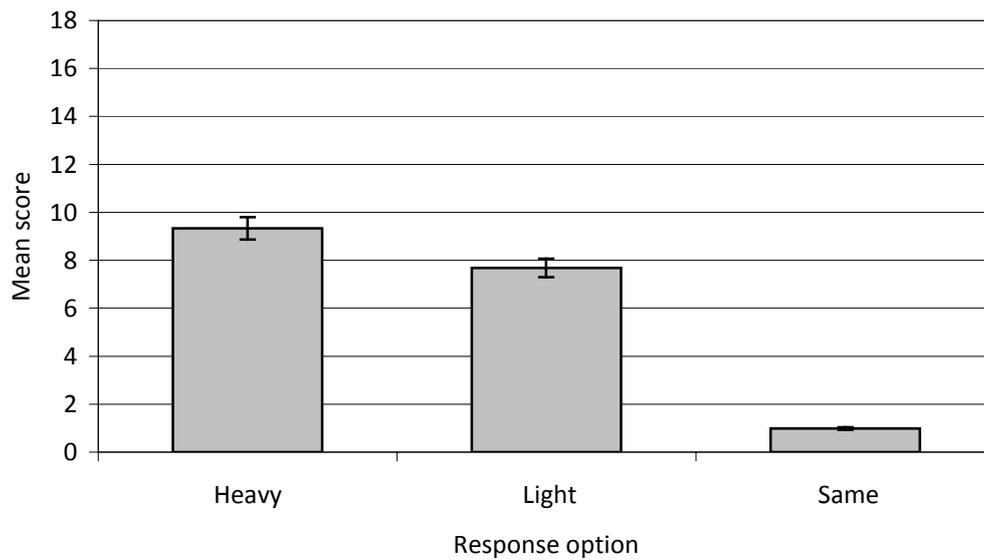
Figure 10.5   Mean scores for overall response options (Maximum possible score = 18)

Figure 10.6 (p. 207) shows the mean scores for overall justification types by age groups. There was a significant interaction of age with response options, both for choosing statements where the heavy ball was faster, $H(3) = 42.69$, $p < .001$, and for choosing statements where the light ball was faster, $H(3) = 45.22$, $p < .001$, but not for same-speed statements.
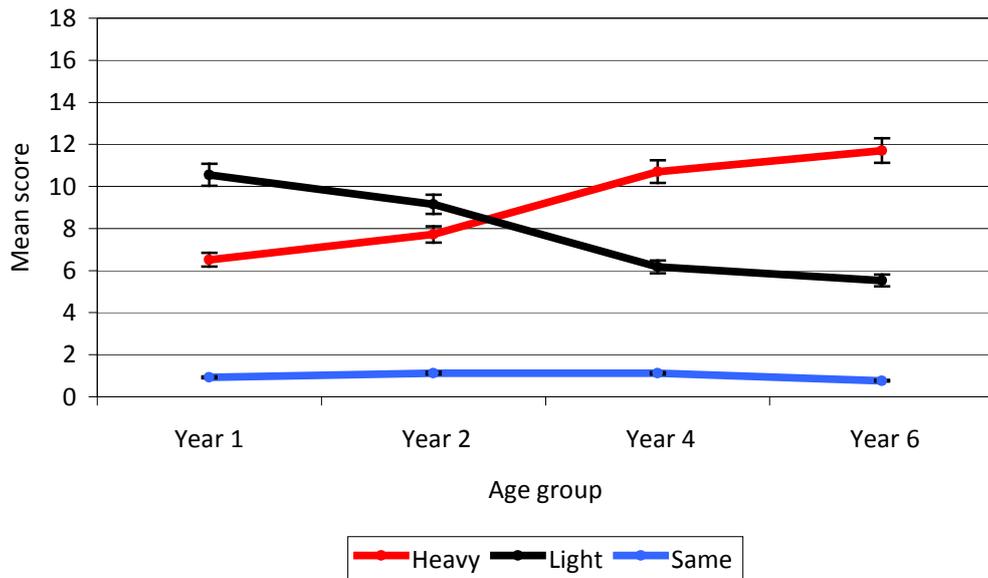
Figure 10.6   Mean scores for overall justification types by age groups (Maximum
              possible score = 18)

10.4.2.1 Motion along a horizontal

Figure 10.7 (p. 208) shows the mean scores for overall faster motion response options in the horizontal motion block, whether the heavy ball or the light ball would be faster, or whether the two would be the same. A maximum score of 6 was obtainable. There was a significant interaction of prediction statement choice with mean scores, $\chi^2(2, N = 127) = 149.99$, $p < .001$. There was a significant preference to choose statements where the light ball ($M = 4.88$, $SD = 1.93$) was faster than the heavy ball ($M = 0.71$, $SD = 1.62$), $T = 8$, $p < .001$, $r = -.75$, but there was no significant difference between choosing statements where the heavy ball was faster or choosing the same-speed options.
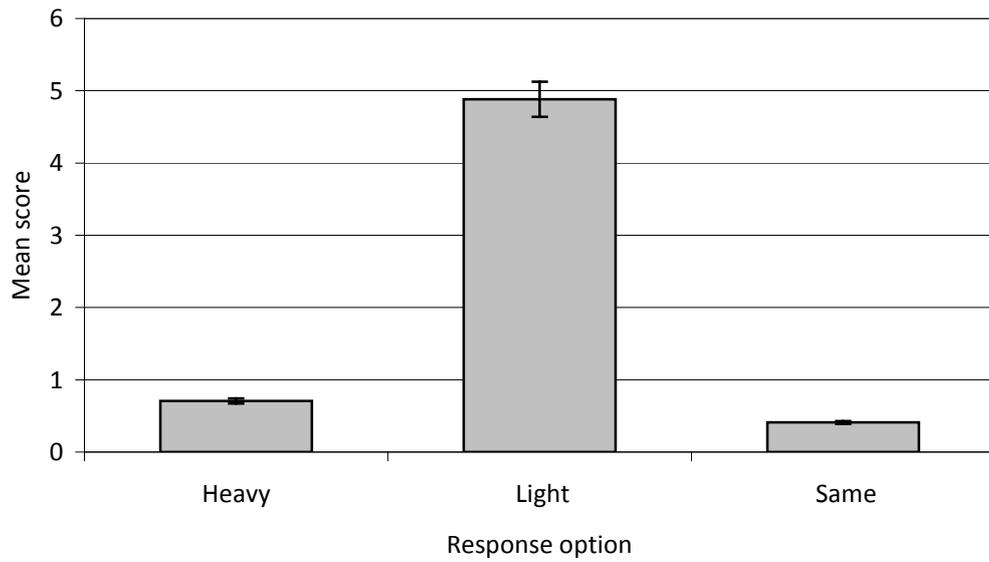
Figure 10.7   Mean scores for response options in horizontal motion (Maximum possible score = 6)

Figure 10.8 (p. 209) shows the mean scores for horizontal motion predictions by age groups. Age did not interact significantly with mean scores. Regardless of age, children consistently predicted the light ball to be faster.
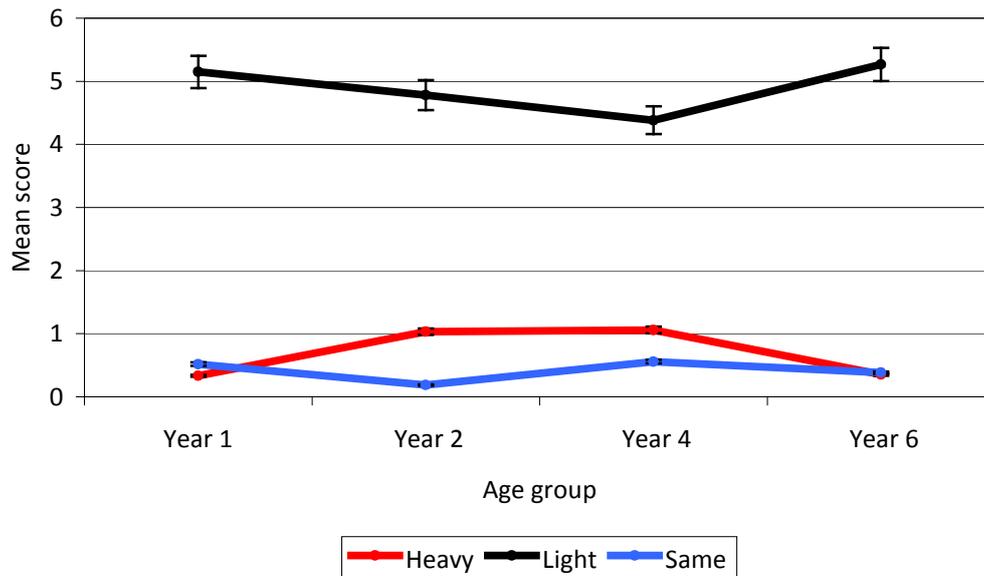
Figure 10.8 Mean scores for predictions in horizontal motion by age groups (Maximum possible score = 6)

10.4.2.2 Motion down an incline

Figure 10.9 (p. 210) shows the mean scores for overall faster motion response options in the incline motion block, whether the heavy ball or the light ball would be faster, or whether the two would be the same. A maximum score of 6 was obtainable. There was a significant interaction of prediction statement choice with mean scores, $\chi^2(2, N = 127) = 53.41$, $p < .001$. There was no significant preference for choosing either of the statements where one ball was faster than the other, but both the heavy ball statements ($M = 3.34$, $SD = 2.84$), $T = 8$, $r = -.69$, and the light ball statements ($M = 2.39$, $SD = 2.81$), $T = 6$, $r = -.57$, were chosen significantly more often than the same-speed options ($M = 0.27$, $SD = 0.98$).
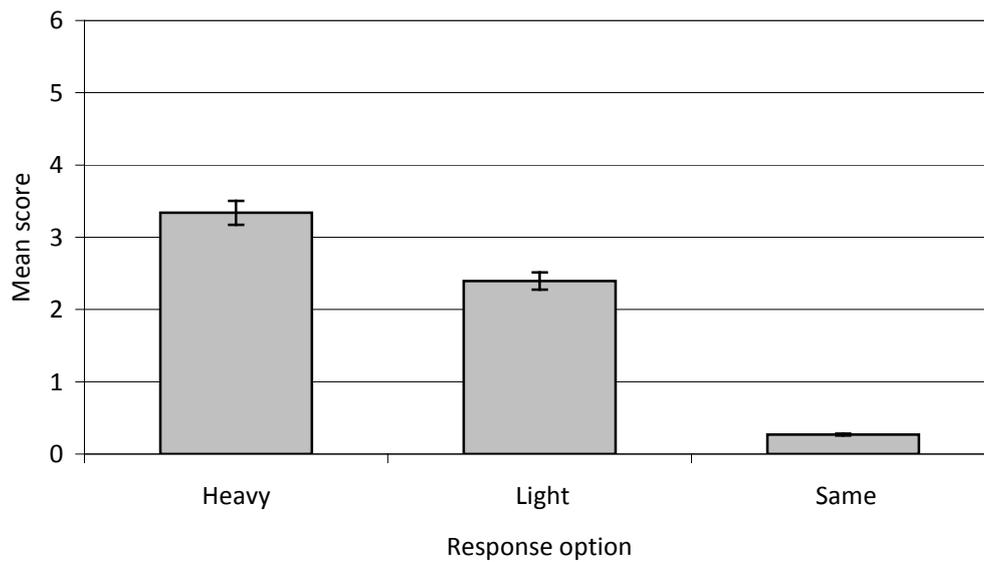
Figure 10.9   Mean scores for response options in incline motion (Maximum possible score = 6)

Figure 10.10 (p. 211) shows the mean scores for incline motion predictions by age groups. There was significant age variation for choosing statements where the heavy ball was faster, $H(3) = 51.67$, $p < .001$, with mean scores increasing with age, $J = 4573$, $z = 7.35$, $r = .65$, and there was significant age variation for choosing statements where the light ball was faster, $H(3) = 52.50$, $p < .001$, with mean scores decreasing with age, $J = 1488$, $z = -7.32$, $r = -.65$. There was no significant interaction of age with mean scores for same-speed options.
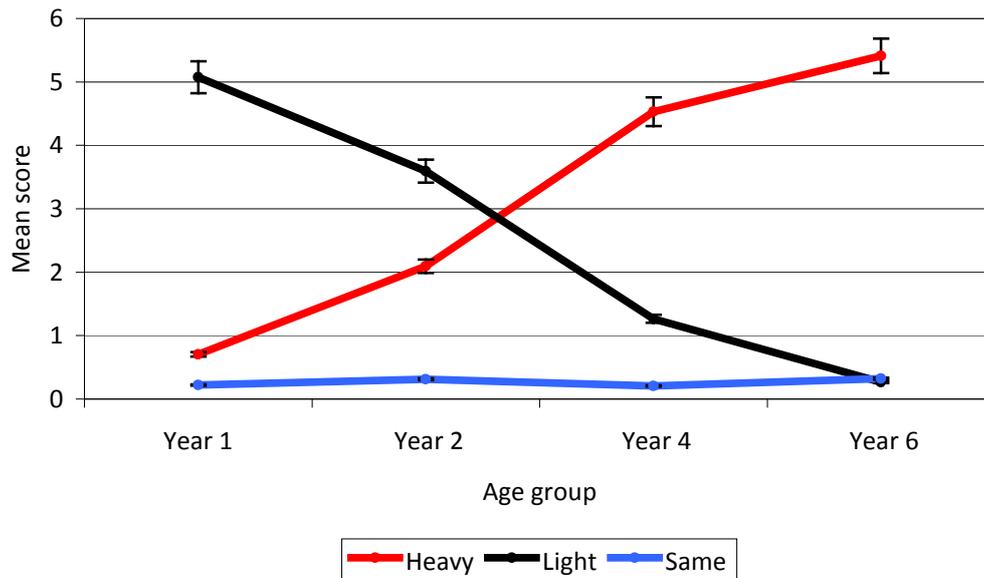
Figure 10.10   Mean scores for predictions in incline motion by age groups
(Maximum possible score = 6)

10.4.2.3 Motion in free fall

Figure 10.11 (p. 212) shows the mean scores for overall faster motion response
options in the free fall motion block, whether the heavy ball or the light ball would
be faster, or whether the two would be the same. A maximum score of 6 was
obtainable. There was a significant interaction of prediction statement choice with
mean scores, χ^2(2, *N* = 127) = 174.66, *p* < .001. There was a significant preference to
choose statements where the heavy ball (*M* = 5.28, *SD* = 1.87) was faster than the
light ball (*M* = 0.41, *SD* = 1.47), *T* = 9, *r* = -.82, but there was no significant difference
between choosing statements where the light ball was faster or choosing the same-
speed options.
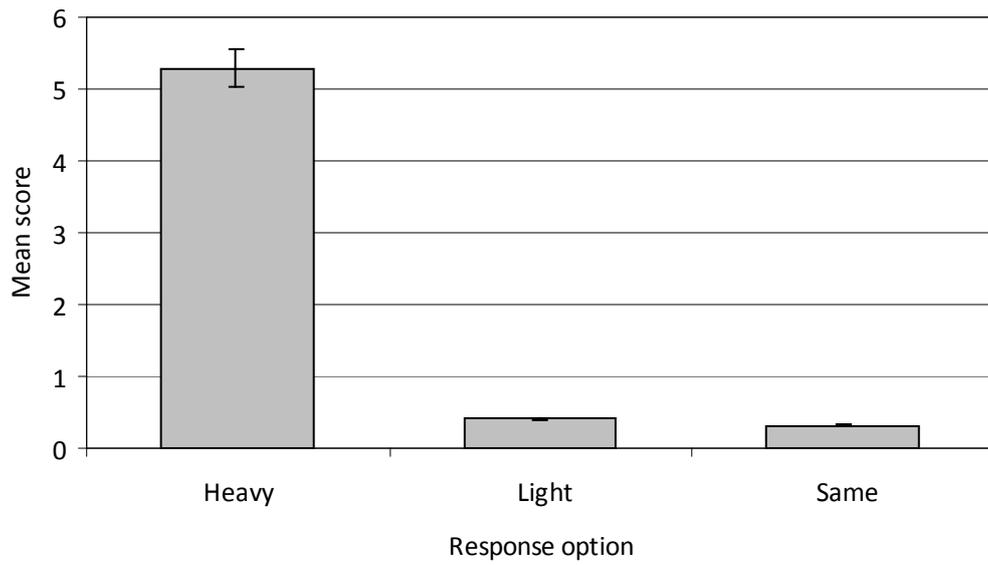
Figure 10.11   Mean scores for response options in free fall motion (Maximum possible score = 6)

Figure 10.12 (p. 213) shows the mean scores for horizontal motion predictions by age groups. Age did not interact significantly with mean scores. Regardless of age, children consistently predicted the heavy ball to be faster.
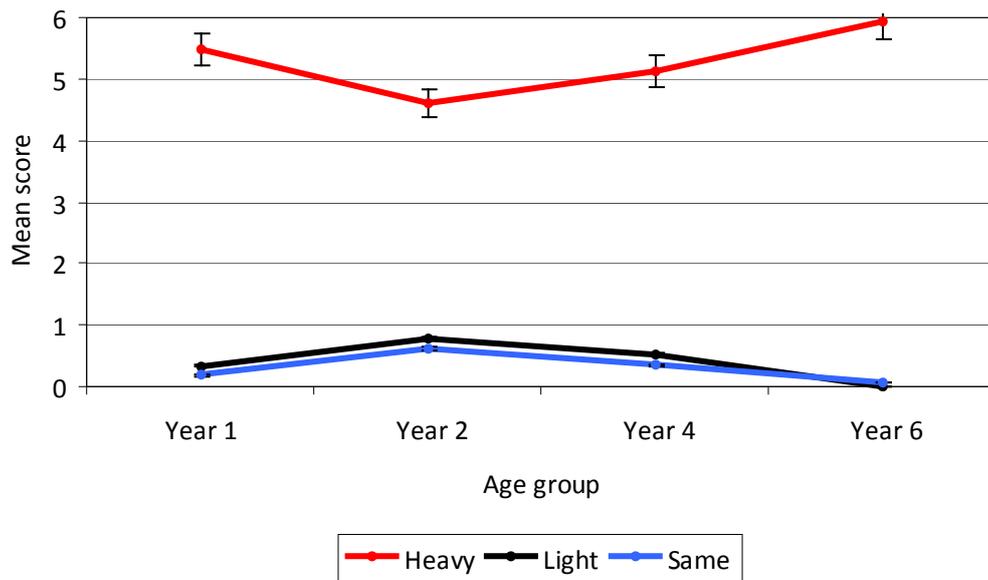
Figure 10.12   Mean scores for predictions in free fall motion by age groups
(Maximum possible score = 6)

10.4.3 Incline height comparisons

Figure 10.13 (p. 214) shows the mean scores for response options in incline comparisons, that is, where children had to compare motion down a high incline with the same ball's motion down a low incline. A maximum score of 6 was obtainable. There was a significant interaction of incline change with mean scores, χ^2(2, *N* = 127) = 37.91, *p* < .001. There was no overall significant preference for statements of faster or slower motion as the incline changed, but both faster motion statements (*M* = 2.72, *SD* = 2.79), *T* = 6, *r* = -.53, and slower motion statements (*M* = 2.76, *SD* = 2.82), *T* = 6, *r* = -.55, were significantly preferred over no change at all (*M* = 0.53, *SD* = 1.41).   There was no overall age variation. There were no significant differences between the heavy ball and the light ball conditions for faster or slower motion statements, but there was a significant difference for same-speed statements, where the light ball (*M* = 0.85, *SD* = 1.81) was more likely to be attributed no change in speed than the heavy ball (*M* = 0.15, *SD* = 0.48) as the incline changed, *U* = 1708, *p* < .05, *r* = -.19.
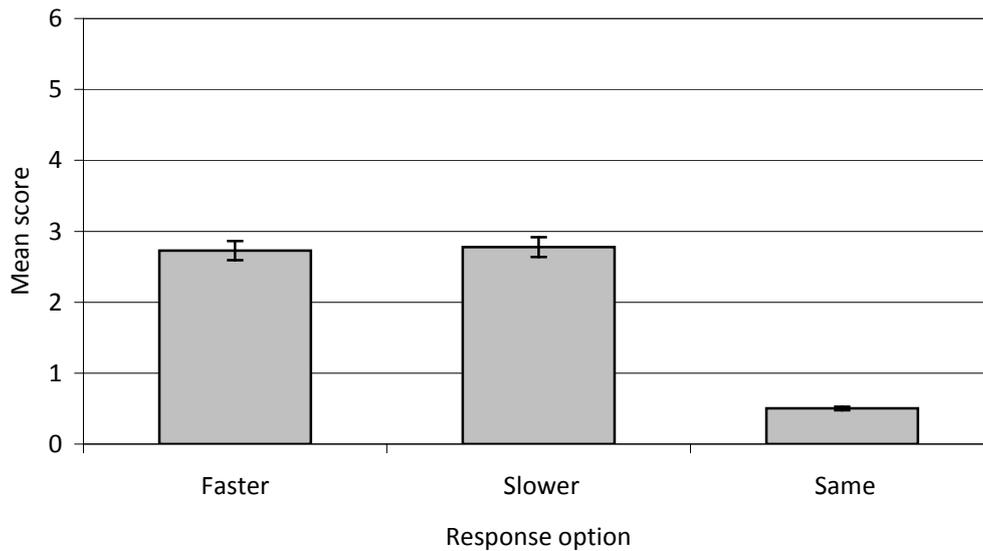
Figure 10.13   Mean scores for response options in incline height comparisons (Maximum possible score = 6)

Figure 10.14 (p. 215) shows the mean scores for response options in incline comparisons by incline height change. A maximum score of 6 was obtainable. There was a significant difference in speed attribution for direction of incline change; prediction statements were chosen where the balls were predicted to be faster (*M* = 5.15, *SD* = 1.67) rather than slower (*M* = 0.30, *SD* = 0.92) when the incline was raised, *T* = 7, *p* < .001, *r* = -.86, and slower (*M* = 5.05, *SD* = 1.92) rather than faster (*M* = 0.47, *SD* = 1.37) when the incline was lowered, *T* = 7, *p* < .001, *r* = -.81.
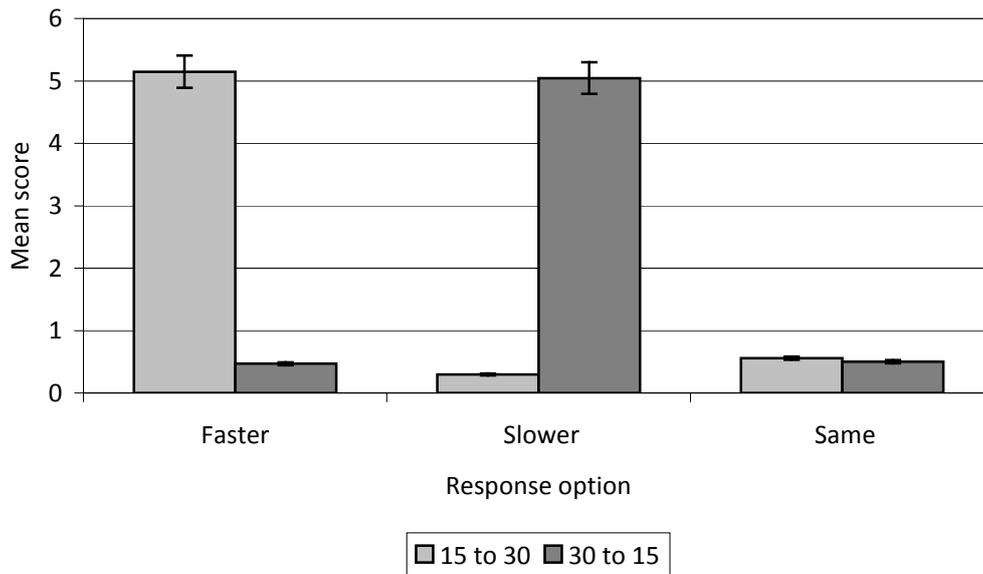
Figure 10.14   Mean scores for response options in incline height comparisons by incline height change (Maximum possible score = 6)

10.4.3.1 Incline height change from 15 cm to 30 cm

There was a significant interaction of prediction statement choice with mean scores, χ^2(2, N = 61) = 88.98, p < .001. Statements were chosen significantly more often where the balls were predicted to be faster (M = 5.15, SD = 1.67) rather than slower (M = 0.30, SD = 0.92) when the incline was raised, T = 7, r = -.86, and there was no significant difference between choosing statements that predicted them to be slower or statements that predicted them to remain unchanged. Ball type had no significant effect.

10.4.3.2 Incline height change from 30 cm to 15 cm

There was a significant interaction of prediction statement choice with mean scores, χ^2(2, N = 66) = 81.46, p < .001. Statements were chosen significantly more often where the balls were predicted to be slower (M = 5.05, SD = 1.92) rather than faster (M = 0.47, SD = 1.37) when the incline was lowered, T = 7, r = -.81, and there was no significant difference between predicting them to be faster or unchanged. Ball type

had no significant effect on choosing different-speed statements, but there was a significant preference, $U = 433$, $p < .05$, $r = -.26$, for statements where the light ball's speed ($M = 0.86$, $SD = 1.73$) rather than the heavy ball's speed ($M = 0.07$, $SD = 0.25$) remained unchanged after incline change.

10.4.4 Changes in speed

For speed change, the children were required to compare speeds of one ball at Points A, B and C, which were indicated on the tube and along the horizontal in the scenarios. Figure 10.15 below shows mean scores for attributions of changes in speed, that is, whether speed changed or not. A maximum score of 6 was obtainable for each distance AB, AC and BC. Response scores varied significantly, $\chi^2(2, N = 127) = 122.97$, $p < .001$. Attribution scores for AB and AC did not differ significantly, but both AB ($M = 5.03$, $SD = 1.69$), $T = 8$, $r = -.74$, and AC ($M = 5.07$, $SD = 1.55$), $T = 8$, $r = -.75$, received significantly more attributions than BC ($M = 1.80$, $SD = 2.32$).
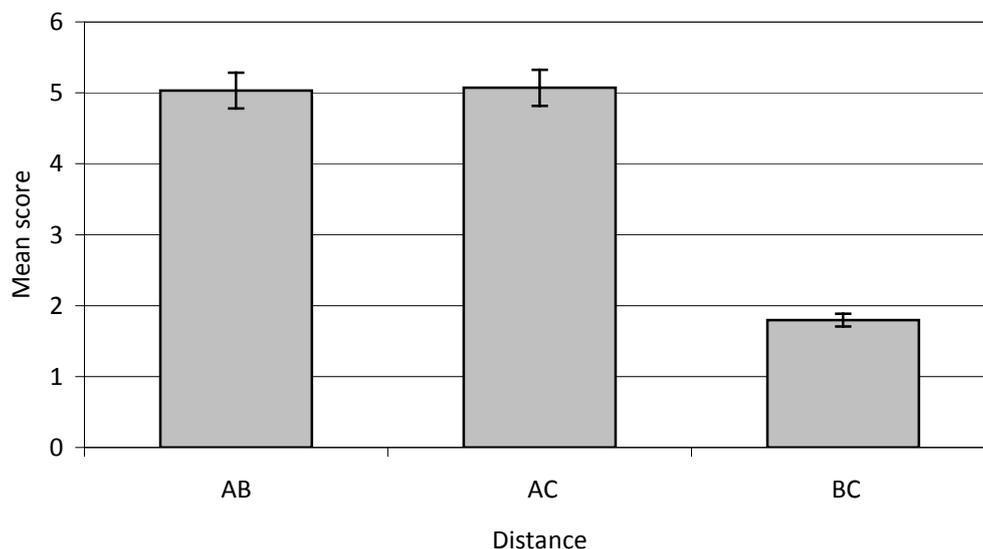
Figure 10.15   Mean scores for attributions of speed change (Maximum possible score = 6)

Figure 10.16 below shows the mean speed change attribution scores by age groups. A maximum score of 3 was obtainable for each distance AB, AC and BC. Age interacted significantly with total attribution score, $H(3) = 28.48$, $p < .001$, with speed change attributions increasing with age, $J = 4201$, $z = 5.23$, $r = .46$. Similar age effects were observed for attribution scores to all three distances (all $p < .05$).
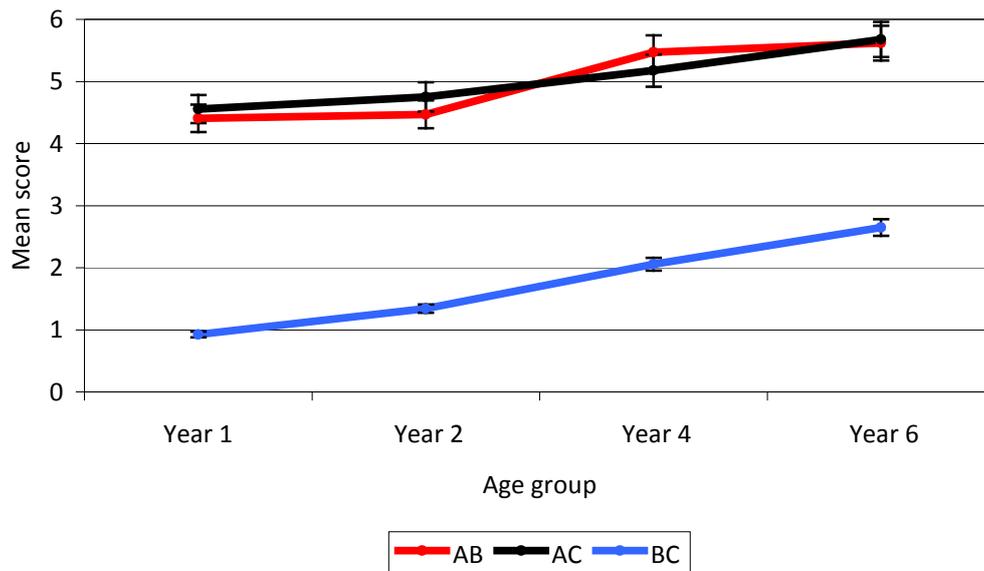
Figure 10.16   Mean scores for attributions of speed change by age groups (Maximum possible score = 6)

Figure 10.17 (p. 218) shows the mean speed change attribution scores by ball weight. A maximum score of 6 was obtainable for each distance AB, AC and BC. The weight of the ball did not interact significantly with overall attribution score, however, there was a significant difference for AB where the heavy ball ($M = 5.44$, $SD = 1.22$) received significantly more attributions than the light ball $(M = 4.68$, $SD = 1.96)$, $U = 1606$, $p < .05$, $r = -.21$.
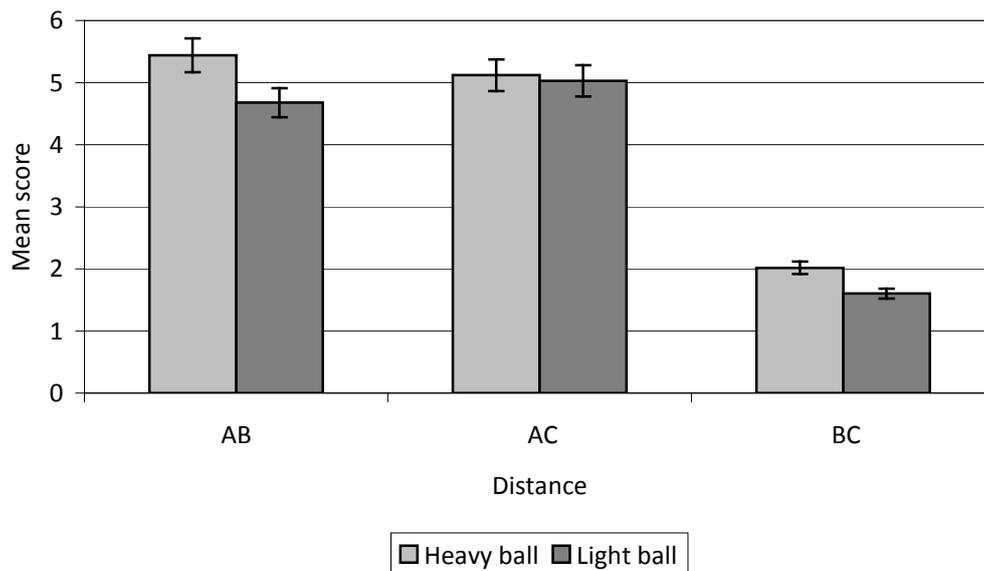
Figure 10.17   Mean scores for attributions of speed change by ball weight
(Maximum possible score = 6)

Figure 10.18 (p. 219) shows the distribution of mean scores for attributions of speed change by motion type. A maximum score of 2 was obtainable for each distance AB, AC and BC in each of the three motion dimensions. Motion type interacted significantly with attributions, $\chi^2(2, N = 127) = 17.47$, $p < .001$. Incline scenarios did not receive significantly more attributions than free fall scenarios, but both incline scenarios ($M = 4.15$, $SD = 1.40$), $T = 4$, $r = -.34$, and free fall scenarios ($M = 4.02$, $SD = 1.33$), $T = 2$, $r = -.22$, received significantly more attributions than horizontal scenarios ($M = 3.73$, $SD = 1.38$). For all three motion types, the attribution pattern was the same: Speed change was attributed to AB and AC significantly more often than to BC (all $p < .025$). There were no differences in attribution between AB and AC.
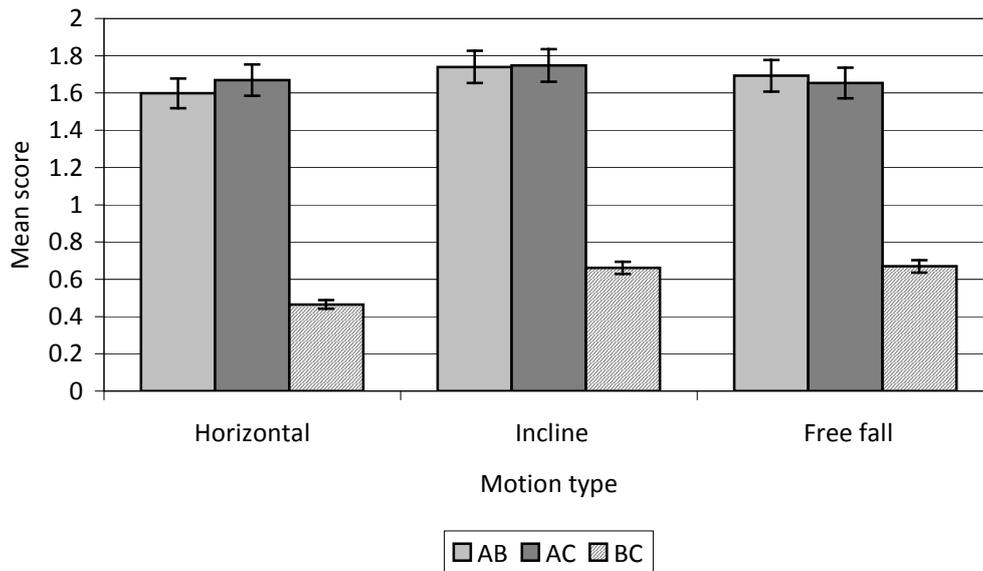
Figure 10.18 Mean scores for attributions of speed change by motion type (Maximum possible score = 2)

10.4.5 Study 2 versus Study 3

10.4.5.1 Horizontal motion, free fall motion and incline motion

There was high external consistency in the overall speed task results. For all three motion types, mean speed prediction scores from Study 2 and mean prediction statement choice scores from Study 3 were positively correlated with each other, τ = .77, p < .001.

10.4.5.2 Incline height change

There was high external consistency in the incline height comparison task results. Mean incline comparison prediction scores from Study 2 and mean prediction statement choice scores from Study 3 were positively correlated with each other, τ = .83, p < .001.

10.4.5.3 Speed change

There was high external consistency in the overall speed change task results. For all three motion types, mean speed change attribution scores from Study 2 and mean attribution statement choice scores from Study 3 were positively correlated with each other, $\tau = .68$, $p < .001$.

10.4.6 Response times

10.4.6.1 Within-block response times

Figure 10.19 below shows the mean response times across trials. Regardless of block type, there was significant variation in mean response times, $\chi^2(5, N = 127) = 429.35$, $p < .001$, with response times decreasing from an average 15084 ms ($SD = 1948$ ms) in Trial 1 to an average 14029 ms ($SD = 1882$ ms) in Trial 6. All block types showed significant decreases (all $p < .001$) over trials. The decrease occurred regardless of order of blocks.
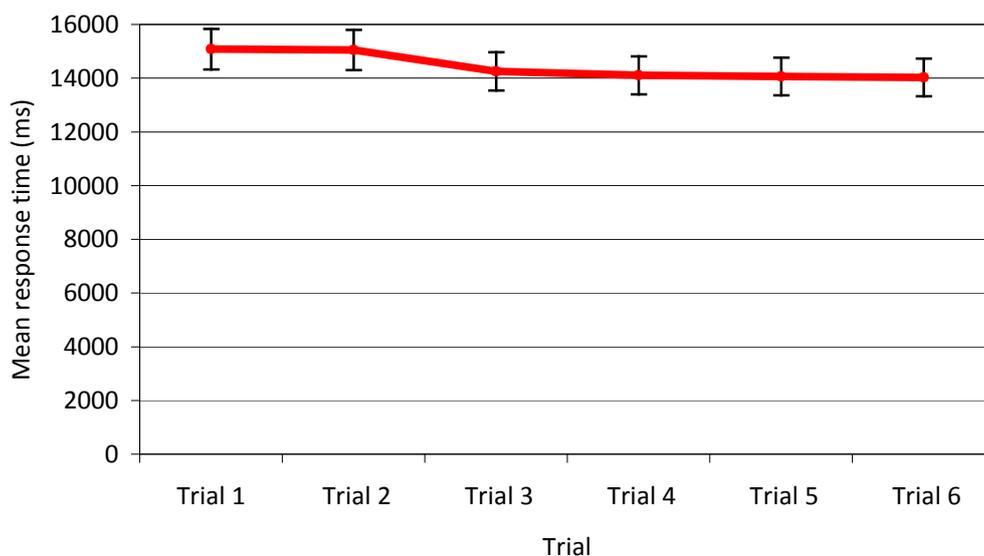
Figure 10.19   Mean response times across trials

10.4.6.2 Between-block response times for speed tasks

Figure 10.20 below shows the mean response times by motion type. There was a significant interaction of motion type with mean response times, $\chi^2(3, N = 127) = 276.48$, $p < .001$. Response times were greatest for the first incline block ($M = 12999$ ms, $SD = 2540$ ms) and smallest for the incline comparison block ($M = 11072$ ms, $SD = 1488$ ms). Post hoc analyses (significance thresholds $p \leq .0167$) showed that response times for incline trials were significantly greater than for horizontal trials, $T = 9$, $r = -.79$. Response times for horizontal trials were significantly greater than for free fall trials, $T = 6$, $r = -.53$. Response times for free fall trials were significantly greater than for incline comparison trials, $T = 9$, $r = -.80$.
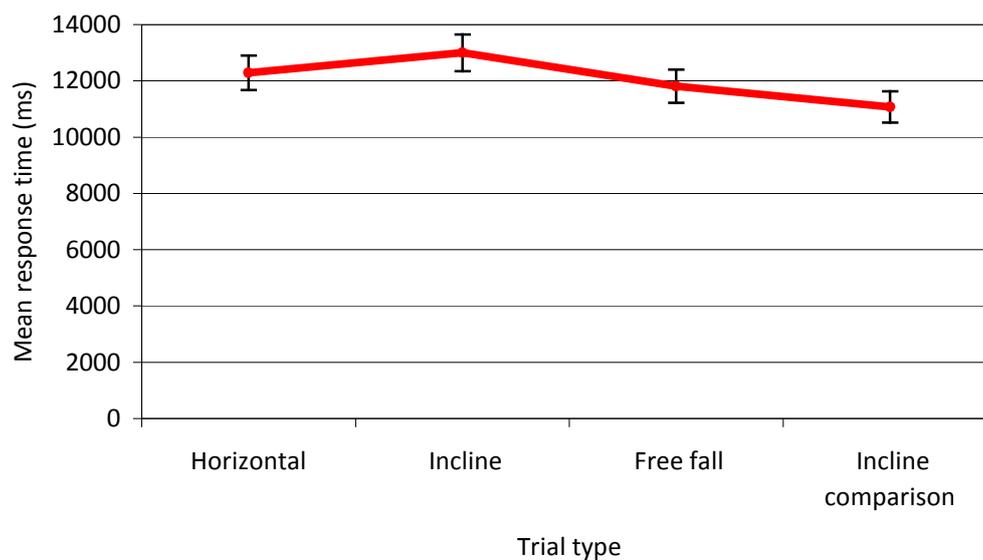
Figure 10.20   Mean response times by motion type

10.4.6.3 Between-block response times for speed change tasks

Figure 10.21 (p. 222) shows the mean response times among speed change blocks. There was significant variation in mean response times, $\chi^2(2, N = 127) = 202.65$, $p < .001$. Response times were greatest for the incline block ($M = 19236$ ms, $SD = 1711$ ms) and were significantly greater than for horizontal trials ($M = 16964$ ms, $SD =$

2099 ms), *T* = 10, *r* = -.87, and for free fall trials (*M* = 16646 ms, *SD* = 2269 ms), *T* = 10, *r* = -.87. Response times did not differ significantly between horizontal and free fall trials.
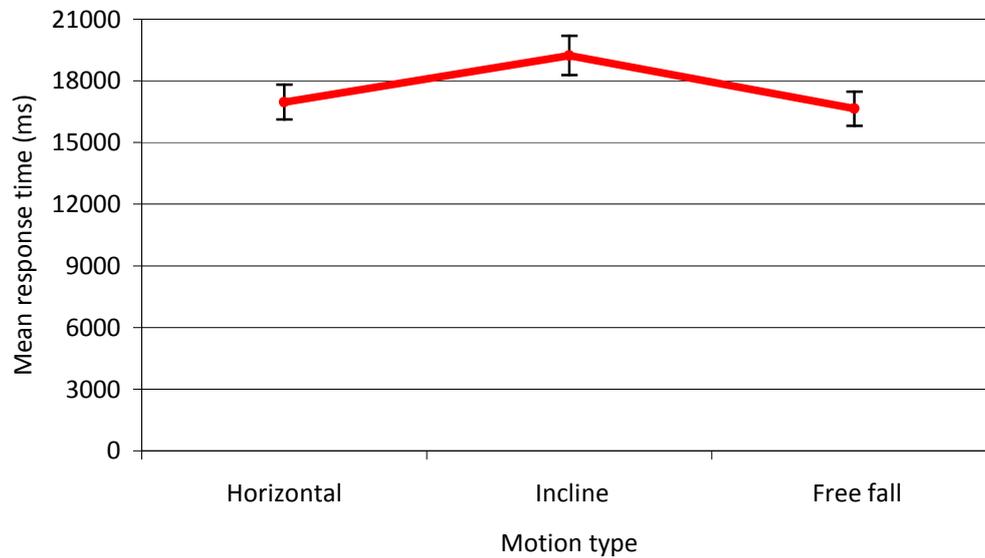
Figure 10.21   Mean response times among speed change blocks

10.5 Discussion

The principal aim of the present study was to assess young children's explicit understanding of object motion within a computer-presented task, and to compare the findings to those emerging from a real-object task, that is, Study 2. Given the increasing use of ICT in schools and the recognition of benefits coming from computer-assisted teaching and learning, it was hoped that this study could provide valuable information towards designing conceptual change programmes in early science education that would incorporate computers. Moreover, the study aimed to provide additional information about young children's explicit beliefs by analysing their response times to tasks.

10.5.1 Using computers to assess explicit beliefs

The results of this study all show high positive correlations between children's explicit predictions made in Study 2 and the same children's statement choices made in Study 3. Even when all options are presented to children in the form of different 'hypotheses', including the correct one, children still made choices consistent with their predictions. This finding lends much support to the possibility of using computers as a tool in conceptual change programmes, as they appear to provide the same information about children's explicit beliefs as related real-object tasks. As in Study 2, almost all of the speed task responses were in favour of differences in motion between the two balls, regardless of direction of the responses. Concerning attribution of changes in speed, the pattern was similar to that observed in Study 2 as well. Both attributions of speed change to AB and attributions of speed change to AC were made in over 80 per cent of cases each, but attributions of speed change to BC only in 30 per cent of cases (which is ten percentage points less than in Study 2, the largest difference observed between the two studies). And over 80 per cent of incline comparison predictions were chosen correctly, as in Study 2. Overall, the findings are confirmatory of the early-age conceptual change approach, whilst being able to incorporate ICT as well, which is consistent with recognition of benefit and potential of computer-based teaching in the literature (e.g. Barton, 2004; Glover et al., 2005; Holliman & Scanlon, 2004; Murphy, 2003; Newton & Rogers, 2001; Smith et al., 2005).

10.5.2 Response times

In Study 2, the idea was introduced that children's explicit understanding of how motion dimensions interact can be explained on the basis of supported versus non-supported motion – younger children associated incline motion more with horizontal motion because of the element of support in inclines, and older children associated it more with free fall motion because of the element of fall in inclines. One advantage of using a computer-presented task over a real-object task to assess explicit knowledge is that response times can be measured at an accurate level. If

children think about horizontal motion and about vertical motion independently, but having to consider *two* dimensions in incline motion, then response times for the incline motion tasks could be expected to be longer. And the results from this study suggest that some trials appeared to be more difficult than others, as more time was spent reasoning about the statements.

Both for speed and speed change tasks, significantly more time was spent on incline motion trials than on any of the other motion type trials. This could provide support to the notion that motion down inclines is perceived to be the result of horizontal and vertical dimensions interacting, whereas reasoning about either horizontal or vertical dimensions alone is much easier, as then only one dimension has to be taken into consideration. One aspect that was not considered in the analyses of response times was the children's ages. This factor was deemed not to provide any particularly useful information about any differences in reasoning processes per se, given that reading ability can be expected to vary among the age groups and within groups as well, and given that some children had to rely on the researcher to read the prediction statements. Nonetheless the response times provide useful information for the interpretation of explicit understanding.

10.6 Summary

The results from this study suggest that children's explicit beliefs about object motion can be assessed either through a real-object task or through a computer-presented task, as the results do not differ substantially. This lends much support to the notion of incorporating ICT into early science education. Furthermore, by incorporating the assessment of response times this study has provided further support for the notion introduced in Study 2 that children's ideas of incline motion are the result of an interaction of horizontal and vertical dimensions but with differing dimension salience across age.

CHAPTER 11:

YOUNG CHILDREN'S TACIT UNDERSTANDING OF OBJECT MOTION (STUDY 4)

11.1 Overview

The final objective, as introduced at the beginning of this thesis, was to see whether children have alternative knowledge sources that could, eventually, provide assistance in the conceptual change process and help to overcome the naïve Aristotelian conceptions identified in Chapter 1. So far, Studies 1 to 3 have all reached similar conclusions: Primary school children's explicit understanding about object motion is limited, and despite variation on incline motion tasks across age groups the children appear to hold consistent beliefs within their age groups across studies. However, is there perhaps an alternative form of knowledge about motion available in children that is not limited, but that cannot be consciously accessed by the individual? The introductory chapters have highlighted that there may well be such an alternative form of knowledge; knowledge that remains unarticulated yet can be demonstrated in use or action (Polanyi, 1967; Wagner & Sternberg, 1985). And if this so-called tacit knowledge can be triggered, how correct are young children's tacit conceptions of object motion, and how do they compare to their explicit beliefs?

Reed et al. (2010), for instance, have shown that people with above average ball playing skills show poor performance on pencil-and-paper prediction tasks, yet when these people are out in the field, they know where, when and how a ball will reach them without being able to give any explanation for their behaviour (Gigerenzer, 2004, 2007; McLeod & Dienes, 1996; McLeod et al., 2008). Do children perhaps have a similar sense of correctness about motion? Some studies suggest a degree of confirmation bias; a tendency to 'observe' what was predicted, even when there was actually a dissociation between predictions and actions (e.g. Baker et al., 2009; Chinn & Malhotra, 2002; Gunstone & White, 1981). Nevertheless the participants in these

studies were typically only shown the correct outcome on which to base their observations. What if children are shown outcomes that are incorrect but that reflect their explicit predictions – do they confirm their beliefs by judging these outcomes as correct, or do they realise that their explicit predictions actually result in dynamics that appear unnatural?

There have been attempts to show motion scenarios and ask participants to judge them as correct or incorrect (Kaiser & Proffitt, 1984; Kaiser et al., 1992; Shanon, 1976), suggesting that non-naturalness of motion can be detected, even if non-natural motion predictions are made. However, Shanon's (1976) conclusion was derived from the results of a somewhat small sample made up of participants who were adult university students; despite not being physics students, nothing is known about their prior educational experience that might have affected the results. Kaiser et al. (1992) included a greater number of students, again adults, of whom approximately three quarters did have relevant experience of physics instruction, and this may certainly have had a crucial effect on detecting naturalness. At the same time, though, violation-of-expectation studies have shown that even very young infants react with surprise and longer looking times when shown dynamic events where motion is unnatural, suggesting that these infants had some internal representation of what naturalness of motion would entail, and seeing incorrect scenarios did not comply with that internal representation (Kannass et al., 1999; Kim & Spelke, 1992).

However, what about the ages in between? Do children who have explicit beliefs about the world that are incompatible with accepted scientific views judge natural dynamic events as correct and unnatural dynamic events as incorrect, or do they judge those outcomes as correct that correspond to their explicit beliefs? If there is a mismatch between explicit reasoning and tacit judgement, then this could provide useful information towards the development of conceptual change programmes in early science, and it could also contribute support to the notion that the underlying knowledge displayed in infancy remains throughout the lifespan (cf. Carey, 2009; Keysers et al., 2008; Santos & Hood, 2009; Spelke, 2000).

On the basis of several studies, Chapter 3 highlighted the inclusion of judgement components into experimental tasks as a possible indicator of underlying tacit knowledge (cf. Broaders et al., 2007). In judgement tasks, participants are typically offered a limited number of options, and they are required to identify the correct option, or whether options are true or false. Computer-presented tasks were deemed to provide a useful tool for this, and a first important step towards this was taken in Study 3 by heightening the possibility of comparing predictions with judgements. Additionally, as tacit judgements are associated with spontaneous responses rather than 'controlled' processing in gesturing, for example (e.g. Broaders et al., 2007), and more importantly with fast processing (cf. Gigerenzer, 2007; Kurzban, 2008) it was hoped that response time data could provide more information in the process of tacit judgements of dynamic events.

11.2 Research questions

1. How do primary school children reason about dynamic events of object motion; how accurate are their judgements?
2. Can response times provide any additional information about children's tacit judgements?
3. How do children's tacit judgements compare with their explicit beliefs about object motion?

11.3 Method

11.3.1 Pilot study

11.3.1.1 Participants

As noted in Chapter 7, the pilot sample for the study consisted of 17 children (nine boys), which included three Year 1 children (two boys; age M = 6.20 years, SD = 0.38), six Year 2 children (four boys; age M = 7.20 years, SD = 0.28), five Year 4

children (three girls; age *M* = 8.90, *SD* = 0.13) and three Year 6 children (two girls; age *M* = 11.31, *SD* = 0.50).

11.3.1.2 Materials

The scenarios were recorded with a Sony DCR-HC35E digital video camera recorder and compiled using Windows Movie Maker. The recordings were of the two test balls used in Study 2 and Study 3 (a bright pink table tennis ball and a dark green solid glass marble) being released into the transparent tube from the previous studies and falling down, rolling down when inclined, or along a horizontal surface after leaving the tube. Recordings were modified so that for each motion type there were three different scenarios. The video clips either showed motion as it actually occurs ('same-speed trials'), or had the motion of one of the balls slowed down, such that there were trials where one ball was half as fast as the other, either the light ball or the heavy ball ('different-speed trials'). For all video clips, motion occurred 5 seconds into the clip, giving the child time to prepare for the task, that is, to note which ball is the heavy ball and which one is the light ball, or which incline is high and which one is low. Total video clip length was always 10 seconds. A screenshot of an example of a trial is shown in Figure 11.1 (p. 229). In addition to the test scenarios, there were practice scenarios consisting of PowerPoint slides on which either a blue triangle or a red circle was shown.
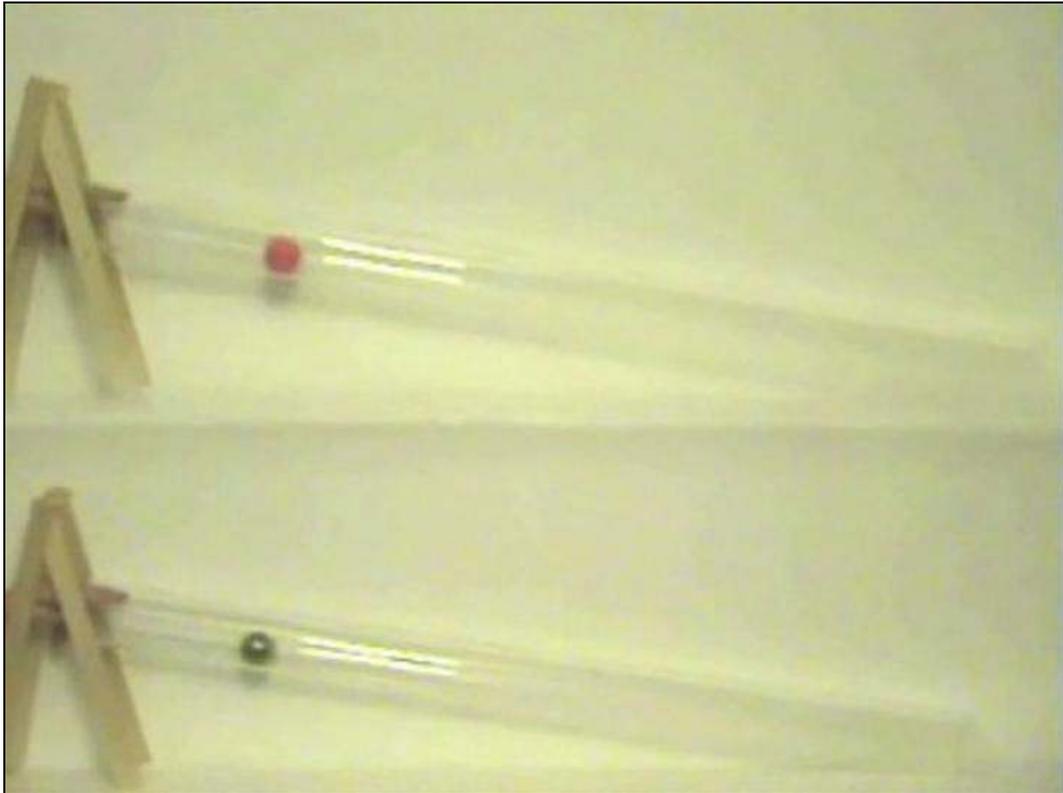
Figure 11.1   Screenshot of a correct incline motion trial in Study 4; the top tube shows the light table tennis ball, the bottom tube shows the heavy glass marble

Trials were presented using DMDX (Forster & Forster, 2003). The software was run on a Sony VAIO VGN-NR21J laptop. Connected to the laptop was an external 15" LCD colour monitor via which the scenarios were presented to the participants. An external KeySonic ACK-3400U Nano keyboard, also connected to the laptop, was used for responses to the scenarios. The keyboard was masked to reduce distractions. Two keys were indicated by colour on the masking. The DMDX programme was set up to allow only these two keys to function; the other keys were disabled. One key was on the left end of the keyboard (the red key), and the other key was on the right end of the keyboard (the blue key), in the same row as the centre key (see Figure 10.4, p. 197 – the yellow key was masked in Study 4). For half of the children the 'yes' response was the right key and the 'no' response the left key, for the other half of the conditions the 'yes' response was the left key, the 'no' response the right key. The 'yes' key was used to start blocks. In addition, two A4 sheets of paper, one with 'yes' and a green tick on it, and the other with 'no' and a

red cross on it, were placed next to the keyboard on the appropriate sides to act as reminder to the participants. Each trial could be seen for the length of the video clip, that is, for 10 seconds, after which the screen would become blank, but responses could be given up to 30 seconds after the start of each video clip, after which a new trial would start without recording a response if none was made within the 30 seconds.

11.3.1.3 Design

There were three kinds of trials. The first showed natural motion. The other two showed manipulated non-natural motion, that is, one of the two balls was slowed down. Of these two non-natural trial types, one reflected explicit predictions observed in Studies 2 and 3 and the other reflected the opposite view. For instance, children would see trials where the heavy ball falls much faster than the light ball – which, at large, reflects their explicit predictions – and trials where the light ball falls much faster than the heavy ball. There were six blocks of trials. All blocks consisted of six trials each, with each of the three trial types appearing twice within a block. Within each block the trials were randomised by the computer program. The order of blocks was known to the researcher, but the order of trials was not. Where incline comparisons had to be made, the same ball was seen for both inclines in the incline comparison block. The horizontal motion blocks always came after the incline motion blocks because horizontal motion, in this case, followed on from motion down the incline. Incline comparisons were also paired together. Motion always occurred in one direction within conditions but was varied between conditions such that one half of the children saw horizontal and incline motion from right to left and the other half of the children saw it from left to right. Free fall trials were not affected by motion direction control. Finally, a practice block consisted of six simple questions, where pictures had to be identified as being a blue circle or not.

11.3.1.4 Procedure

Children were assessed on an individual basis. The task was carried out outside of the classrooms but in an open and publicly accessible area of the school. The apparatus of transparent tube and incline frame used in Study 2 and shown in the trials was present at all times and was set up as for the incline tasks (see Figure 9.1, p. 163). Prior to a child joining, the computer program was set up and a condition was selected at random. The necessary information for each child was entered at this point. Upon arrival, the child was reminded about the previous tasks in Study 2 and Study 3 and was shown the apparatus used, and was told that this time there would be a computer where they would see short videos of the apparatus and hands holding balls into the tube and letting the balls go so that they would roll or fall. The two test balls used in Study 2 and shown in the computer-presented scenarios – the table tennis ball and the glass marble – were made available to the child at this point, and the child could handle them at any time but was asked not to carry out any relevant motions with the objects when having to respond to the computer scenario items, that is, not to roll them across the table or deliberately let them fall. It was made clear to the child that participation was voluntary and that completion of individual items or the study as a whole was not compulsory.

The child first saw a blank screen, and the researcher familiarised the child with the monitor and the keyboard. The researcher explained that one of the keys meant 'yes' and pointed out the sheet of paper stating 'yes' and a green tick next to that key, and that the other key meant 'no' and pointed out the sheet of paper stating 'no' and a red cross next to that key. The researcher then asked the child to point out each key according to its colour and meaning. Following the introduction the child was told that there would be some very easy trials to practise the use of the keyboard, where decisions had to be made whether what was shown on the monitor was a blue circle or not. This practice block consisted of six trials; three trials showed a red triangle and three trials showed a blue circle. The child was then asked to press the 'yes' key (either the red key or the blue key, depending on the condition), which elicited the practice block.

Before each test block the child was told which scenario type to expect. The child was given the following instruction: "Next, you are going to see two hands holding these two balls [researcher points out table tennis ball and marble] inside the tube and letting them go. Watch carefully, and decide, as quickly as you can, whether it looks right or not. If it looks right, press 'yes' [researcher points to 'yes' key and corresponding sheet of paper] and if it does not look right, press 'no' [researcher points to 'no' key and corresponding sheet of paper]." In the case of the horizontal motion block, the first part of the instruction was slightly modified: "Next, you are going to see these two balls [researcher points out table tennis ball and marble] rolling across the screen." At the end of each block, the child was given the option to either take a short break or continue with the next block. The task lasted approximately 10 to 15 minutes for each child.

11.3.1.5 Outcomes of the pilot study

During the first session of the pilot study some of the children were asked to explain how they would respond to the trials, that is, state which key they would press and why they would press it. They were not required to justify their responses per se, but needed to state that they pressed a key because of the response it is associated with. This was to ensure that the process of matching responses with the key colours was understood. As the piloting was not concerned with collecting data or information about response times, it was not crucial that the children responded as quickly or even accurately as they would in the main study. Trials were therefore set to last until a response was made, giving the children time to explain their choices. No difficulties in understanding instructions or the computer apparatus were registered. During a second piloting session the remaining children received the task without having to explain their response processes. Here, the trial length was put to the test, and each trial was set to last for 30 seconds only. No difficulties were apparent.

<u>11.3.2 Main study</u>

11.3.2.1 Participants

The Study 4 main sample consisted of 136 children (76 girls) from the sample noted in Chapter 7, which included 31 Year 1 children (17 girls; age M = 6.31 years, SD = 0.31), 35 Year 2 children (21 girls; age M = 7.27 years, SD = 0.28), 34 Year 4 children (20 girls; age M = 9.29, SD = 0.31) and 36 Year 6 children (18 girls; age M = 11.28, SD = 0.24). An additional seven children participated but were excluded from data analysis due to insufficient completion of the practice trials, not completing the study, or technical errors.

11.3.2.2 Materials

The materials were the same as used in the pilot study, but the trial length was set to last for 30 seconds only for all children.

11.3.2.3 Design

The general design was the same as in the pilot study. Altogether, there were eight different conditions (see Table 11.1, p. 234). For each half of a condition sample the 'yes' response was the right key and the 'no' response the left key, for the other half of the condition sample the 'yes' response was the left key, the 'no' response the right key. Each child contributed to all six blocks. In each trial there were always two options to choose from; either the trial looked correct or it did not. Overall, each child scored between 0 (if all trials were judged to look incorrect) and 36 (if all trials were judged to look correct). For each block the score was between 0 and 6. Approximately equal numbers of children per age group were selected for each condition. Overall, there were 17 children per condition. From each age group, four children were selected for each condition, and the remaining eight children were distributed over the eight conditions at random, one child per condition.

Table 11.1   Conditions in Study 4

	Condition							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Motion direction	Left to right		Right to left		Right to left		Left to right	
Block 1	Practice trials							
Block 2	Incline at 15 cm (two balls)	Incline at 30 cm (two balls)	Incline at 15 cm (two balls)	Incline at 30 cm (two balls)	Free fall (two balls)			
Block 3	Incline comparisons with heavy ball only		Incline comparisons with light ball only		Incline at 15 cm (two balls)	Incline at 30 cm (two balls)	Incline at 15 cm (two balls)	Incline at 30 cm (two balls)
Block 4	Incline comparisons with light ball only		Incline comparisons with heavy ball only		Incline comparisons with heavy ball only		Incline comparisons with light ball only	
Block 5	Horizontal (two balls)				Incline comparisons with light ball only		Incline comparisons with heavy ball only	
Block 6	Free fall (two balls)				Horizontal (two balls)			

11.3.2.4 Procedure

The general procedure was the same as in the pilot study; the piloting revealed no procedural issues that needed to be addressed.

11.4 Results

11.4.1 Method of analysis

In order for data to be considered for analysis, children had to correctly complete at least 4 out of the 6 practice trials and had to complete the study. 136 of the 143 children who participated were able to fulfil these requirements, so their data

qualified for analysis. Data were collected in form of 'correct' or 'incorrect' choices, that is, whether a trial looked correct or not (see 11.3.2.3). Data were also collected in form of response times to trials. As motion only occurred 5 seconds after the start of each clip but response times were recorded from 0 seconds onwards, 5000 ms were taken off each response time data point. Because responding to trials did not rely on reading prediction statements, unlike in Study 3, age differences in response times could be considered here.

Kolmogorov-Smirnov tests on the normality of distribution of data showed that all distributions, including response time distributions, deviated significantly from normality. Therefore assumptions for parametric tests were not met. Mean scores and mean response times were analysed using Friedman's ANOVAs and post hoc Wilcoxon signed-rank tests, with Bonferroni corrections applied (all significance thresholds $p \leq .025$ except when specified otherwise). Correlations were analysed using Kendall's tau tests. Effects of gender, effects of handedness and effects of key response (i.e. whether the left or the right key was the 'yes' response) were analysed with Mann-Whitney tests. Effects of age and effects of condition were analysed with Kruskal-Wallis tests and post hoc Jonckheere-Terpstra tests. No significant gender, handedness, key or condition effects were found, therefore these are not considered further.

In addition, chi-square analyses were conducted on children's performance accuracy (judging trials correctly versus judging trials incorrectly regardless of trial type), on scoring hits (judging correct trials to be correct) versus misses (judging correct trials to be incorrect) and on scoring correct rejects (judging incorrect trials to be incorrect) versus false alarms (judging incorrect trials to be correct). All data were analysed using PASW (Predictive Analytics Software, formerly SPSS) Statistics version 18.

11.4.2 Overall response times

11.4.2.1 Within-block response times

Figure 11.2 below shows the mean response times across trials. Regardless of block type, there was a significant interaction of trial number with response times within blocks, χ^2(5, *N* = 136) = 494.10, *p* < .001, decreasing from an average of 3742 ms (*SD* = 1250 ms) in Trial 1 to an average of 2034 ms (*SD* = 903 ms) in Trial 6. All block types showed significant decreases (all *p* < .001) over trials. Trials were responded to faster over time within each block. There was a significant interaction of age with mean response times, *H*(3) = 57.14, p < .001, with response times decreasing over age, *J* = 1521, *z* = -7.56, *r* = -.65.
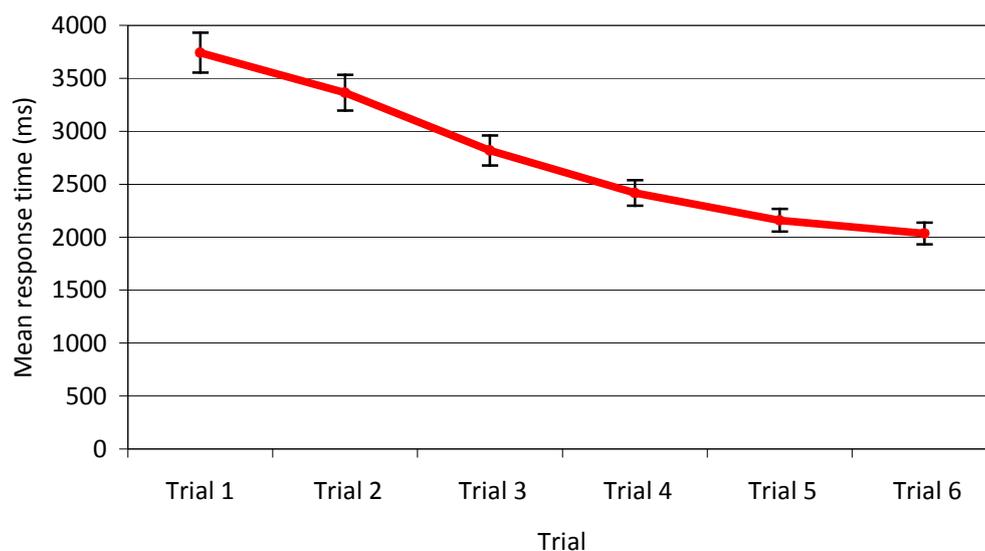
Figure 11.2   Mean response times across trials

11.4.2.2 Between-block response times

Figure 11.3 (p. 237) shows mean response times by block type. There was a significant interaction of block type with response times, χ^2(4, *N* = 136) = 381.74, *p* < .001. Post hoc analyses (significance thresholds *p* ≤ .0125) showed that response

times were greatest for horizontal blocks (*M* = 3641 ms, *SD* = 1266 ms) and smallest for the incline height comparison trials (heavy ball incline comparisons: *M* = 1883 ms, *SD* = 1383 ms; light ball incline comparisons: *M* = 1893 ms, *SD* = 1162 ms). Response times for horizontal trials were significantly slower than for incline trials, *T* = 7, *r* = -.58. Response times for incline trials were significantly slower than for free fall trials, *T* = 10, *r* = -.88. Response times for free fall trials were significantly slower than for light incline comparison trials, *T* = 9, *r* = -.79. Response times for the comparison trials did not differ significantly from each other. There was also a significant interaction of within-block trial type with response times. Response times decreased from 2975 ms (*SD* = 1077 ms) at first viewing to 2538 ms (*SD* = 905 ms) at second viewing of the same trial, *T* = 9, *p* < .001, *r* = -.78. The same effect was noted in all blocks.
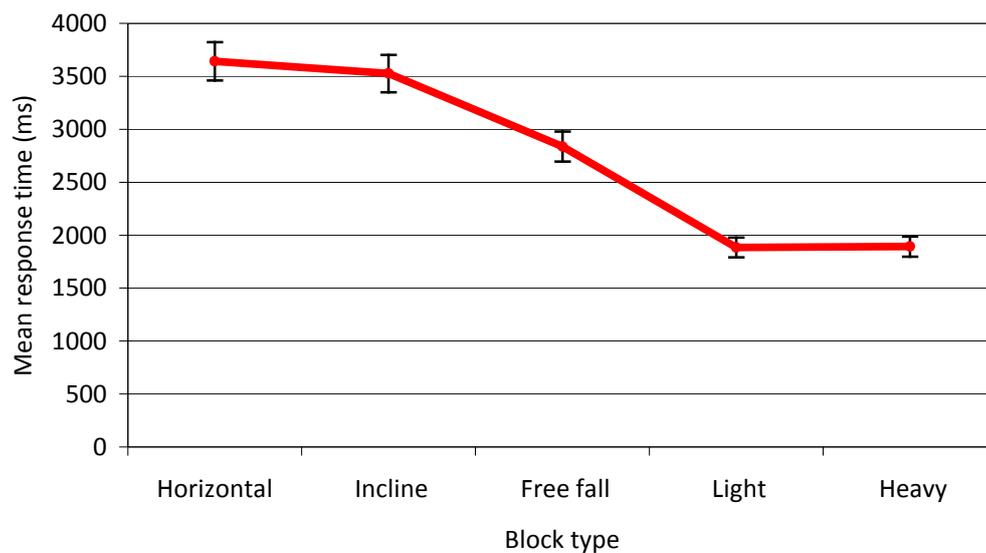
Figure 11.3   Mean response times by block type

11.4.3 Ball comparisons

Figure 11.4 (p. 238) shows mean scores for choosing trials as correct; trials could either show the heavy ball being faster than the light ball ('heavy'), the light ball being faster than the heavy ball ('light'), or both balls travelling at the same speed. A

maximum score of 6 was obtainable. There was a significant interaction of trial type with mean correctness scores, χ^2(2, N = 136) = 140.31, $p < .001$. Same-speed trials (M = 4.62, SD = 1.38) were chosen as correct significantly more often than different-speed trials (M = 3.14, SD = 1.55), T = 6, r = -.49. There were no significant differences between judging scenarios as correct when either of the balls was faster.
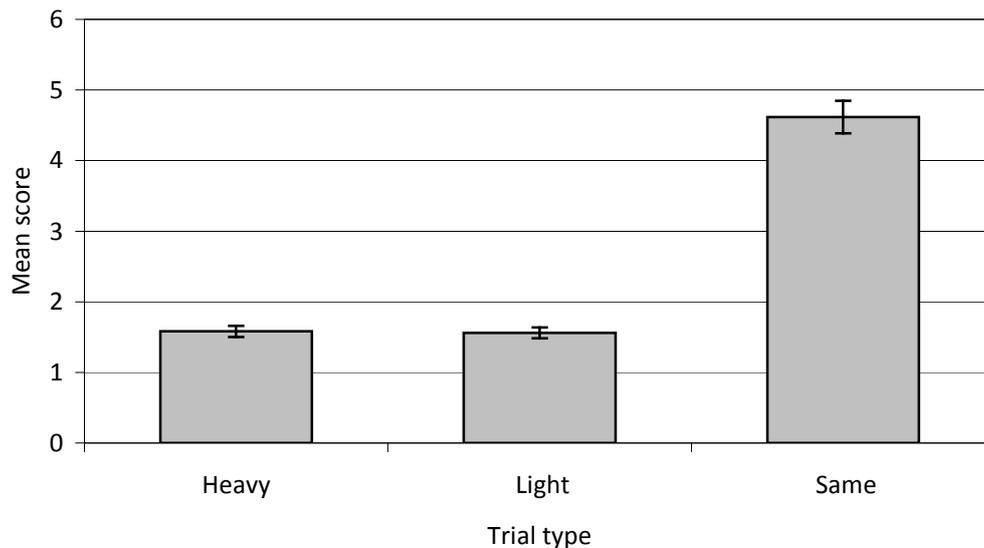
Figure 11.4   Mean scores for choosing trials as correct (Maximum possible score = 6)

Figure 11.5 (p. 239) shows mean scores for choosing trials as correct by age groups. There was no significant interaction of age with judging same-speed trials as correct, but age interacted significantly with judging trials as correct when the heavy ball was faster, H(3) = 7.98, $p < .05$, with judgements increasing with age, J = 4158, z = 2.80, r = .24. There was also a significant interaction of age with judging trials as correct when the light ball was faster, H(3) = 8.08, $p < .05$, with judgements decreasing with age, J = 2764, z = -2.83, r = -.24.

238
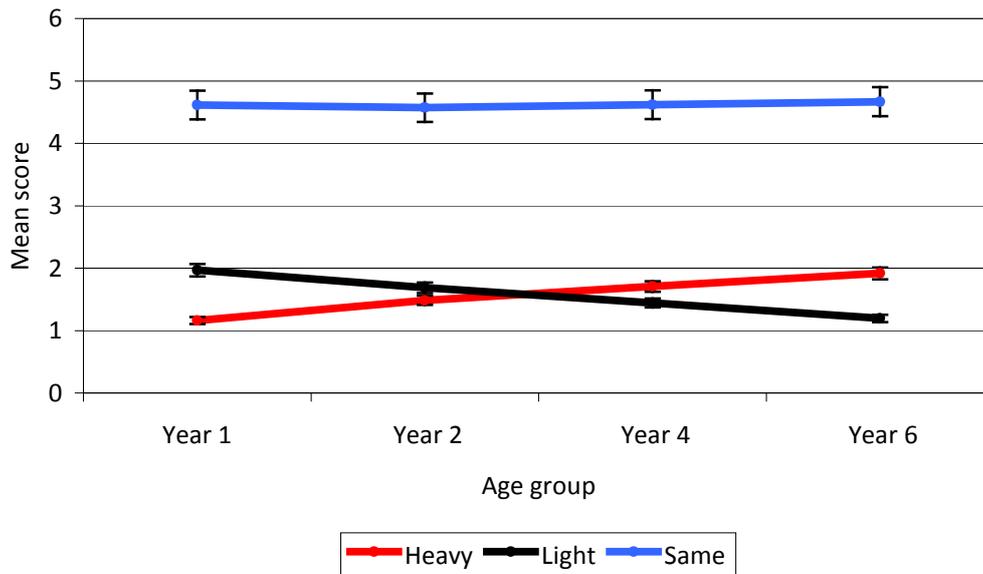
Figure 11.5   Mean scores for choosing trials as correct by age groups (Maximum possible score = 6)

Children were significantly more accurate (*M* = 6.74, *SD* = 2.58) than inaccurate (*M* = 2.26, *SD* = 1.71) in their motion judgements, χ^2(1, *N* = 2448) = 606.01, *p* < .001. They scored significantly more hits (*M* = 4.62, *SD* = 1.38) than misses (*M* = 1.38, *SD* = 1.38) for all motion trials, χ^2(1, *N* = 816) = 237.25, *p* < .001. They also scored significantly more correct rejects (*M* = 8.86, *SD* = 1.55) than false alarms (*M* = 3.14, *SD* = 1.55), χ^2(1, *N* = 1632) = 370.88, *p* < .001. Their performance was therefore significantly better both for correct and incorrect trials.

11.4.3.1 Motion along a horizontal

Figure 11.6 (p. 240) shows the distribution of mean scores for choosing trials as correct for motion along a horizontal; trials could either show the heavy ball being faster than the light ball ('heavy'), the light ball being faster than the heavy ball ('light'), or both balls travelling at the same speed. A maximum score of 2 was obtainable. There was a significant interaction of scenario type with mean correctness scores for horizontal motion trials, χ^2(2, *N* = 136) = 127.00, *p* < .001. Same-speed trials (*M* = 1.51, *SD* = 0.75) were chosen as correct significantly more

often than trials where the light ball (*M* = 0.92, *SD* = 0.82) was faster, *T* = 8, *r* = -.65, and trials were chosen as correct more often when the light ball was faster than when the heavy ball (*M* = 0.10, *SD* = 0.33) was faster, *T* = 4, *r* = -.36.
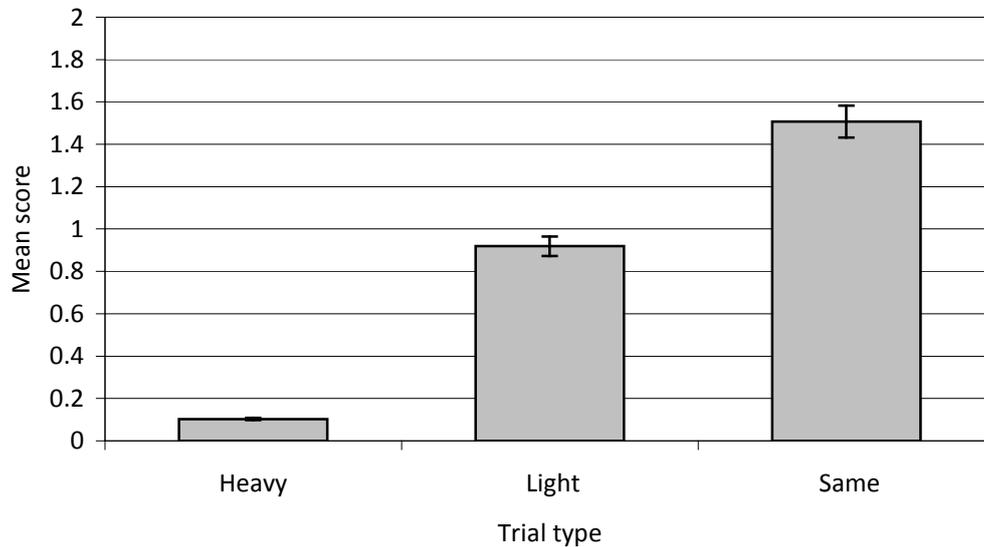
Figure 11.6   Mean scores for choosing horizontal motion trials as correct (Maximum possible score = 2)

Figure 11.7 (p. 241) shows the mean scores for horizontal motion judgements by age groups. Age did not interact significantly with mean scores. Regardless of age, children consistently judged trials as correct in the same pattern.
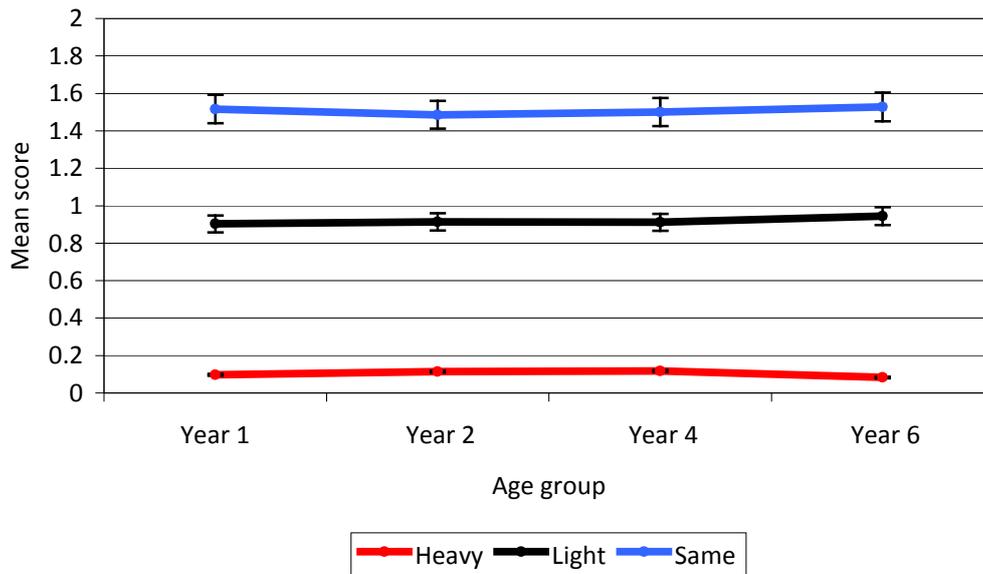
Figure 11.7 Mean scores for horizontal motion trial judgements by age groups (Maximum possible score = 2)

Children were significantly more accurate (*M* = 2.24, *SD* = 1.09) than inaccurate (*M* = 0.76, *SD* = 0.84) in their horizontal motion judgements, χ^2(1, *N* = 816) = 200.02, *p* < .001. Children scored significantly more hits (*M* = 1.51, *SD* = 0.75) than misses (*M* = 0.49, *SD* = 0.75), χ^2(1, *N* = 272) = 70.01, *p* < .001. They also scored significantly more correct rejects (*M* = 2.98, *SD* = 0.85) than false alarms (*M* = 1.02, *SD* = 0.85), χ^2(1, *N* = 544) = 130.07, *p* < .001. Their performance was therefore significantly better both for correct and incorrect trials.

11.4.3.2 Motion down an incline

Figure 11.8 (p. 242) shows the distribution of mean scores for choosing trials as correct for motion down an incline; trials could either show the heavy ball being faster than the light ball ('heavy'), the light ball being faster than the heavy ball ('light'), or both balls travelling at the same speed. A maximum score of 2 was obtainable. There was a significant interaction of scenario type with mean correctness scores for incline motion trials, χ^2(2, *N* = 136) = 72.15, *p* < .001. Same-speed trials (*M* = 1.52, *SD* = 0.77) were chosen as correct significantly more often

than trials where the heavy ball (*M* = 0.57, *SD* = 0.71) was faster, *T* = 7, *r* = -.59, and more often than trials where the light ball (*M* = 0.54, *SD* = 0.76) was faster, *T* = 7, *r* = -.58. The two different-speed trials did not differ from each other.
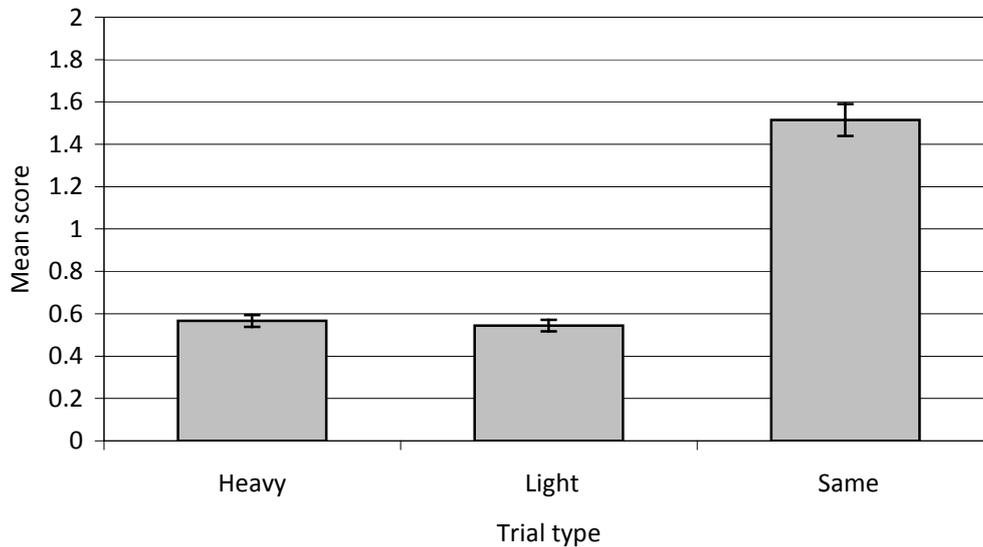
Figure 11.8   Mean scores for choosing incline motion trials as correct (Maximum possible score = 2)

Figure 11.9 (p. 243) shows the mean scores for incline motion judgements by age group. There was no significant interaction of age with judging same-speed trials as correct, but age significantly interacted with judging trials as correct when the heavy ball was faster, *H*(3) = 20.20, *p* < .001. As age increased, these scenarios were increasingly likely to be judged correct, *J* = 4504, *z* = 4.55, *r* = .39. Age also significantly interacted with judging trials as correct when the light ball was faster, *H*(3) = 19.37, *p* < .001, but this time scenarios were decreasingly likely to be judged as correct as age increased, *J* = 2497, *z* = -4.35, *r* = -.37.
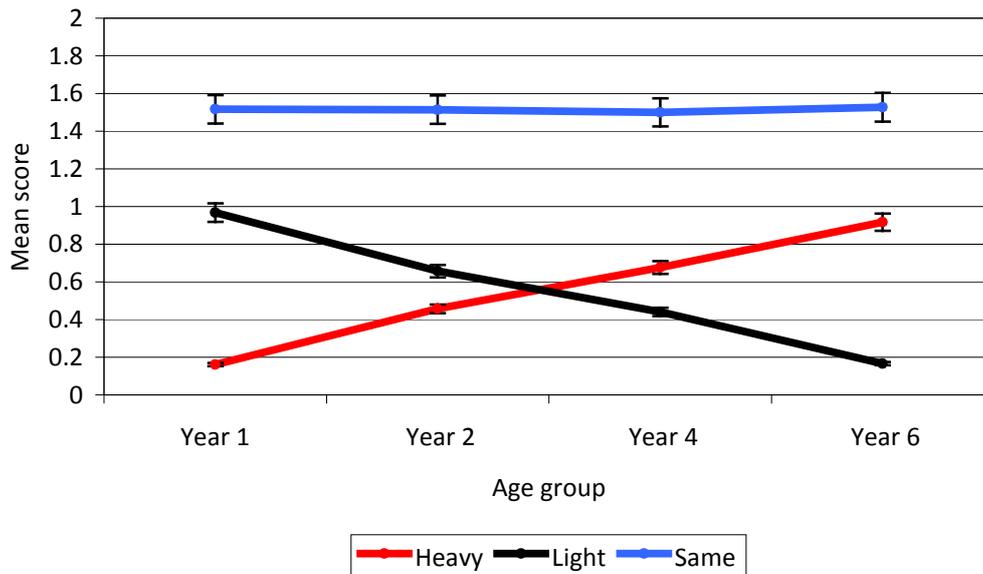
Figure 11.9   Mean scores for incline motion trial judgements by age groups (Maximum possible score = 2)

Children were significantly more accurate (*M* = 2.20, *SD* = 1.09) than inaccurate (*M* = 0.78, *SD* = 0.90) in their incline motion judgements, χ^2(1, *N* = 816) = 178.83, *p* < .001. They scored significantly more hits (*M* = 1.51, *SD* = 0.77) than misses (*M* = 0.49, *SD* = 0.77), χ^2(1, *N* = 272) = 72.06, *p* < .001. They also scored significantly more correct rejects (*M* = 2.89, *SD* = 0.92) than false alarms (*M* = 1.11, *SD* = 0.92), χ^2(1, *N* = 544) = 130.07, *p* < .001. Their performance was therefore significantly better both for correct and incorrect trials.

11.4.3.3 Motion in free fall

Figure 11.10 (p. 244) shows the distribution of mean scores for choosing trials as correct for motion in free fall; trials could either show the heavy ball being faster than the light ball ('heavy'), the light ball being faster than the heavy ball ('light'), or both balls travelling at the same speed. A maximum score of 2 was obtainable. There was a significant interaction of scenario type with mean correctness scores for free fall motion trials, χ^2(2, *N* = 136) = 146.11, *p* < .001. Same-speed trials (*M* = 1.60, *SD* = 0.71) were chosen as correct significantly more often than trials where the heavy ball

(*M* = 0.91, *SD* = 0.77) was faster, *T* = 5, *r* = -.42, and trials were chosen as correct more often when the heavy ball was faster than when the light ball (*M* = 0.10, *SD* = 0.32) was faster, *T* = 8, *r* = -.67.
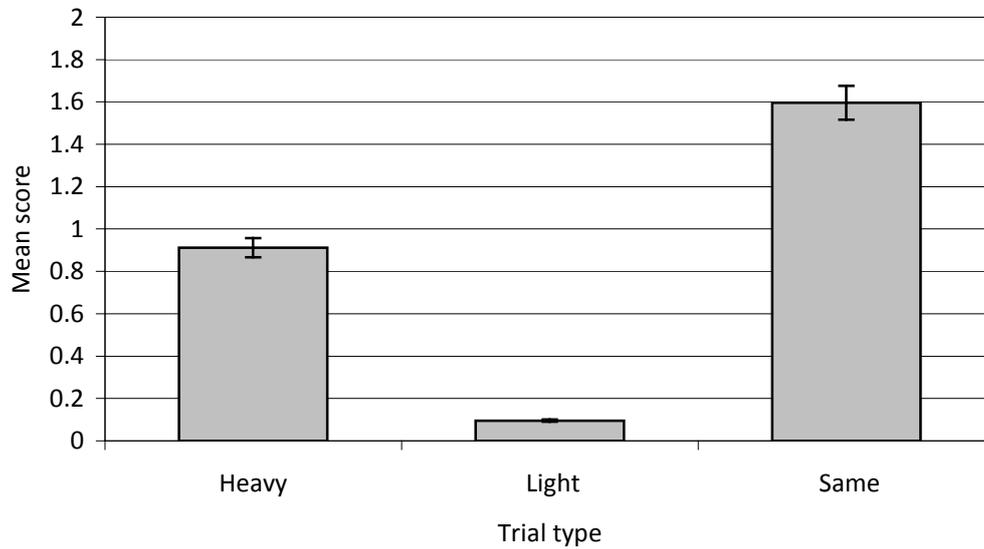
Figure 11.10   Mean scores for choosing free fall motion trials as correct (Maximum possible score = 2)

Figure 11.11 (p. 245) shows the mean scores for free fall motion judgements by age groups. Age did not interact significantly with mean scores. Regardless of age, children consistently judged trials as correct in the same pattern.
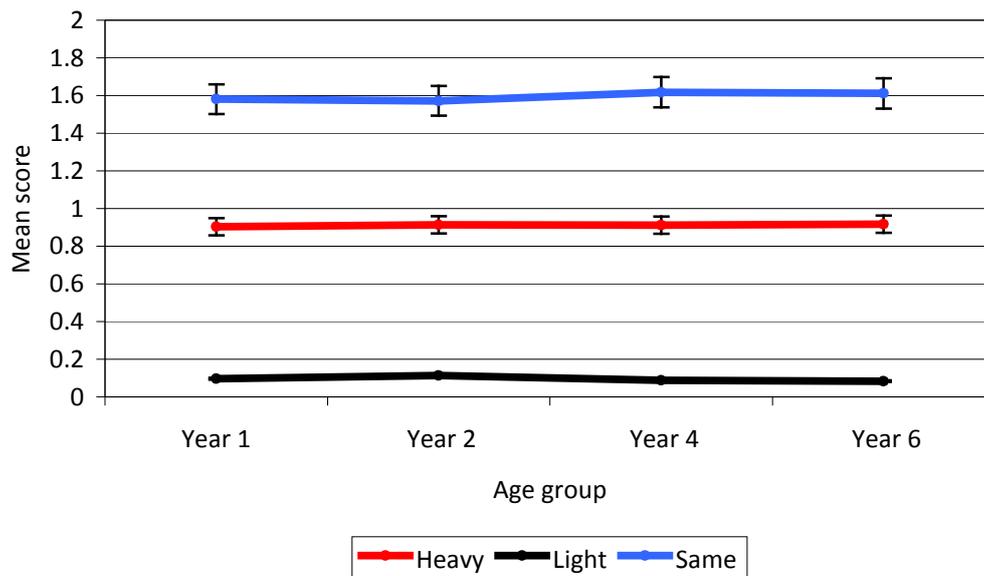
Figure 11.11   Mean scores for free fall motion trial judgements by age groups (Maximum possible score = 2)

Children were significantly more accurate (*M* = 2.29, *SD* = 1.04) than inaccurate (*M* = 0.71, *SD* = 0.83) in their free fall motion judgements, χ^2(1, *N* = 816) = 228.71, *p* < .001. They scored significantly more hits (*M* = 1.60, *SD* = 0.71) than misses (*M* = 0.40, *SD* = 0.71) for free fall motion trials, χ^2(1, *N* = 272) = 96.49, *p* < .001. Children also scored significantly more correct rejects (*M* = 2.99, *SD* = 0.83) than false alarms (*M* = 1.01, *SD* = 0.83) for free fall motion trials, χ^2(1, *N* = 544) = 134.01, *p* < .001. Their performance was therefore significantly better both for correct and incorrect trials.

11.4.3.4 Response times

Figure 11.12 (p. 246) shows the distribution of mean response times for trials over the three different motion types. Trial type had a significant effect on mean response times for trials in the horizontal motion block, χ^2(2, *N* = 136) = 234.10, *p* < .001. More time was spent on trials where the light ball was faster (*M* = 4399 ms, *SD* = 1336 ms) than on same-speed trials (*M* = 3543 ms, *SD* = 1339 ms), *T* = 10, *r* = -.85, and more time was spent on same-speed trials than on trials where the heavy ball was faster (*M* = 3849 ms, *SD* = 1337 ms), *T* = 9, *r* = -.81. There was no overall significant

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variation in mean response times for trial types in the incline motion block, though significantly less time was spent on same-speed trials (M = 3182 ms, SD = 1346 ms) than on trials where the light ball was faster (M = 3668 ms, SD = 1946 ms), T = 4, r = -.37. Trial type had a significant effect on mean response times for trials in the free fall motion block, χ^2(2, 136) = 201.63, p < .001. More time was spent on trials where the heavy ball was faster (M = 3849 ms, SD = 1337 ms) than on same-speed trials (M = 2374 ms, SD = 1141 ms), T = 10, r = -.87, but response times did not differ significantly between same-speed trials and trials where the light ball was faster.
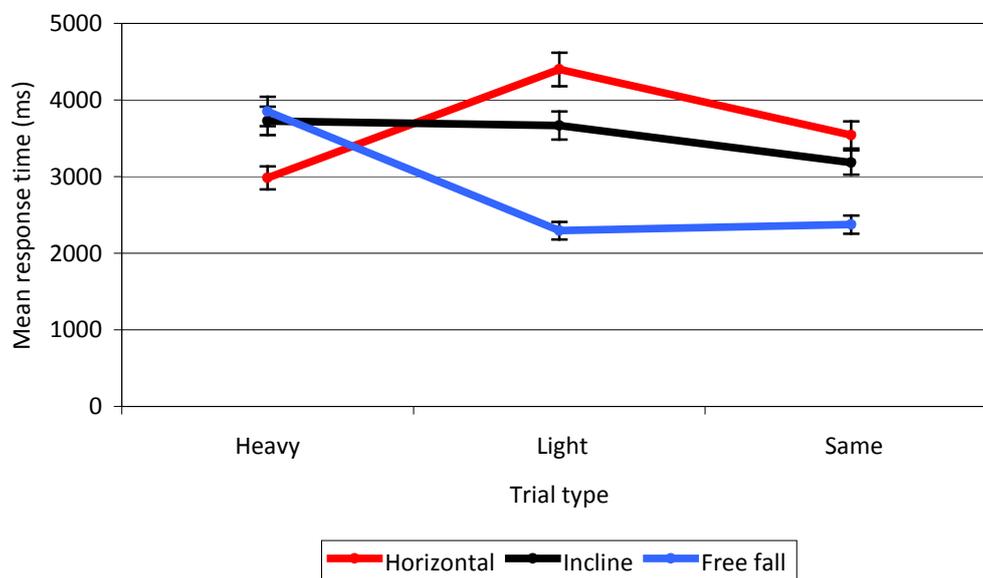
Figure 11.12   Mean response times by motion type

Figure 11.13 (p. 247) shows mean response times for trials chosen as correct. There was a significant interaction of judgements with response times. When different-speed trials were chosen to be correct, response times were significantly higher than when same-speed trials were chosen to be correct. This was the case for horizontal motion trials, U = 1294, p < .001, r = -.30, for incline motion trials, U = 1242, p < .001, r = -.32, and for free fall trials, U = 992, p < .001, r = -.41.
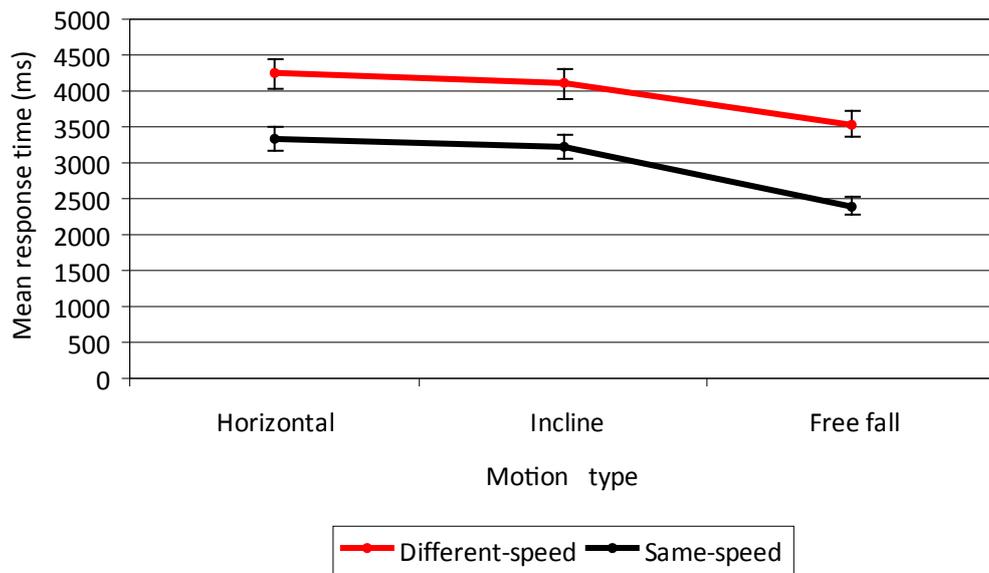
Figure 11.13   Mean response times for trials chosen as correct

11.4.4 Incline height comparisons

Figure 11.14 (p. 248) shows mean scores for incline height comparison trials; trials could either show the ball being faster down the high incline than down the low incline ('high incline'), being faster down the low incline than down the high incline ('low'), or travelling down both inclines at the same speed. A maximum score of 4 was obtainable. There was a significant interaction of incline height with mean response scores, χ^2(2, N = 136) = 225.55, p < .001. Trials where motion down the high incline was faster (M = 3.65, SD = 0.61) were chosen as correct significantly more often than same-speed trials (M = 0.68, SD = 1.00), T = 10, r = -.86, and same-speed trials were chosen as correct significantly more often than trials where motion down the low incline was faster (M = 0.14, SD = 0.49), T = 5, r = -.44. There were no significant differences between the heavy ball and the light ball; both followed the same pattern.
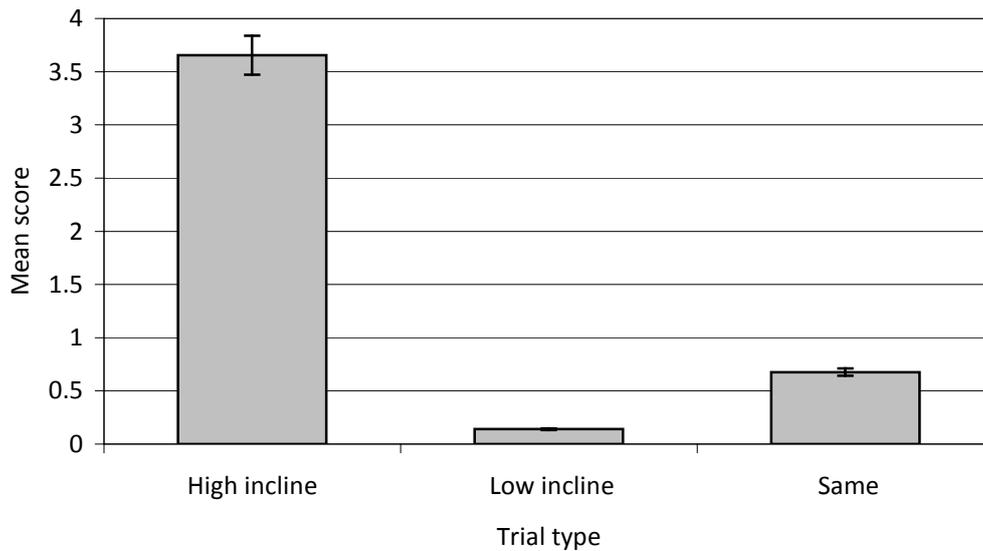
Figure 11.14   Mean scores for incline comparison trials (Maximum possible score = 4)

Children were significantly more accurate (*M* = 5.42, *SD* = 1.98) than inaccurate (*M* = 0.58, *SD* = 0.92) in their incline height comparison judgements, χ^2(1, *N* = 1632) = 1061.19, *p* < .001. There was significant variation with age; children were increasingly likely with age to be accurate than inaccurate, χ^2(3, *N* = 1632) = 27.9, *p* < .001. Children scored significantly more hits (*M* = 3.65, *SD* = 0.61) than misses (*M* = 0.35, *SD* = 0.61), χ^2(1, *N* = 544) = 372.24, *p* < .001. There was significant variation with age; children were increasingly likely with age to score hits rather than misses, χ^2(3, *N* = 544) = 14.8, *p* < .05. Children also scored significantly more correct rejects (*M* = 7.18, *SD* = 1.10) than false alarms (*M* = 0.82, *SD* = 1.10), χ^2(1, *N* = 1088) = 689.30, *p* < .001. There was again significant variation with age; children were increasingly likely with age to score correct rejects rather than false alarms, χ^2(3, *N* = 1088) = 14.7, *p* < .05. Overall, their performance was therefore significantly better both when seeing correct trials and when seeing incorrect trials.

11.4.4.1 Response times

Figure 11.15 below shows mean response times for incline height comparison trials. Incline height had a significant effect on mean response times, χ^2(2, *N* = 136) = 68.87, *p* < .001. More time was spent looking at same-speed scenarios (*M* = 2399 ms, *SD* = 1056 ms) than at trials where motion down the low incline was faster (*M* = 1647 ms, *SD* = 781 ms), *T* = 8, *r* = -.67. Given the accuracy on this task, this would suggest that the children were able to quickly identify the correctness or incorrectness of a scenario when one of the inclines caused faster motion because the difference between the two was visible soon enough. With the same-speed scenarios, they may have waited to see if a change would come after all but would then still be accurate enough to judge those scenarios as incorrect.
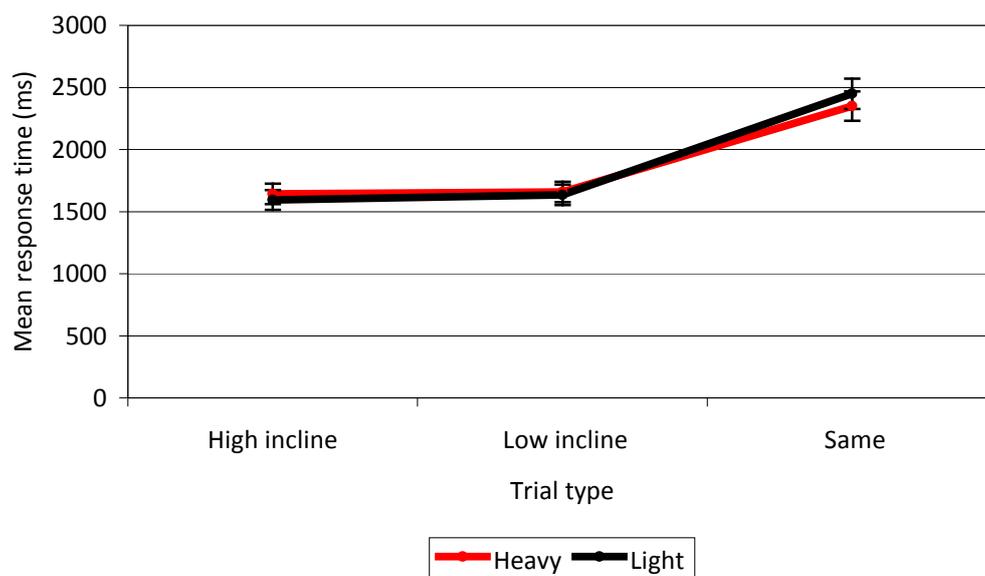
Figure 11.15   Mean response times for incline comparison trials

11.4.5 Explicit versus tacit tasks

11.4.5.1 Ball comparisons

Figure 11.16 (p. 251) shows the response accuracy for ball comparisons in Study 3 (explicit reasoning) contrasted with accuracy of judgements in Study 4 (tacit

reasoning). The tasks show an inverse relationship to each other. While in explicit reasoning a different-speed response was usually selected, $T = 10$, $r = -.89$, in the judgement tasks same-speed responses were perceived to be correct more often than different-speed responses, $T = 9$, $r = -.81$. Whenever a different-speed scenario was judged to be correct in the judgement tasks rather than the same-speed scenario, the same pattern as in the explicit task was followed: Across all age groups, children were more likely to select the horizontal scenarios where the light ball was faster as correct, $\chi^2(2, N = 46) = 74.06$, $p < .001$, and the free fall scenarios where the heavy ball was faster, $\chi^2(2, N = 41) = 59.84$, $p < .001$. The incline scenarios resulted in no significant overall preference for either different-speed scenarios, but there was a significant age effect on judging scenarios as correct when the light ball was faster, $H(3) = 16.57$, $p < .05$, with judgements decreasing over age, $J = 207$, $z = -4.03$, $r = -.59$, and there was a significant age effect on judging scenarios as correct when the heavy ball was faster, $H(3) = 25.58$, $p < .001$, with judgements increasing over age, $J = 632$, $z = 4.96$, $r = .73$. There was also a difference in Study 4 in response time patterns between these two groups. Mean response times were significantly higher for blocks where different-speed scenarios were chosen to be correct ($M = 3961$ ms, $SD = 656$ ms) than for blocks where same-speed scenarios were chosen to be correct ($M = 2986$ ms, $SD = 1211$ ms), $U = 1083$, $p < .001$, $r = -39$.
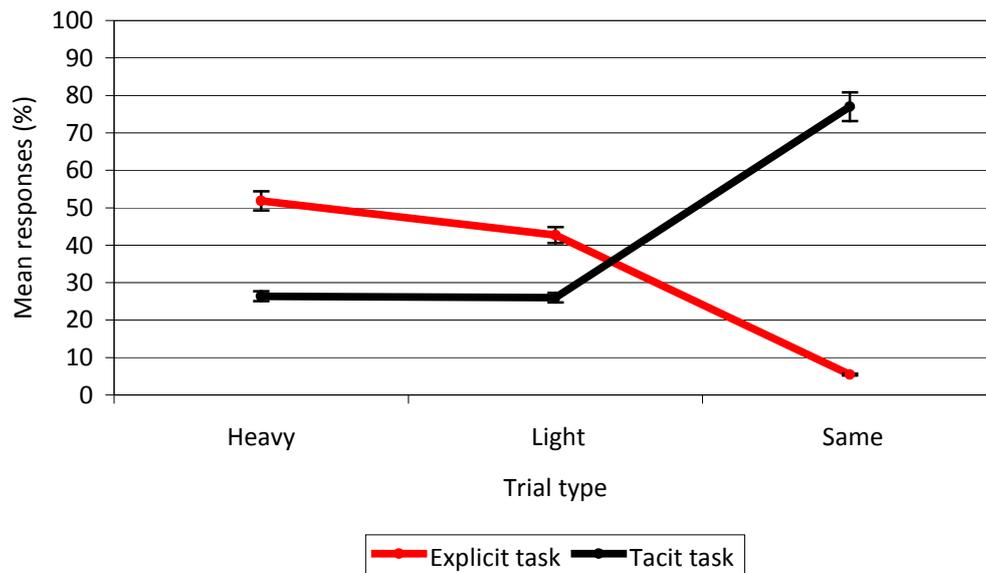
Figure 11.16   Comparison of response accuracy for ball comparisons in Study 3 with judgement accuracy in Study 4

11.4.5.2 Incline comparisons

Figure 11.17 (p. 252) shows the response accuracy for incline comparisons in Study 3 (explicit reasoning) and Study 4 (tacit reasoning). Both tasks show a similar pattern: The high incline was consistently predicted to cause faster motion in explicit reasoning, $T = 9$, $r = -.81$, no matter whether the heavy ball or the light ball was used, and when shown, this scenario was consistently chosen to be correct, $T = 10$, $r = -.86$, no matter which ball was shown.

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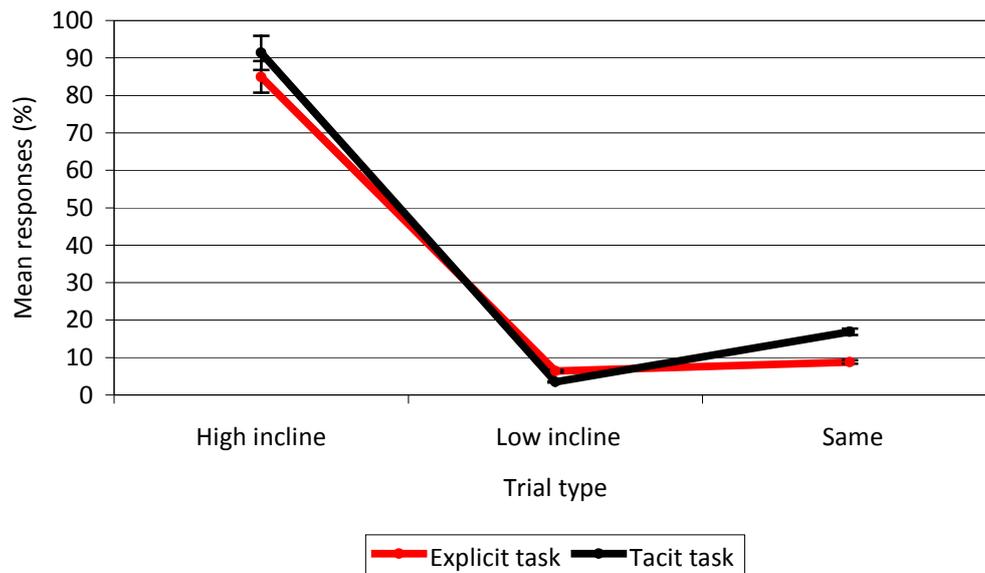
Figure 11.17   Comparison of response accuracy for incline comparisons in Study 3 with judgement accuracy in Study 4

11.5 Discussion

This study was concerned with trying to discover whether children are able to identify correct motion scenarios, even when their explicit beliefs are different. Specifically, the study investigated how primary school children's tacit judgements about object speed and acceleration compare with the beliefs they showed in Studies 2 and 3. By making use of approaches employed in previous work (Kaiser & Proffitt, 1984; Kaiser et al., 1992; Kannass et al., 1999; Kim & Spelke, 1992; Shanon, 1976) the study was an attempt to unveil underlying tacit knowledge about object motion and to compare and contrast it with findings from the explicit knowledge studies.

11.5.1 Accuracy of judgements

As opposed to Studies 2 and 3, where practically all predictions made when two balls had to be compared were different-speed predictions, Study 4 shows a different picture. Here, over 75 per cent of same-speed trials were judged to be correct,

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whereas only just over 25 per cent of the different-speed trials were judged to be correct. Given the high accuracy levels observed in previous studies that used judgement methodologies, it perhaps comes as no particular surprise that in the present study, too, children consistently judged those trials as correct where the ball rolling down the high incline was faster than the same ball rolling down the low incline, regardless of ball type. One problem to bear in mind at this point is the extent to which children might perceive some objects to be faster than others – perhaps the incorrect scenarios shown to them displayed too great a dissonance between the two balls' motion patterns; their beliefs may well hold that motion would be different, but not to such an extent, and therefore the same-speed motion trials may simply be more similar to their explicit beliefs than the different-speed trials. However, overall it would appear that young children are indeed able to recognise naturalness of motion and appreciate that it is correct; these findings are consistent with those of previous studies (Kaiser & Proffitt, 1984; Kaiser et al., 1992; Kannass et al., 1999; Kim & Spelke, 1992; Shanon, 1976).

Although same-speed scenarios were chosen to be correct significantly more often than different-speed scenarios, it is interesting to note that when looking at the numbers of different-speed trials that were judged as being correct, they show the same pattern as observed in the explicit reasoning tasks in Studies 2 and 3. When different-speed trials were judged as correct, it was mainly the trials where the light ball was faster that were chosen in the horizontal motion blocks, and mainly the trials where the heavy ball was faster that were chosen in the motion in free fall blocks. In blocks where motion was down an incline, the responses were in balance. However, as in the explicit reasoning tasks, the association of faster motion down an incline with the light ball shifted with increasing age to an association of faster motion down an incline with the heavy ball. It seems, therefore, that the responses can be separated into two groups: Either the judgements are accurate, or they reflect explicit beliefs. Trials that reflected neither of these two options were hardly ever selected as appearing to be correct. However, from accuracy alone it is difficult to know how seriously the researcher's instructions were followed. Did children respond as quickly as they could, or did they, on a small scale, take their time to

reflect about the trials? Or, as they knew beforehand what motion type to expect, that is, horizontal, incline or free fall, perhaps they prepared themselves in advance as to which trials they thought they should look for. Response times may help to analyse this aspect.

11.5.2 Response times

The results from this study suggest that some trials appeared to be more difficult than others, as responses were made later in the trial. Significantly more time was spent on horizontal motion trials than on any of the other motion type trials, and incline comparison trials were judged significantly faster than trials where two different balls had to be compared. When different-speed trials that matched children's explicit beliefs were judged to be correct, response times were observed to be significantly higher than when same-speed trials or when different-speed trials that did not match children's explicit beliefs were judged to be correct. Combining this with the directions of variables, it seems that children spent more time watching trials when they ended up judging different-speed trials as correct, thereby making it a less spontaneous judgement than when same-speed trials were judged to be correct, perhaps falling back on explicit beliefs.

11.5.3 Explicit reasoning versus tacit judgement

The principal aim of Study 4 was to provide data that permit young children's explicit reasoning about object motion to be compared with their judgements of motion naturalness. Although a reasonable number of different-speed trials were still judged as being correct, same-speed trials were recognised as being correct far more often than in Studies 2 and 3. Many children can seemingly identify inappropriate scenarios almost instantly; trials that are neither correct nor match their explicit beliefs (that is, when the heavy ball is faster along the horizontal, or when the light ball is faster in free fall). Not only were these scenarios usually judged as being incorrect, but response times were faster for these trials as well. So it is a question between correct scenarios and expected scenarios. It could well be that children who

chose trials as correct when they matched their explicit expectations were simply being biased in their observation. However, despite some unresolved questions it is clear that there is a mismatch between explicit reasoning and tacit judgement, with children recognising naturalness of motion.

11.6 Summary

When shown a variety of dynamic events, both natural and non-natural in nature, primary school children are able to identify those events that do, in fact, depict natural motion with reasonable accuracy, and well above chance levels. At each trial, chance level would be 50 per cent of judging the trial as correct and 50 per cent of judging it as incorrect. Yet children clearly performed far above this level. Response time recordings have helped explore these differences and the results suggest that if children act 'on a whim' they are more likely to appreciate naturalness of motion than when they spend more time making a decision. It is evident that children's tacit judgements, as in studies with adults, can be differentiated from their explicit beliefs quite clearly.

CHAPTER 12:

SUPPLEMENTARY CROSS-STUDY ANALYSES

Individually, Studies 1 to 4 all provide information on children's predictions of object motion – using, across the first three studies, different objects or different assessment approaches – and on the same children's judgements of object motion.

On the other hand, while correlation analyses were carried out between two consecutive studies, that is, comparing the results from Study 2 with those from Study 3 and comparing the results from Study 3 with those from Study 4, these on their own provide limited information on the continuity of children's performance. The correlations merely indicate a similarity or lack thereof between scores from two studies, but do not state very much – particularly between Study 3 and Study 4 – about the ways in which the sets of scores are comparable or the ways in which way they are not. Therefore additional analyses spanning these three studies were conducted in the hope of remedying this.

It is also worth looking at whether anything can be noted about children's variable use in their reasoning about everyday object motion, as was done in Study 1, and their judgements of dynamic events, as was done in Study 4. Is there any link between children's reliance on particular object variables in predictions and their ability to judge motion scenarios as correct or incorrect in an accurate manner? It was noted in Study 1 that generally speaking there was little consistency within age groups and across age groups in the use of variables when having to predict motion of everyday objects. And in Study 4, while there was a fair degree of consistency in accuracy levels, there was still a substantial group of children who did not perform as well. Looking at whether either of the two groups of children – those who performed well and those who did not – displayed any particular patterns in their everyday object predictions may help to understand these differences in judgements.

Two sets of supplementary cross-study analyses are presented in this chapter. First, the development of performance across Studies 2, 3 and 4 is analysed, displaying the trends of performance across these three studies. Following these, logistic regression analyses evaluate the relationships, if any, between variable use in Study 1 and judgement accuracy in Study 4, presenting any possible regression models that may help to establish predictions of accuracy in judgement tasks on the basis of variable use in everyday object reasoning.

12.1 Development of performance across Studies 2, 3 and 4

12.1.1 Methods of analysis

In order to ease comparison between mean performance scores from Study 2 and mean scores from Study 3, the mean scores for Study 3 were all averaged so that the maximum score matched that of Study 2 – in Study 3, the same trial for which a prediction had to be made in Study 2 was seen three times. Maximum scores for Study 4 were already equal to those for Study 2, thus also being equal to the averaged scores for Study 3. Mean scores were analysed using Friedman's ANOVAs and post hoc Wilcoxon signed-rank tests, with Bonferroni corrections applied (all significance thresholds $p \leq .025$). All data were analysed using PASW (Predictive Analytics Software, formerly SPSS) Statistics version 18.

12.1.2 Motion along a horizontal

Figure 12.1 (p. 258) shows the mean performance scores for the horizontal motion tasks from Study 2, Study 3 and Study 4. 'Heavy' refers to predicting that the heavy ball would be faster than the light ball (Studies 2 and 3) and to judging trials as correct when the heavy ball rolled faster than the light ball (Study 4). 'Light' refers to predicting that the light ball would be faster than the heavy ball (Studies 2 and 3) and to judging trials as correct when the light ball rolled faster than the heavy ball (Study 4). 'Same' refers to predicting that both balls would roll as fast as each other

(Studies 2 and 3) and to judging trials as correct when both balls rolled as fast as each other (Study 4). A maximum score of 2 was achievable in each task.

Figure 12.1   Mean performance scores for predictions and judgements in horizontal motion by task type (Maximum possible score = 2)

There was significant variation among mean performance scores across the studies for predicting the heavy ball to be faster (Studies 2 and 3) and judging trials to be correct when the heavy ball travelled faster (Study 4), χ^2(2, *N* = 121) = 14.78, *p* < .001. There was no significant difference between performance in Study 2 and performance in Study 3 or between performance in Study 3 and performance in Study 4.

There was also significant variation among mean performance scores across the studies for predicting the light ball to be faster (Studies 2 and 3) and judging trials to be correct when the light ball travelled faster (Study 4), χ^2(2, *N* = 121) = 63.20, *p* < .001. There was no significant difference between performance in Study 2 and performance in Study 3. However, there was a significant decline in frequency of

scores from Study 3 (*M* = 1.64, *SD* = 0.64) to Study 4 (*M* = 0.92, *SD* = 0.81), *T* = 6, *r* = -.58.

Finally, there was significant variation among mean performance scores across the studies for predicting both balls to travel at the same speed (Studies 2 and 3) and judging trials to be correct when both balls travelled at the same speed (Study 4), χ^2(2, *N* = 121) = 176.71, *p* < .001. There was a significant increase in frequency of scores from Study 2 (*M* = 0.06, *SD* = 0.23) to Study 3 (*M* = 0.13, *SD* = 0.34), *T* = 2, *r* = -0.22, and a significant increase in frequency of scores from Study 3 to Study 4 (*M* = 1.51, *SD* = 0.74), *T* = 9, *r* = -0.83.

12.1.3 Motion down an incline

Figure 12.2 (p. 260) shows the mean performance scores for the incline motion tasks from Study 2, Study 3 and Study 4. 'Heavy' refers to predicting that the heavy ball would be faster than the light ball (Studies 2 and 3) and to judging trials as correct when the heavy ball rolled faster than the light ball (Study 4). 'Light' refers to predicting that the light ball would be faster than the heavy ball (Studies 2 and 3) and to judging trials as correct when the light ball rolled faster than the heavy ball (Study 4). 'Same' refers to predicting that both balls would roll as fast as each other (Studies 2 and 3) and to judging trials as correct when both balls rolled as fast as each other (Study 4). A maximum score of 2 was achievable in each task.

Figure 12.2   Mean performance scores for predictions and judgements in incline
motion by task type (Maximum possible score = 2)

There was significant variation among mean performance scores across the studies
for predicting the heavy ball to be faster (Studies 2 and 3) and judging trials to be
correct when the heavy ball travelled faster (Study 4), χ^2(2, *N* = 121) = 35.70, *p* <
.001. There was no significant difference between performance in Study 2 and
performance in Study 3. However, there was a significant decline in frequency of
scores from Study 3 (*M* = 1.16, *SD* = 0.94) to Study 4 (*M* = 0.59, *SD* = 0.73), *T* = 5, *r* = -
.47.

There was also significant variation among mean performance scores across the
studies for predicting the light ball to be faster (Studies 2 and 3) and judging trials to
be correct when the light ball travelled faster (Study 4), χ^2(2, *N* = 121) = 14.15, *p* <
.05. There was no significant difference between performance in Study 2 and
performance in Study 3. However, there was a significant decline in frequency of
scores from Study 3 (*M* = 0.75, *SD* = 0.93) to Study 4 (*M* = 0.49, *SD* = 0.73), *T* = 3, *r* = -
.25.

Finally, there was significant variation among mean performance scores across the
studies for predicting both balls to travel at the same speed (Studies 2 and 3) and

judging trials to be correct when both balls travelled at the same speed (Study 4), $\chi^2(2, N = 121) = 190.52$, $p < .001$. There was no significant difference between performance in Study 2 and performance in Study 3. However, there was a significant increase in frequency of scores from Study 3 ($M = 0.09$, $SD = 0.32$) to Study 4 ($M = 1.53$, $SD = 0.76$), $T = 9$, $p < .001$, $r = -.83$.

12.1.4 Motion in free fall

Figure 12.3 (p. 262) shows the mean performance scores for the free fall motion tasks from Study 2, Study 3 and Study 4. 'Heavy' refers to predicting that the heavy ball would fall faster than the light ball (Studies 2 and 3) and to judging trials as correct when the heavy ball fell faster than the light ball (Study 4). 'Light' refers to predicting that the light ball would fall faster than the heavy ball (Studies 2 and 3) and to judging trials as correct when the light ball fell faster than the heavy ball (Study 4). 'Same' refers to predicting that both balls would fall as fast as each other (Studies 2 and 3) and to judging trials as correct when both balls fell as fast as each other (Study 4). A maximum score of 2 was achievable in each task.
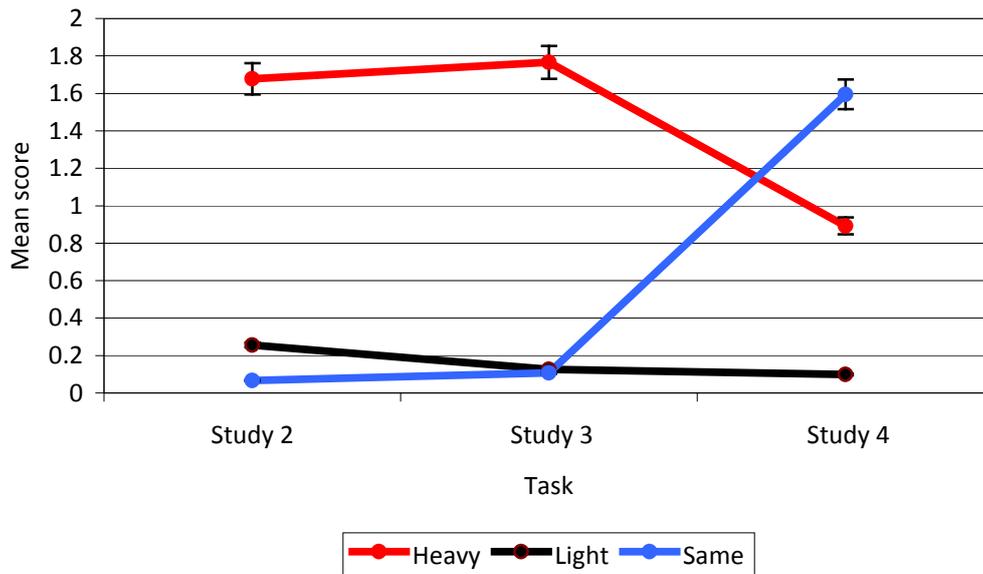
Figure 12.3   Mean performance scores for predictions and judgements in free fall motion by task type (Maximum possible score = 2)

There was significant variation among mean performance scores across the studies for predicting the heavy ball to be faster (Studies 2 and 3) and judging trials to be correct when the heavy ball travelled faster (Study 4), χ^2(2, *N* = 121) = 91.09, *p* < .001. There was no significant difference between performance in Study 2 and performance in Study 3. However, there was a significant decline in frequency of scores from Study 3 (*M* = 1.77, *SD* = 0.62) to Study 4 (*M* = 0.89, *SD* = 0.79), *T* = 7, *r* = -0.66.

There was also significant variation among mean performance scores across the studies for predicting the light ball to be faster (Studies 2 and 3) and judging trials to be correct when the light ball travelled faster (Study 4), χ^2(2, *N* = 121) = 16.40, *p* < .001. There was a significant decline in frequency of scores from Study 2 (*M* = 0.26, *SD* = 0.47) to Study 3 (*M* = 0.13, *SD* = 0.47), *T* = 3, *r* = -.24. However, there was no significant difference between frequency of scores in Study 3 and frequency of scores in Study 4.

Finally, there was significant variation among mean performance scores across the studies for predicting both balls to travel at the same speed (Studies 2 and 3) and judging trials to be correct when both balls travelled at the same speed (Study 4), χ^2(2, N = 121) = 192.09, p < .001. There was no significant difference between performance in Study 2 and performance in Study 3. However, there was a significant increase in frequency of scores from Study 3 (M = 0.11, SD = 0.42) to Study 4 (M = 1.60, SD = 0.71), T = 9, r = -.84.

12.1.5 Incline height comparisons

Figure 12.4 (p. 264) shows the mean performance scores for the incline height comparison tasks from Study 2, Study 3 and Study 4. 'High incline' refers to predicting that a ball would be faster down the high incline than down the low incline (Studies 2 and 3) and to judging trials as correct when the ball rolled faster down the high incline than down the low incline (Study 4). 'Low incline' refers to predicting that a ball would be faster down the low incline than down the high incline (Studies 2 and 3) and to judging trials as correct when the ball rolled faster down the low incline than down the high incline (Study 4). 'Same' refers to predicting that a ball would roll at the same speeds down both inclines (Studies 2 and 3) and to judging trials as correct when a ball rolled as fast down both inclines (Study 4). A maximum score of 2 was achievable in each task.
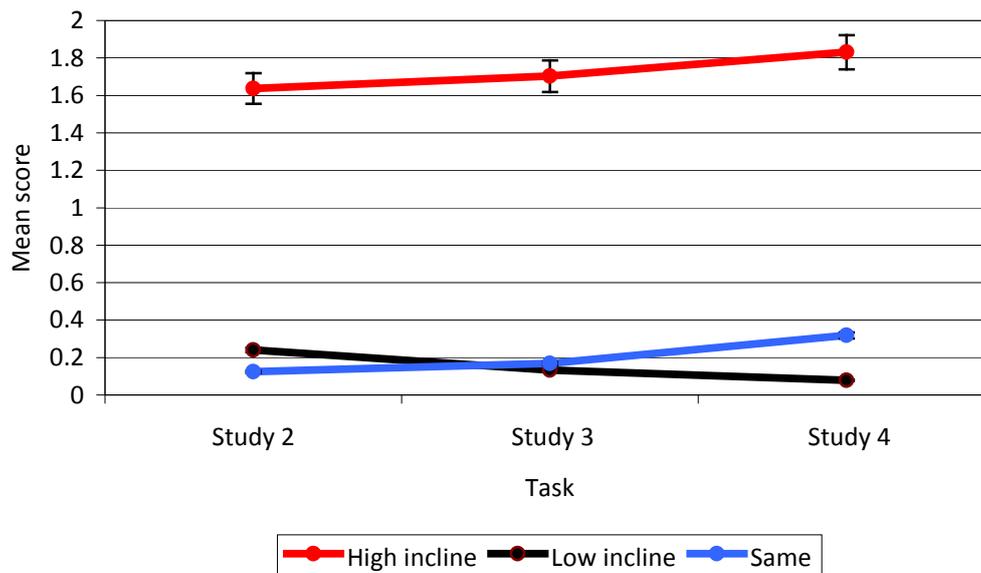
Figure 12.4   Mean performance scores for predictions and judgements in incline height comparisons by task type (Maximum score = 2)

There was no significant variation among mean performance scores across the studies for predicting the high incline ball to be faster (Studies 2 and 3) and judging trials to be correct when the high incline ball was faster (Study 4). There was also no significant variation among mean performance scores across the studies for predicting the low incline ball to be faster (Studies 2 and 3) and judging trials to be correct when the low incline ball was faster (Study 4).

However, there was significant variation among mean performance scores across the studies for predicting both balls to travel at the same speed (Studies 2 and 3) and judging trials to be correct when both balls travelled at the same speed (Study 4), $\chi^2(2, N = 121) = 27.89$, $p < .001$. There was no significant difference between performance in Study 2 and performance in Study 3. However, there was a significant increase in frequency of scores from Study 3 ($M = 0.17$, $SD = 0.47$) to Study 4 ($M = 0.32$, $SD = 0.50$), $T = 3$, $r = -.24$.

12.2 Relationship between variable use in Study 1 and performance in Study 4

12.2.1 Methods of analysis

Forward stepwise binary logistic regression analyses were carried out to see how children's likelihood of performing with an accuracy level above chance when judging trials in Study 4 could be predicted by the same children's use of variables in general predictions of faster motion in Study 1. Accuracy in Study 4 was determined from judging correct trials as being correct as well as from judging incorrect trials as being incorrect. Analyses were conducted both with general variable use (i.e. reliance on weight, size, shape, texture and other reasons) and with variable directions (i.e. reliance on heavy, light, big, small, round, uneven, smooth and rough). By using the stepwise procedure, whether variables or variable directions would make any significant contribution to a model and whether they were therefore considered in a model was automatically determined by the statistical program. Any chosen variables or variable directions not listed in the model were deemed not to contribute significantly to the model. All data were analysed using PASW (Predictive Analytics Software, formerly SPSS) Statistics version 18.

12.2.2 Motion along a horizontal

Above chance level accuracy of horizontal motion judgements in Study 4 was defined as obtaining a score of at least 4 out of 6 points, that is, identifying at least 4 out of 6 horizontal motion trials correctly. The only variable entered by PASW into the regression model was object shape. The strength of association was very poor, only describing 3.7% (Cox & Snell R^2) and 5.2% (Nagelkerke R^2) of the variance in response; this relationship was statistically significant ($\chi^2(1) = 5.10$, $p < .05$). No further variables were added. In the model, for every additional "shape" point the logit (p) decreases by 0.303 points, and the likelihood of not performing above chance level increases by 42.5%, that is, the increase in usage of "shape" in predictions (Study 1) decreases the chances that the level of judgements is above accuracy (Study 4). This means the more frequently "shape" was relied on in Study 1,

the lower the judgement accuracy was in Study 4. This relationship is statistically significant (Wald(1) = 4.83, p < .05). The logistic regression equation for this model is:

$$logit\ (p) = 1.542 - 0.303\ shape$$

The overall percent correctly predicted increases to 69.9% upon adding the variable, which implies that whether judgements are performed at above chance level or not can be differentiated on the basis of the use of the variable "shape" in Study 1.

When using variable directions rather than variables alone, the only variable direction entered by PASW into the regression model was object roundness. The strength of association was very poor, only describing 3.4% (Cox & Snell R^2) and 4.8% (Nagelkerke R^2) of the variance in response; this relationship was statistically significant (χ^2(1) = 4.73, p < .05). No further variables were added. In the model, for every additional "round" point, the logit (p) decreases by 0.290 points, and the likelihood of not performing above chance level increases by 42.8%, that is, the increase in usage of "round" in predictions (Study 1) decreases the chances that the level of judgements is above accuracy (Study 4). This means the more frequently "round" was relied on in Study 1, the lower the judgement accuracy was in Study 4. This relationship is statistically significant (Wald(1) = 4.50, p < .05). The logistic regression equation for this model is:

$$logit\ (p) = 1.507 - 0.290\ round$$

12.2.3 Motion down an incline

Above chance level accuracy of incline motion judgements in Study 4 was defined as obtaining a score of at least 4 out of 6 points, that is, identifying at least 4 out of 6 incline motion trials correctly. No variables were included in the model by PASW, thereby suggesting there is no significant relation between variable use in Study 1 and accuracy of judgements in Study 4. This was the case both for general variables and for variable directions.

12.2.4 Motion in free fall

Above chance level accuracy of fall motion judgements in Study 4 was defined as obtaining a score of at least 4 out of 6 points, that is, identifying at least 4 out of 6 fall motion trials correctly. No general variables were included in the model by PASW, therefore suggesting no significant relation between general variable use in Study 1 and accuracy of judgements in Study 4.

When using variable directions, the only variable entered by PASW into the regression model was object smallness. The strength of association was initially very poor, only describing 4.3% (Cox & Snell R^2) and 6.4% (Nagelkerke R^2) of the variance in response; this relationship was statistically significant ($\chi^2(1) = 6.01$, $p < .05$). No further variables were added. In the model, for every additional "small" point, the logit (p) decreases by 1.658 points, and the likelihood of not performing above chance level increases by 62.4%, that is, the increase in usage of "small" in predictions (Study 1) decreases the chances that the level of judgements is above accuracy (Study 4) performance is above accuracy. This means the more frequently "small" was relied on in Study 1, the lower the judgement accuracy was in Study 4. This relationship is statistically significant (Wald(1) = 5.94, $p < .05$). The logistic regression equation for the model is:

$$\text{logit (p)} = 1.253 - 1.658 \text{ small}$$

12.2.5 Incline height comparisons

Above chance level accuracy of incline comparison judgements in Study 4 was defined as obtaining a score of at least 7 out of 12 points, that is, identifying at least 7 out of 12 incline comparison trials correctly. No variables were included in the model by PASW, therefore suggesting no significant relation between variable use in Study 1 and accuracy of judgements in Study 4. Because of the very high degree of performance accuracy observed in Study 4 (only a very small number of children performed at or below chance level), a more rigid boundary was set at scoring at

least 11 out of 12 points. Still no variables were identified as contributing towards a significant relation between variable use in Study 1 and accuracy of judgements in Study 4.

However, when using prediction directions as variables rather than variables alone, the only variable entered by PASW into the regression model was object heaviness. The strength of association was initially very poor, only describing 4.1% (Cox & Snell R^2) and 5.8% (Nagelkerke R^2) of the variance in response; this relationship was statistically significant ($\chi^2(1) = 5.72$, $p < .05$). No further variables were added. In the model, for every additional "heavy" point, the logit (p) increases by 0.543 points, and the likelihood of performing above chance level increases by 35.2%, that is, the increase in usage of "heavy" in predictions (Study 1) increases the chances that the level of judgements is above accuracy (Study 4). This means the more frequently "heavy" was relied on in Study 1, the higher the judgement accuracy was in Study 4. This relationship is statistically significant (Wald(1) = 4.76, $p < .05$). The logistic regression equation for the model is:

$$\text{logit (p)} = 0.543 \text{ heavy} + 0.458$$

12.3 Discussion

The analyses presented in this chapter were carried out in order to provide detailed information about the development of children's performance across Studies 2, 3 and 4, and to evaluate the relationship between children's variable use in Study 1 and their judgement accuracy in Study 4.

12.3.1 Development of performance across Studies 2, 3 and 4

Across the three motion trials – horizontal motion, incline motion and free fall motion – performance changed to some degree across studies. Children's predictions in Study 2 and Study 3 generally showed no changes (with the exception of a slight increase in same speed predictions for horizontal motion trials and a slight

decrease in light-as-faster predictions for incline motion trials), thereby suggesting a general consistency in predictions. On the other hand, there was always a significant increase or decline between Study 3 and Study 4 – always in favour of higher accuracy, that is, a large increase in same speed judgements and a decrease in heavy-as-faster and light-as-faster. Given no substantial change between Study 2 and Study 3, the same changes in score frequencies can be noted between Study 2 and Study 4. Where incline height comparisons were concerned, there was consistency in predicting and judging the high incline ball to roll faster than the low incline ball across all three tasks (with the exception of a slight increase in same-speed judgements from same-speed predictions).

Overall, the findings from these analyses confirm the correlation analyses that were carried out in the respective study chapters. The scores from Studies 2 and 3 had been found to be highly positively correlated, and no substantial change was observed in these additional analyses. The scores from Studies 3 and 4, on the other hand, had been found to differ significantly, and the information provided here gives a clearer picture how these scores differ, while also allowing Study 2 to be more directly contrasted with Study 4. The additional analyses also provide further support for the notion of using computer-presented scenarios (Study 3) to assess predictions in the same manner as using real objects (Study 2).

12.3.2 Relationship between variable use in Study 1 and performance in Study 4

Study 1 had revealed that there are a number of variables children use in their reasoning of everyday object motion events, and that there is little consistency across age groups, even within age groups, in use of these variable. At the same time, a considerable number of children did not judge motion scenarios correctly in Study 4, and this raised the question whether this particular subset of children was possibly identifiable by their general variable use in Study 1.

Only few variables relied on in Study 1 – and never more than one per regression model – were considered to have any predictable effect on performance in Study 4.

The variables concerned as well as their relation to the judgement tasks are not particularly surprising. The more children relied on external attributes in Study 1, that is, shape or size, the less likely they were to perform above chance in Study 4 judgements where neither shape nor size differed between the two balls. It seems thus reasonable to suggest that children who rely heavily on external features of objects would find it more difficult to accurately judge motion if no differences in external properties are available to them. Similarly, the more children relied on weight in Study 1, the more likely they were to perform above chance level in Study 4 judgements where weight did differ between the two balls and did cause a difference in motion. Here, it seems reasonable to suggest that children who rely heavily on weight would find it easier to judge motion if the crucial difference affecting motion, as is the case for incline comparisons, is weight.

"Nature has contrived to have it both ways, to get the best out of fast dumb systems *and* slow contemplative ones, by simply refusing to choose between them." (Fodor, 1985, p. 4)

CHAPTER 13:

GENERAL DISCUSSION

The work of the ancient Greek philosopher Aristotle (trans. 2008) and the thinking of many people today reveal a striking similarity – both provide claims about motion in the physical world that are limited, incorrect, and therefore incompatible with science. Perhaps not everyone wants to be a scientist. But perhaps others do and are discouraged by the fact that they just cannot grasp basic physical concepts well enough, and that their prior conceptions are resistant to any change through educational processes. Perhaps, though, alternative approaches are available? This thesis sought to find an answer.

13.1 Aims of the present work

A wealth of research, which now adds up to over 8,000 studies (cf. Duit, 2009), has investigated the conceptions that students in the classroom hold across a range of disciplines – biology, chemistry, astronomy, medicine, and notably physics. The consensus is that children do not enter the classroom as tabula rasa, but instead that they possess rich prior conceptions about the physical world. But instead of finding

these prior conceptions helpful when learning about scientific concepts, students are thought to have to undergo conceptual change (Nersessian, 2003), because despite their richness their conceptions are often inaccurate and differ fundamentally from the scientific conceptions to be taught in the classroom. While the naïve conceptions that are formed in this way can be satisfactory in explaining and dealing with everyday motion problems (Hammer, 1996, 2000; Reif, 2008; Tao & Gunstone, 1999), the nature of these naïve conceptions poses a problem for learning science, as often they do not comply with accepted scientific notions and are typically resistant to change through instruction (Bloom & Weisberg, 2007; Chi & Roscoe, 2002; Duit & Treagust, 2003; Duit et al., 2008; Ferrari & Chi, 1998; Finegold & Gorsky, 1991; D. Kuhn, 1989).

Motion is a ubiquitous phenomenon in everyday life, and humans have much interchange with motion in the physical world. Consequently, these everyday experiences have a significant effect on conceptions about motion from an early age. Speed and acceleration are fundamental to motion. The literature on the understanding of speed and acceleration presented in the earlier chapters of this thesis has shown, too, that children often do not hold views consistent with the materials to be taught. However, this work is limited in that there is no integration of children's understanding about different motion paths. How do children understand motion paths in relation to each other; are horizontal motion and free fall motion related in any way? And how is motion down an incline perceived? One aim of the thesis was therefore to investigate primary school children's beliefs about object speed and acceleration by looking at the predictions they make about motion, and what factors affect their decision-making. In addition, the work attempted to integrate beliefs for three different motion paths – horizontal, vertical and incline – into a larger scheme of motion that is not just limited to individual paths.

A further aim of the work was to see if computers could be useful in the assessment of explicit knowledge. The use of ICT in schools has greatly increased over the last years, and the National Curriculum for England (Department for Education and Employment, 1999) emphasises the incorporation of ICT in the curriculum. The

general benefit of computer-based teaching has been recognised in a range of recent publications (e.g. Barton, 2004; Glover et al., 2005; Holliman & Scanlon, 2004; Murphy, 2003; L. R. Newton & Rogers, 2001; H. J. Smith et al., 2005). Regarding science education in particular, ICT brings with it the advantage of creating simulations, as these can generate abstract scenarios, dynamic events that could otherwise not be observed in the real world (Gould et al., 2006; Hennessy, 2006; Hennessy et al., 2007; Rogers, 2004; Steinberg, 2000). Several authors have highlighted the use of computers in the promotion of conceptual change (Andaloro et al., 1997; diSessa, 1982; Doerr, 1997; Hennessy et al., 1995a, b; Papert, 1980; Twigger et al., 1991), and it was hoped that these last two points could be combined – creating dynamic events that do not occur in the everyday world but that may match the beliefs children hold, and facilitating conceptual change.

The thesis' final objective was to investigate whether an alternative to the standard explicit belief assessment is available that could assess children's tacit understanding of object motion – an understanding that "consists of representations that merely reflect the properties of objects or events without predicating them of any particular entity" (Dienes & Perner, 1999, p. 752); an understanding that remains unarticulated yet can be demonstrated in use or action (Polanyi, 1967; Wagner & Sternberg, 1985). Much like the above-average ball players who cannot make sufficient predictions on paper about where, when and how to catch a ball (Reed et al., 2010) yet out in the playing field their catching behaviour suggests otherwise (Gigerenzer, 2004, 2007; McLeod & Dienes, 1996; McLeod et al., 2008), the present research was interested to find out whether young children display similar dissociations in their explicit predictions and their tacit understanding of object speed and acceleration.

In order to assist with the issue of how to determine tacit understanding, the judgement task approach was introduced in Chapter 3 (cf. Broaders et al., 2007). It was felt that in combination with computers as an assessment tool children's explicit conceptions could be explored as well as contrasted with children's judgements of related object motion events, in order to see if the former process differs from the latter. In the long run, a possible dissociation between explicit and tacit reasoning

could be utilised in early science education to promote change of common Aristotelian ideas, as introduced in Chapter 1, thereby overcoming the difficulties of the process of conceptual change noted in Chapter 2.

13.2 Summary of the results

13.2.1 Variables used in children's explicit reasoning

From Study 1 it was established that children's predictions about object motion are based on a range of variables. Overall, the results are in concordance with Galili's (2001) idea of weight being an important variable in reasoning about the physical world, but justifications varied among motion types. While weight was a principal variable in free fall motion, weight-based justifications were not used as often in the other two motion types; size and shape were mainly used in horizontal motion justifications, and texture in incline motion justifications. However, these results have to be considered carefully, as the objects used in each of the motion types were different, thereby making cross-motion-type comparisons a little difficult. Using the two test balls in Study 2 enabled control of several of the variables that emerged from children's reasoning about object motion in Study 1. Size and shape became obsolete, and differences in texture were sufficiently minimal that hardly any reference was made, and even when children did refer to texture, they always did this in combination with object weight. Instead, with the exception of those children who made same-speed predictions, the children's predictions were always made on the basis of the balls' weights.

13.2.1.1 Directions of variables in justifications

In Study 1 it was found that when shape and texture were used as a justification, faster speed was almost always associated with roundness and smoothness of objects, no matter which motion type was concerned. However, where object weight and size are concerned, a different picture emerged from the results. Given the substantial literature on the understanding of object motion in free fall (e.g.

Baker et al., 2009; Champagne et al., 1980, as cited in McDermott, 1984; Chinn & Malhotra, 2002; Nachtigall, 1982; Sequeira & Leite, 1991; van Hise, 1988), it was not particularly unexpected that children mainly associated faster fall with heavier objects across all ages. This said, children in the youngest age group also referred to size reasonably often, almost as frequently as to weight, and faster motion was associated with bigger objects. Faster horizontal motion, on the other hand, was associated with lighter and smaller objects, again fairly consistently across all ages; this, too, seems to be in concordance with previous work suggesting that in horizontal scenarios children under 12 years of age associate heavy objects with higher resistance to motion (Howe, 1991, as cited in Howe, 1998). There was less consistency across age groups for incline motion. While younger children predicted faster motion for lighter and smaller objects, there was a clear shift in conceptions, with older children predicting faster motion for heavier and bigger objects, again consistent with previous findings (e.g. Howe et al., 1992, as cited in Howe, 1998).

Studies 2 and 3 confirmed these findings, though reduced to weight alone, as size no longer varied. For incline motion, it seems that there was not a particular age point where children suddenly switched from associating faster incline motion with lightness to associating it with heaviness. Instead, it seems to be a gradual process, which suggests that even though the changes go from one incorrect view to another incorrect view, without affecting same-speed predictions at all, there is little resistance to change in conceptions within the total age range, at least where motion down an incline is concerned. This is a crucial observation and lends much support to the notion that conceptual change should be tackled in the early years. Given the extensive literature on children's prior conceptions and the mismatch between these and accepted scientific views, not only concerning children's understanding of motion, it may come as no particular surprise that here, too, children held views about object speed that were incompatible with science.

13.2.2 Interaction of motion types

It might seem fair to conclude that motion in the horizontal dimension and motion in the vertical dimension are not considered in the same way, at least as far as justification for directions of predictions are concerned. In fact, inverse pictures emerged for the two motion types – while all three explicit task studies showed that faster motion along a horizontal was generally associated with small and light objects, faster motion in free fall was associated with big and heavy objects, and both views were held consistently over age. So indeed, the two motion types do seem to be differentiated psychologically from each other at least to some degree, lending support to previous ideas (Hayes, 1979; Howe, 1998). However, what about motion down an incline? Is it perceived to be an integration of horizontal and vertical dimensions, or do children treat it as a third, independent, dimension that bears no significant relation to either horizontal or vertical paths? Study 1 could not offer any conclusive response to resolve this question because of the comparability of the object groups, or rather, lack thereof. However, Study 2 offered a clearer picture. It would appear that, at least in terms of the objects used, younger children associate motion down an incline more with motion along a horizontal than with motion in free fall, and that over age this association crosses over, such that as children get older they associate motion down an incline more with motion in free fall and less with motion along a horizontal. As with the directions of variables, even though the changes go from one incorrect view to another incorrect view, there is little resistance to change in conceptions and adds further support to the notion that conceptual change should be engaged with early on.

13.2.2.1 Incline comparisons

Much like the shift in understanding of support observed in Baillargeon's work with infants (Baillargeon & Hanko-Summers, 1990; Baillargeon et al., 1992; Needham & Baillargeon, 1993), young children, too, appear to undergo a shift in conception of incline motion in relation to the involvement of support. Younger children associated faster incline motion with lightness of objects and older children associated it with

heaviness of objects, yet all children seemed to understand that the degree of incline affects the interaction of horizontal and vertical dimensions and the resulting object motion changes. It would thus appear that children's notion of diagonal dimensions is informed by their understanding of both horizontal and vertical dimensions at all ages, but that younger children associate incline motion more with supported horizontal motion and that older children integrate elements of free fall more frequently into their conception of inclines, thereby reasoning similarly about those two dimensions.

It is suggested that the children's understanding of how incline changes from low to high (or vice versa) affect motion might contribute to understanding how the three motion types interact in terms of the children's reasoning about them. The children's predictions in Studies 2 and 3 proved to be consistent with accepted scientific views. However, as they did not give any justifications, it is difficult to conclude whether they knew that incline height increases result in faster speed or that incline height decreases result in slower speed, regardless of the object, because the force acting on the objects along the slope increases.[8] Alternatively, they may have responded without knowing the reasons per se but arrived at the correct conclusion simply because the changes affect all objects in the same way, as long as friction can be overcome.

13.2.3 Attribution of changes in speed

Studies 2 and 3 also investigated children's appreciation of changes in speed, which is deemed to be an important factor in understanding naturalness of motion. Both studies suggest that children appreciate that there must be a change in speed between a starting point and any subsequent point. This is rather similar to Piaget's

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[8] As laid out in the section on the physics behind object speed and acceleration, motion down an incline can be calculated using the formula $a = [(mg \sin\theta) - (\mu\, mg \cos\theta)] / m$. If object weight mg and friction coefficient μ do not change, but the angle θ of incline does, acceleration a changes accordingly, increasing as θ increases and decreasing as θ decreases, for any object, as long as friction is overcome.

(1970a) observation of children initially perceiving acceleration in incline motion as a short and intensive effort, or Nachtigall's (1982) similar findings about children's understanding of speed changes in free fall motion. In horizontal motion, children probably hold the beliefs in a similar way, only inversely: As soon as a ball rolls along a horizontal following a dimension change, that is, from incline motion to horizontal motion, it instantly slows down, therefore being slower at any point after leaving the tube. Results from previous work by Howe et al. (2010a) on children's understanding of horizontal motion suggest young children do not anticipate changes in speed along horizontals. The results provided by Studies 2 and 3 do not refute those findings, and are not necessarily incompatible with them. However, Howe et al. (2010a) did not incorporate any change in dimension. If no dimension change had been provided in Studies 2 and 3, that is, if children had not been told that the balls had been rolling down the incline first, then quite possibly horizontal speed change would not have been anticipated by the children.

Again, this point of dimension change affecting speed change suggests that incline motion is not exactly like horizontal motion, and that even for the youngest children there must be some appreciation of an integration of horizontal and vertical dimensions, despite supported motion perhaps being more salient to them. However, attributions were made far less frequently between two points where a change in speed might be less obvious because neither point is a starting or stopping point. This indicates that children's explicit understanding of speed change appears to be limited, and unlike Piaget (1970a), there appeared to be no developmental trend over age in attributions, despite using the same age range – children in all age groups seemed just as likely to make attributions beyond the starting point. Of course, Piaget's work was not directly replicated here, so it is difficult to draw any clear parallels to it.

Interestingly, the weight of the ball also had an effect on speed change attributions. The heavier ball was more likely than the lighter ball to be associated with a change in speed as it moved, regardless of motion dimension. This certainly stands in conflict particularly with the observed understanding of horizontal motion, where heaviness

was seemingly seen as a hindrance to faster motion. It is unclear why this would be so. However, Aristotelian physics (cf. Aristotle, trans. 2008) notes that heavier objects have more internal impetus and are therefore more able to cut through resistance caused by air. Although Aristotle only referred to speed and not to speed change, it seems plausible that children may associate heaviness with a prolonged ability to overcome resistance, thus being more able to accelerate (albeit temporarily) than lighter objects.

13.2.3.1 Speed change and realignment of the incline dimension

As mentioned already, there is a shift from younger children associating motion down inclines more with horizontal motion to older children associating motion down inclines more with motion in free fall. The increasing awareness of speed change with age may help to further understand why this realignment occurs. On the one hand, there is a clear increase with age in associating the heavy ball with faster motion down inclines, that is, the alignment shifts from the horizontal to the vertical dimension. At the same time, awareness of speed change increases. Younger children show little awareness of speed change at all, and their predictions suggest they associate incline motion more with horizontal motion. Yet as the awareness of speed change improves, the incline dimension is realigned. It would appear, thus, that younger children who do not have an understanding of speed change view incline motion in terms of it being supported, like horizontal motion, thus aligning the two, and as children gain awareness of speed change and gain awareness that acceleration (rather than deceleration) occurs down inclines like it does in free fall, they shift their alignment. Certainly, a more in-depth examination of the development of speed change awareness and the realignment effect would be worthwhile.

13.2.4 Effectiveness of using computers

Given the rapidly increasing use of ICT in schools and the recognition of benefits that come from computer-assisted teaching and learning, it was hoped that the current

research could also provide valuable information towards designing conceptual change programmes in early science education that would incorporate computers. The results all show high positive correlations between children's explicit predictions made in Study 2 and the same children's statement choices made in Study 3. Even when all options are presented to children in form of different 'hypotheses' rather than questions, including the correct one, children will still make choices consistent with their predictions. This finding lends much support to the suggestion of possibly using computers as a tool in conceptual change programmes, as they appear to result in the same observations of children's explicit beliefs as real-object tasks. As in Study 2, almost all of speed task responses in Study 3 were in favour of differences in motion between the two balls, regardless of direction of the responses. Concerning attribution of changes in speed and changes in incline height, the pattern was similar to that observed in Study 2 as well. Overall, the findings are confirmatory of the early-age conceptual change approach, whilst being able to incorporate ICT as well.

13.2.5 Explicit reasoning versus tacit judgement

As opposed to Studies 2 and 3, where practically all predictions made when two balls had to be compared were different-speed predictions, Study 4 showed that the children judged same-speed trials to be correct more often than they accepted different-speed trials. From the explicit studies it was unclear what the children actually meant when they predicted that one object would be faster than the other (how much faster?), so quite possibly the same-speed scenarios simply seemed more similar to their explicit beliefs than the different-speed scenarios. However, then they could have selected the same-speed trials as incorrect as well, which was rarely done. Thus it is suggested that, overall, young children are indeed able to recognise naturalness of motion and appreciate that it is correct; these findings are consistent with those of previous motion research (Kaiser & Proffitt, 1984; Kaiser et al., 1992; Kannass et al., 1999; Kim & Spelke, 1992; Shanon, 1976). The differences between explicit predictions and tacit judgements observed here are also in concordance with related recent findings on conscious versus unconscious judgement knowledge, and in turn the results receive support from findings that distinguish guessing from

intuition (Dienes, 2008; Dienes & Scott, 2005; Fu et al., 2010a, b; Scott & Dienes, 2010).

It was additionally observed, though, that there were several occasions where different-speed trials were judged as being correct, and the ones chosen to be correct corresponded to the pattern found in the children's explicit predictions in Studies 2 and 3; in these cases, horizontal motion was judged as correct when the light ball was faster, free fall motion was judged as correct when the heavy ball was faster, and incline motion judgements varied with age, shifting from associating the light ball with faster motion to associating the heavy ball with faster motion. The conclusion from this was that the responses were separable into two groups – children's tacit judgements were often accurate, but when their judgements were not, they reflected the explicit beliefs that emerged in Studies 2 and 3.

It is suggested that this was a result of prolonged observations of trials, which in turn resulted in reasoning based on explicit beliefs rather than spontaneous judgements based on tacit understanding. The response time data gathered in Study 4 support the idea of two distinct reasoning approaches. Whenever the children spent *less* time to reach a decision about the correctness of a trial they were *more* likely to make correct decisions. But when the children seemingly engaged with the trials for longer, they would choose those dynamic events as correct that reflected their explicit beliefs expressed in the previous studies. It seems, therefore, that fast responding (Kurzban, 2008), a quick 'gut feeling' response (Gigerenzer, 2007), provides a higher likelihood of being accurate about dynamic events, and that expressly thinking about the events results in referring to explicit knowledge that is different from underlying tacit knowledge.

13.3 Model-based reasoning – one model but two pathways?

The importance of modelling in understanding scientific phenomena has been recognised for some time (e.g. Confrey & Doerr, 1994; Frederiksen & White, 1998; Lehrer & Schauble, 2000, 2003). Mental models are conceptual systems consisting of

elements, relations, operations and rules (Lesh & Doerr, 2003) and act as prototypes of particular kinds of conceptual models, which can then enable a person to simulate similar behaviour with new objects (Nersessian, 1992, 2002a, 2003). When solving a problem, learners construct a mental model of the problem and use that model as the basis for prediction and inference (Jonassen, 2003, 2004; Morgan, 1999). Mental models and model-based reasoning can provide important information about the underlying knowledge structures from which they are generated. This highlights the relevance for mental modelling in the process of establishing conceptual limitations in children's explicit thinking about the physical world. But how can mental models be integrated into the current work, particularly in relation to children's tacit judgements?

The findings from the current work offer support for two distinct forms of knowledge that may nonetheless be connected somehow. Vosniadou (2002a) suggests that mental models can help to draw on implicit physical knowledge, which can be then used to solve problems, and that by doing so the implicit knowledge becomes explicit. However, this does not seem to be quite consistent with the results described here. If in the current work this implicit model were relied on in explicit reasoning, then the model would obviously be faulty to some degree – and yet the tacit task suggests that there is some ability to reach appropriate conclusions about the naturalness of object motion. Though perhaps the idea should not be dismissed per se, but instead it may require some form of modification. An extension of Vosniadou's (2002a) idea is depicted in Figure 13.1 (p. 283) and is outlined next.
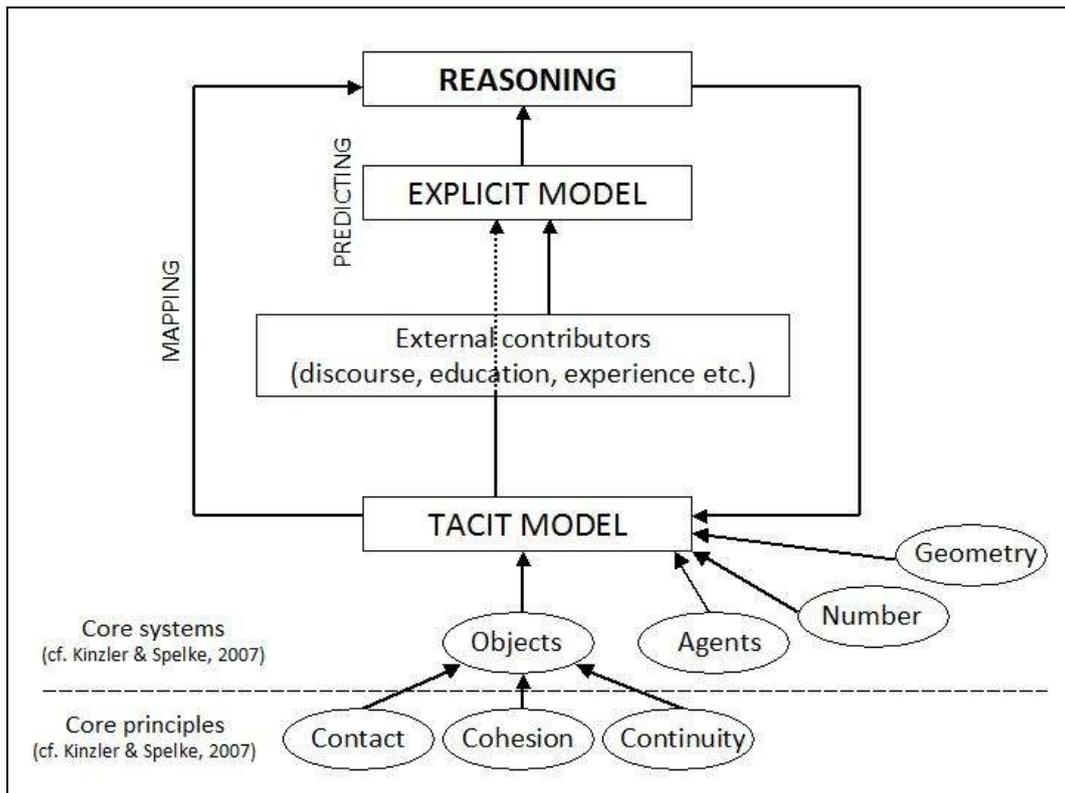
Figure 13.1   A dual-pathway model of reasoning

The extension works in the following way. Given the notion of the possible innateness of basic principles according to Spelke and colleagues (Kinzler & Spelke, 2007; Spelke, 1991, 1994, 2000, 2004; Spelke et al., 1992; Spelke & Kinzler, 2007; Spelke, Phillips, & Woodward, 1995) and of basic concepts according to Carey and colleagues (Carey, 1992, 2000b, 2004, 2009; Carey & Sarnecka, 2006), there is a set of core cognition elements that are loosely connected in appropriate combinations to form domain-specific prototypical models – much like D. E. Brown and Hammer's (2008) notion of conceptual change models described in Chapter 2. When infants display an understanding of events in violation of expectation tasks, they map what they see onto the tacit model they hold and base decisions of possibility versus impossibility of events on the goodness-of-fit between external observation and internal model. As they grow older, additional external contributors such as language, sociocultural factors, or experience with particular instances come into play. When reasoning by making explicit predictions, elements of the tacit model are elevated and 'filtered' through these contributors, resulting in a new explicit model

that still incorporates the tacit elements but nonetheless differs substantially from the tacit model.

Tacit models are not replaced by explicit models, they still remain and are used in performing tasks such as catching balls, but in predictive reasoning the explicit models have to be used. Furthermore, a range of tasks with very young children (Ahmed & Ruffman, 1998; Berthier et al., 2001; Clements & Perner, 1994; Garnham & Ruffman, 2001; Hofstadter & Reznick, 1996; Hood et al., 2003; Low, 2010; Mash et al., 2003; Ruffman et al., 2001) suggest that while these children's explicit knowledge, expressed through reaching behaviour or verbal responses, is often not correct, their looking behaviour indicates that there must be some underlying representation of the correct responses. According to Goldin-Meadow and Alibali (1999), this underlying knowledge is implicit in its nature. It is therefore certainly plausible to assume that tacit knowledge continues to exist beyond infancy but that the acquisition of language in early childhood interferes with the children's tacit beliefs.

Support for the notion that the explicit representations are based on underlying tacit models appears elsewhere in the research literature. For instance, explicit mathematical computations are made possible through a number of automatic processes that are inaccessible to consciousness, that is, through underlying tacit structures. This includes the automatic activation of core processes and approximate representations of numerical magnitudes (cf. Stanescu-Cosson et al., 2000). At the same time, when core processes are damaged in some way or another, mental arithmetic becomes very difficult and suffers (Lemer, Dehaene, Spelke, & Cohen, 2003). This clearly illustrates how explicit and tacit processes are linked, and that explicit processes cannot operate on their own, lending strong support to the idea of a combined structure of thinking and understanding.

And reasoning on the basis of such explicit models is how prior conceptions emerge by the time children enter school, if not sooner, that are inconsistent with the actual concepts to be taught. The suggestion made here also allows for two somewhat

different notions from the literature to be under the same roof. While one view holds that mental models are dictated by a person's general background knowledge about the world (e.g. Miščević, 1992), an alternative view is that thought experiments draw on imagined transformations that depend on innate knowledge of three-dimensional space (e.g. Shephard, 2008). It is argued here that the models that are retrieved during explicit reasoning might essentially be the result of an interaction of (possibly innate) core principles and external contributors.

13.3.1 The role of language in the dual pathway model

The results from Study 4 appear to suggest that the underlying tacit knowledge displayed in children's judgements of dynamic events remains unchanged across the age groups assessed. So it would appear that tacit models establish themselves at least by about the age of 5 years and remain consistent throughout childhood. Given the lack of additional age groups in the present research, it is difficult to make any suggestion as to when exactly these tacit models are established and whether they do indeed remain consistent into adulthood. However, related work with adults (e.g. Kaiser & Proffitt, 1984) indicates only limited improvement in accuracy of judgements between middle childhood and adulthood, thus suggesting that tacit knowledge probably does remain stable beyond early childhood. And yet the results from the first three studies collectively suggest that explicit conceptions differ from tacit conceptions and change with age. Knowledge that is represented by explicit symbols differs from core cognition (Carey, 2009). Most knowledge is not considered to be innate and does not remain constant throughout the course of development, because relations among explicit symbols can be revised. It is clear, then, that language must play an important part in this differentiation. And as was noted in Chapter 3, language unquestionably plays a role in the development of conceptual knowledge and in the elevation of underlying tacit knowledge to the explicit level (Carey, 2009).

The dual pathway idea depicted in Figure 13.1 (p. 283) does take into account that there is, essentially, just one model, the model that Vosniadou (2002a) is referring

to, but because of the re-routing in explicit reasoning this model is altered unintentionally, that is, something is lost in the process of translation from tacit to explicit, caused by the interference from external factors. Vosniadou and colleagues (Stathopoulou & Vosniadou, 2007; Vosniadou, 1994a, 2003, 2007c) do suggest that the situative or sociocultural contexts play an important role in the construction of beliefs and conceptual change, and "of course human beings also have language – the main medium for the cultural transmission of acquired learning" (Carey, 2004, p. 59). There is no reason to assume that it would be any different in the current proposition; once language can be used in the construction of beliefs, explicit models are created and altered through beliefs of others, that is, parents, teachers and peers, via discourse – but the corresponding tacit models would remain untouched by this. So indeed it would appear that Fodor (1985) made an appropriate statement about two systems. While mapping would be a fast and straightforward process, predicting would take longer because of the re-routing and the resulting integration of external contributors. Other previous work, too, supports the idea of language being the decisive element in the elevation of tacit knowledge to the explicit level.

Despite language acquisition possibly having its origins in core cognitive systems (cf. Chomsky, 1965; Gleitman et al., 2005; Pinker, 1984, 1989; Spelke & Newport, 1998), it would appear that language learning itself does not affect core or tacit knowledge but builds upon it without modifying it. This, too, is in line with the observation that judgements seemingly based on underlying tacit knowledge structures remain constant throughout the tested age ranges. It seems likely that language continues to develop in its sophistication, and certainly there are concepts whose semantics are only appreciated at later ages. Semantics are necessary in order to give meaning to concepts so that they can be made explicit. These semantics are acquired through associations between spoken words, by parents, teachers or peers, and the objects or events concerned (Ganea et al., 2005; Harris, 2002).

It was also noted in Chapter 3 that children construct semantic systems, and not merely lists of independent words, because of the relations between words (Kuczaj & Hill, 2003), that words at the far ends of a semantic dimension are learned before

words that are in between (Kuczaj, 1975, 1982), and that for young children words at the far ends of the dimension are more salient (Kuczaj, 1999). When children made predictions based on object properties in Studies 1, 2 and 3, such as weight or size, they did so by using a term from one end of the relevant semantic dimension, and presumably having an idea of where the other object in a pair would be placed within that semantic dimension. But it has also been noted that in order to appreciate the semantics of an object or an event and to incorporate the semantics into one's language system a workable concept of that object or event must already be in existence (Spelke, 2003). This may explain why judgements of conceptual events can be made with reasonable accuracy. So it is clear that even if semantics play a role in conceptual knowledge, it does not appear to interfere with underlying knowledge structures as such, but merely in the process of elevating that underlying knowledge to the explicit level.

There is no certainty about the existence of core cognition, and even if it does exist, then most knowledge is not directly encapsulated in it. On the contrary: "There are no innate perceptual analysers, nor innate learning mechanisms, that pick out the electrons, the tables, the stars, or the wombats in our environment" (Rosenberg & Carey, 2009, p. 184). Semantics do not interfere with core knowledge. Instead, they enable the embellishment of its repertoire by establishing newly combined conceptual systems (Spelke, 2003). Language learning – particularly semantics – is supported by core cognition rather than being the cause of it. But the role of language in the development of conceptual understanding beyond what is available in the core cognitive system remains important, as does its relevance in making underlying knowledge accessible and shareable. Even if children have every kind of knowledge represented in their core cognitive system, they still need to acquire appropriate language skills to make that knowledge explicit.

13.3.2 The possible impact of science education on model formation

An important aspect that might very likely contribute to explicit model formation is the influence of education. When looking at the National Curriculum for England's

(Department for Education and Employment, 1999) specifications for primary school science teaching, it becomes clear that children are already expected to be taught several relevant aspects of the work covered in the four studies here. Not only are the scientific skills they are taught relevant but also the specific content they encounter in class. While the former is not seen as particularly disconcerting, as if anything, those skills have probably facilitated task performance for the children, the latter may have largely helped to establish explicit models of motion. In Key Stage 1 (ages five to seven years), children learn about speed change, in Key Stage 2 (ages seven to 11 years) they learn about gravity, friction and air resistance. How this teaching content has an impact on the results here is difficult to estimate, but it seems reasonable to suggest that learning about these elements leads to integrating them into a generic explicit model of motion, and clearly this is not working well, as their explicit beliefs are limited. By incorporating children's tacit understanding of motion into the curriculum, support might be provided when learning about these concepts.

This might certainly suggest that incline motion and speed change might be affected by curriculum contents and educational practice. At the same time, though, it is very worthwhile to note that the prior work by Howe et al. (1992, as cited in Howe, 1998), which revealed a similar crossover in children's reasoning about motion down inclines as found in the present work, was carried out in Scotland, where the National Curriculum does not apply. Moreover, data for that study was collected at a time when science did not constitute a part of primary education within Scotland (C. Howe, personal communication, May 4, 2010). So while some impact of science education on model formation *may* be present, it is difficult to establish whether it does or not, but on the basis of other research it seems somewhat unlikely to be the case.

13.4 The role of executive function and inhibition of responses

As aforementioned, several studies have noted that toddlers often fail tasks by searching at incorrect locations or giving incorrect verbal responses, yet their looking

behaviour suggests they do know the correct location (Ahmed & Ruffman, 1998; Berthier et al., 2001; Clements & Perner, 1994; Garnham & Ruffman, 2001; Hofstadter & Reznick, 1996; Hood et al., 2003; Low, 2010; Mash et al., 2003; Ruffman et al., 2001). It would appear that the under-developed nature of executive control in this age range interferes with underlying knowledge structures, although these limitations can eventually be overcome. What role might developing facility with executive function play in the current theoretical model?

Firstly, a developmental trend can be noted. Young infants – at the time that their visual system is fully developed – do not possess appropriate motor or language abilities to perform particular tasks. But tasks such as those following the violation-of-expectation paradigm are able to rely purely on their visual responses and suggest underlying knowledge. Infants who have then developed sufficient motor abilities can be assessed on their conceptual understanding in simple reaching tasks such as the A not B search task. However, younger infants within this group tend to fail these tasks first, and cannot search correctly until they have sufficiently mastered executive control over their actions and are able to overcome inhibitions. Yet up to the point when they are able to solve these tasks correctly, some task variations (e.g. Ahmed & Ruffman, 1998) have revealed that infants may reach for the wrong location but look at the correct location, thus indicating that whilst they have not been able to overcome inhibition of motoric responses, their underlying knowledge is still accessible through visual responses.

During toddlerhood, an increase in search task sophistication level, that is, having more than two possible search locations (e.g. Baker et al., in press; Berthier, DeBlois, Poirier, Novak, & Clifton, 2000; Haddad, Kloos, & Keen, 2008; Hood et al., 2000, 2003, 2006; Keen et al., 2008), young children again first fail to solve tasks accurately by reaching for the wrong location when asked to retrieve an object, yet they will visually search at the right location. Similarly, while language develops rapidly at this age, toddlers fail verbal tasks but their visual response suggests an underlying knowledge of the correct response (Low, 2010). Eventually, young children are able to master these more sophisticated reaching tasks and verbal tasks. When reaching

the age group assessed in this thesis, it would appear that explicit functioning is not yet appropriately developed, whatever the cause of this may be – and it would appear that language most probably plays a large role in this. However, when relying on visual responses (and some minor motor "search" responses through pressing one of two buttons) it seems possible to show that these children do appear to understand the concept correctly.

It has been suggested in the neuropsychological literature that the development of the prefrontal cortex plays a role in executive function and inhibition response development (cf. Baird et al, 2002; Diamond, 1988, 1991, 2006; M. H. Johnson, 2005; Wood & Grafman, 2003). One theory of its involvement is that when skills are mastered in the prefrontal cortex, that skill is outsourced to other specialist areas of the cortex, and the prefrontal cortex then deals with new skills (Csibra et al., 1998; M. H. Johnson et al., 1998; Mareschal et al., 2004; Thatcher, 1992). Are perhaps visual and motoric response abilities outsourced, but for some reason responses in relation to language are not? Certainly, the prefrontal cortex continues to develop well into adolescence; while recognition memory is stable by the age of 8 years, performance requiring advanced planning and working memory does not appear to reach levels of sufficient competency before the age of 12 (Fabiani & Wee, 2001; Luciana, 2003), which is also the oldest age group tested in the current research. In line with this, several studies (e.g. Davidson, Amso, Anderson, & Diamond, 2006; Zelazo, Craik, & Booth, 2004; Zelazo, Müller, Frye, & Marcovitch, 2003) also indicate that executive function continues to develop throughout childhood and into adulthood, and is seen as a growth in conscious control (Zelazo, 2004) – a growth in *explicit* representation of knowledge?

How does the ability to predict motion develop? Again, a developmental trend can be established. According to Leslie, Xu, Tremoulet and Scholl (1998), young infants are eventually able to continue tracking a moving object once it becomes occluded. They propose that this is done through deployment of an attentional index, which guides the infants to the object's likely location. Yet because the object is invisible, the attentional index is only an approximation, and similar conclusions have been

drawn from search tasks with toddlers – if the object is visible for part of its trajectory, children are more able to search successfully (e.g. Butler, Berthier, & Clifton, 2002). What the present prediction tasks demand from the child is essentially the same; they are not able to see any trajectory but need to have an approximate understanding of this trajectory in order to make their predictions. They do not seem to be successful at deploying their index accurately, though. As language development has been suggested to play a crucial role in the retrieval ability of underlying concepts (to which such an attentional index must belong if prelinguistic infants hold it), it would seem that language interferes too strongly with the retrieval process of the underlying index information. Yet when the trajectory is fully visible, as in the judgement tasks, they are more likely to match that trajectory of motion with their anticipated attentional indices – in a process where language does not play any role.

On the basis of these aspects – development of task and skill sophistication levels and the role of the prefrontal cortex – it is thus proposed that similar to Karmiloff-Smith's (1992) notion of redescription, where mastery at a skill level needs to be achieved before a new level can be attained, it appears that as sophistication requirements increase, from simple visual responses to simple motoric choices to more complex motoric choices to use of language, children have to learn mastery of a new skill before they can appropriately solve tasks. If their new skill is not fully mastered, underlying knowledge can still be reflected in equally appropriate skills that have previously already been mastered. However, unlike Karmiloff-Smith (1992) it is proposed that it is not a case of redescription per se but a case of 'layering' based on core knowledge system accessibility; adding skills to an existing repertoire of knowledge without compromising prior skills. It is suggested that while all skills are technically accessible in a particular task (depending on age), they are only consciously accessible in relation to task relevance – verbal tasks require language, search tasks require motoric skills, and non-search tasks can rely on visual representation only. When solving tasks, only the most relevant skill is drawn upon. Underlying tacit knowledge, on the other hand, can still be represented through any of these skills, as long as they have been mastered sufficiently. Quite possibly,

language processing in the kind of explicit tasks presented in this thesis is too complex to overcome and therefore responses cannot be inhibited appropriately. Incorporating eye-tracking methods into the explicit tasks might reveal that children look at the response their underlying knowledge tells them is right, but they are simply making incorrect choices because they cannot sufficiently inhibit the linguistic processing.

13.5 Limitations of the present work

Despite the findings that have been presented so far, the work has limitations, and these are discussed here. Perhaps the main limitation is that the work has not taken into account the impact of language or of outside school factors, such as parent education levels. Although these should not have an effect on the tacit models if these are based on innate conceptual knowledge or very early experiences alone (cf. Baillargeon & Hanko-Summers, 1990; Baillargeon et al., 1992; Needham & Baillargeon, 1993), they most probably do play a crucial role in explicit reasoning. One might be tempted to suggest, for instance, that if parents have a higher education degree in, say, physics, they might be more likely to convey correct information to their children. Particularly if the model suggested above places an emphasis on the impact that external contributors have on the development and retrieval of explicit models, it is important to be aware of how strong the impact of these contributors is, and to what extent they dilute the tacit models during predictive reasoning. As aforementioned, these external contributors presumably do indeed have an effect, and this notion finds support in the literature (cf. Stathopoulou & Vosniadou, 2007; Vosniadou, 1994a, 2003, 2007c). However, the current work does not touch on this aspect.

A further aspect that is not considered in the present work is generic theories of motion. None of the tasks in the present work looked at children's generic theories, or whether they even have any. For instance, do children believe that, as a matter of principle, heavier objects always fall faster than lighter ones, or does this depend on the specific objects that are used? Study 1 did touch upon the fact that there are

several variables that children rely on in their justifications, and often even consider multiple variables – occasionally, children predicted same speeds because one was heavier, although at the same time the other was bigger, and both variables seemed to have the same effect on the objects. Despite this providing a basic idea that if they do have generic naïve theories of motion they would not be limited to weight, the work does not provide enough in-depth information to draw conclusions on this matter.

An additional limitation of the current research is that the studies do not take into account any *qualitative* developmental trends of understanding of object speed and acceleration, neither individually nor collectively. Despite similar results across the ages where motion along a horizontal and motion in free fall are considered, is a five-year-old child's belief about faster motion the same as it is for an 11-year-old? They clearly are not the same where motion down an incline is concerned, as their predictions about faster motion change with age. Previous work on children's understanding of object speed and acceleration where a range of ages was considered (Howe, Tolmie, & Rodgers, 1992; Inhelder & Piaget, 1958; Piaget, 1970a) has concluded that children's understanding changes qualitatively with age; it becomes more sophisticated over time as children pass from one stage of development to another. On the other hand, it is worth noting here that none of these studies looked at motion in free fall. So it may well be that older children have a more sophisticated understanding about motion – as children get older, they may have a better understanding of what factors affect motion, such as gravity, friction, or drag, and use them in their reasoning process, but without arriving at any different solution in the present context.

One methodological drawback of the current work has possibly been the use of computer screen and keyboard rather than working with an integrated system, that is, using a touch screen monitor. Unfortunately the computer program used was not compatible with the screen used, hence the need to resort to an external keyboard. Despite having made the keyboard as simple as possible by masking it off and matching responses and keys by colour, the response process involved an additional

step by matching responses with keys. By designing a computer program compatible with touch screens or interactive whiteboards, this additional step could be avoided and possibly lead to more accurate results, particularly in the tacit reasoning task. In addition, by making the studies compatible with touch screens or interactive whiteboards the work could become more useful in the designing of conceptual change programmes for the classroom.

Another methodological issue to consider is the role of the tube in horizontal scenarios. The horizontal motion trials in Study 3 and Study 4 included a small section of the incline being visible. The initial argument for horizontal motion trials in Studies 2 to 4 was that somehow horizontal motion needed to be induced without any subjective influence such as pushing – if one object is pushed harder than the other, it might expectedly go faster because of the greater push. So the children were instructed that the balls would have been (in the case of predictions) or had been (in the case of judgements) released down the tube at an incline in such a way that both balls reached the end of the tube at the same time, thereby offering no indication as to whether the two balls had been released at the same time or not. However, it is difficult to know how exactly this may have affected their predictions and judgements of horizontal motion. Following the instructions, the children might not necessarily have expected the two balls to have travelled the same distance; they might have felt the balls could have been released simultaneously at different points in the tube, or that one tube was, in fact, shorter than the other. But given their familiarity with the apparatus by then, given the availability of the physical tube during all relevant studies, and given that no additional apparatus was introduced at any point, this does not seem very likely to be the case. Certainly in Study 2, where children needed to give verbal justifications for their choices, no child made any indication that the balls might behave differently from each other because of issues relating to the apparatus. It seems reasonable to suggest that the Study 3 trials *could* have been arranged such that they showed the incline and the horizontal in the same picture. This, however, brings with it the issue of scaling. Firstly, the individual pictures would have been much smaller, and secondly, the relation of size to the other trials, notably the fall trials, would in itself possibly had had an effect on

predictions. As far as Study 4 is concerned, if the entire set-up had been shown, that is, the tube at an incline and the horizontal, then – leaving aside the aspect of size – the children would have seen the two balls rolling down the incline and they may have made their judgements purely on how the balls compared along the incline. And if for a child the incline motion does not look right to begin with, then why would the horizontal motion considered to possibly be right? Similarly, if the incline motion does look right then children may again assume that the horizontal motion will be right and base judgements on the incline motion alone. Nonetheless it was felt that showing the exit of the tube was necessary in order to reassure the children how the horizontal motion had come about to begin with. In light of the issues mentioned here, it seems that the risk of bias is so small that the advantages of using the approach outweigh alternative approaches, which could themselves bring problems with them. But of course it is difficult to say with any certainty that the current approach might not have created any participant bias, as unlikely as it would seem to be, and it is worth keeping this point in consideration.

A further apparatus issue to consider is the fact that for the fall conditions in Studies 2, 3 and 4 the balls fell (or were predicted to fall) inside a tube. It could be argued that the tube may have been a contributing factor in predictions and judgements. However, the tube was used to enable a more direct comparison between fall and incline motion by using the exact same distance for both task types, and to provide indicators of distance for the speed change tasks. From a physical perspective, the incorporation of the tube in the fall tasks should not have made a difference per se, as both balls would have been affected in the same way due to their similarity in shape and size. From a physical point of view the buoyancy effect should be greater within a tube; the buoyancy effect is determined by the volume of the objects (i.e. shape and size) and the density of the medium (i.e. air). Yet both balls had the same volume and the tube was the same for both objects in the same atmospheric conditions. If they were indeed slightly slowed down in their fall, because of increased pressure within the tube, then the two balls would have both been slowed down similarly. It was also the same tube for both balls, therefore the same dimensional effects occurred, that is, the same tube diameter for same-sized and

same-shaped objects. In addition, the tube itself did not restrict any motion, as at 6.5 cm it was much wider in diameter than the two balls at 4 cm. Even though the free fall condition is not strictly free fall because of the tube, it does not seem conceivable that this would have had any effect on predictions or judgements throughout the studies.

A final issue that arose early on was that of the lack of cross-study counterbalancing. The reason for not counterbalancing was because of the prolonged designing of the two computer studies. At the same time, however, it was felt that counterbalancing the studies would not have made a difference, as the children were not provided with any feedback on their predictions. They were neither told whether they were correct or not, and they did not see any motion occurring which would have enabled them to verify their predictions. Similarly, having the judgements task first would not have caused any differences in explicit predictions, because again, the children did not receive feedback on their judgements and thus would not have had any indication as to whether their judgements were correct or incorrect. The data collected subsequently to assess whether there was any order effect in task presentation (see Chapter 7 and the appendix, pp. 350-353) supports this by showing no indication of predictive performance in Study 3 affecting judgement performance in Study 4 or vice versa. The only possible effect that may have been achieved in not counterbalancing across all studies – though this is merely speculation at this point – is that children might have relied more intensively on object weight in the Study 1 task if they had performed on the other tasks first, where weight was the crucial difference between the two balls. In light of this possible outcome, however, it would appear more beneficial to have had Study 1 prior to any of the other studies for precisely that reason, as the wealth of justifications observed in Study 1 may otherwise not have been noted.

13.6 Suggestions for future work

13.6.1 Furthering of the explicit-tacit distinction

The results emerging from the present work offer additional questions to be explored in order to improve understanding of how explicit reasoning and tacit judgement are related to each other. For example, do explicit prediction tasks impose additional demands, or even entirely qualitatively different demands on brain activity than tacit judgement tasks? Scheuerecker et al. (2007), for instance, found a distinction at the neurological level between explicit and implicit processes in the evaluation of emotional facial expressions – while functional magnetic resonance imaging scans showed that both processes activated similar neural substrates the explicit task engaged additional networks as compared to the implicit task. Another recent study, by Chiu et al. (2006), investigated brain responses of explicit and implicit memory by measuring event-related potentials. Their work suggests that the two memory types can be differentiated on the basis of brain activation. So on the basis of these two studies one might indeed expect to find neurological differences between explicit and tacit reasoning processes within the current framework, too.

This in turn opens additional aspects worth investigating in order to further the understanding of the distinction between explicit reasoning and tacit judgement. If the underlying tacit knowledge about objects and motion can be assumed to remain unchanged throughout the lifespan (cf. Carey, 2009; Keysers et al., 2008; Santos & Hood, 2009; Spelke, 2000), then *true* tacit reasoning ought to activate the same brain regions at any given age, whether in early infancy or in adulthood. If, at the same time, reasoning on the basis of explicit knowledge is the result of language, education and any other factors interfering with the information retrieval process as described above, then one might expect to find differences in brain activity across development, possibly with an increase in the areas involved or in intensity of activity of the same areas as acquisition of language and knowledge transmission increase. Granted, entirely eliminating all factors that could potentially contribute to

making tacit knowledge explicit would probably be rather difficult, so any assessment of what here is called *true* tacit reasoning would presumably pose a formidable challenge.

Another research technique that might provide useful information with regard to tacit judgements in particular involves eye pupil dilation measures when watching events. For example, young infants have shown heightened pupil dilations when watching impossible scenarios rather than possible scenarios during a violation of expectation experiment (Jackson & Sirois, 2009). Applying this technique to the present context, would young children (or adults, for that matter), too, show heightened pupil dilations when seeing incorrect trials during tacit reasoning? Would they perhaps show heightened dilations even if they judged incorrect trials as correct, thereby registering the naturalness of the event but being in conflict with their explicit representation that they may have accessed by that point? This is a similar notion to that of the dissociation observed between search errors or incorrect verbal problem solving and a display of underlying knowledge about correct locations expressed by looking behaviour in late infancy and early childhood (e.g. Ahmed & Ruffman, 1998; Clements & Perner, 1994; Garnham & Ruffman, 2001; Hofstadter & Reznick, 1996; Hood et al., 2003; Low, 2010; Mash et al., 2003; Ruffman et al., 2001).

13.6.2 Applications to educational practice

Whether making use of tacit knowledge can facilitate conceptual change in early science cannot be assumed on the basis of the current results, as no intervention study was conducted. The current work has merely looked at distinguishing explicit reasoning from tacit judgements in primary school children. But can tacit knowledge effect conceptual change in children and modify their existing explicit beliefs? The current research cannot offer any conclusive support, neither in favour of successful changes nor against it. However, what it does do is offer suggestions for the construction of conceptual change programmes. In the light of the current work, conceptual change would need to make use of the distinction between explicit

knowledge and tacit reasoning by making the tacit model accessible (but not explicit) to the child. In doing so, the internal conflict between explicit beliefs and tacit understanding becomes available to the child.

Howe, Taylor Tavares and Devine (2010c) have begun to assess such an approach. Primary school children aged 8 to 12 years were assessed on two computer-presented tasks described earlier in Chapter 6 (Howe et al., 2010a, b) but combining both explicit predictions and tacit judgements of predictions. When predictions were made, the children received feedback about their predictions, that is, whether they were correct or incorrect. In both cases, they were then invited to see what happens if their predictions are carried out. So children who predicted correctly would see correct motion, and children who predicted incorrectly would see incorrect motion. The latter group would then also be able to see the correct motion. In a pre-test the children needed to make predictions of motion. A few days later, some children worked through the teaching software, that is, the integration of predictions and outcomes, and some children did not. A post-test several weeks later identified that while at the pre-test stage all children were equivalent in performance, those that worked with the software made superior predictions to those children who did not work with the software, both for horizontal motion and for free fall.

In Chapter 2, the notion was introduced that in order to change conceptions there must be conflict and dissatisfaction with current views. Although there are issues with this approach in its applications to education, the incorporation of tacit knowledge assessment may bring the conflict to a much more individual level and help to increase the likelihood of conflict and dissatisfaction, thus eliciting a change in conceptions. This may be fruitful in adjusting the explicit model and bringing it closer to the tacit model by making the tacit model an external contributor in its own right. Of course one cannot simply cut out the other external contributing factors such as language or sociocultural influences (see the dual pathway model displayed in Figure 13.1, p. 283), as science education does require an explicit understanding of concepts (for how else could teachers know if children *understand* the concepts to be taught?), and the external contributors are after all what defines explicitness of

knowledge in the first place. But by making the tacit model 'explicit' in the sense that it becomes a contributor without being diluted of other contributors it is hoped that conceptual change can be facilitated appropriately. However, the effectiveness or lack thereof is something that requires further investigation through an intervention study examining children's explicit understanding some time after an in-depth confrontation with the tacit models.

CONCLUSION:

AN EPILOGUE TO THE THESIS

At the very beginning of this thesis, a quote was given. Albert Einstein asked what the fish knows about the water in which he swims all his life – a very meaningful and interesting question. This quote was adapted to a long-term problem, that of our understanding of the physical world we live in. Two questions were asked, and their difference may not have been very clear to begin with. Firstly, what do we know about the physical world, and secondly, what do we *really* know about it? Like Aristotle so many years ago, many children and adults today hold beliefs about the world that are inconsistent with science. Evidently, despite these erroneous notions the human species has nonetheless managed to survive. But it has not done so well in changing naïve notions in order to produce efficient scholars that can deal with physics in appropriate ways.

The first question – what we know about our physical world in general – can be answered on the basis of the introductory chapters of this thesis. The answer is that as individuals we believe to know a lot, but this knowledge is often limited or incorrect. The first three studies in this thesis have confirmed this idea; children's

understanding of object motion is rich, but limited, and too alike Aristotelian theories. As conceptual change in science education does not seem to be a particularly effective way, on a large scale, to incite change of conceptions, the question arose whether judgements of dynamic events would reveal an answer to the second question – what we *really* know about our physical world. The results of the fourth study in this thesis, and other research, have indicated that children's spontaneous judgements of events support the notion of underlying tacit knowledge structures that accurately reflect the physical world.

It is clear, then, that two 'forms' of understanding about the same topic are available in young children. Early science education ought to begin taking this differentiation into consideration, and hopefully future research programmes investigating whether tacit judgements can facilitate change of explicit conceptions will provide stronger support for this. The quest for knowledge continues, and probably will never end. But one further step has already been taken now.

REFERENCES

Acredolo, C., Adams, A., & Schmid, J. (1984). On the understanding of the relationships between speed, duration, and distance. *Child Development, 55*, 2151-2159.

Acredolo, C., & Schmid, J. (1981). The understanding of relative speeds, distances, and durations of movement. *Developmental Psychology, 17*, 490-493.

Aguiar, A., & Baillargeon, R. (1998). Eight-and-a-half-month-old infants' reasoning about containment events. *Child Development, 69*, 636-653.

Ahmed, A., & Ruffman, T. (1998). Why do infants make A not B errors in a search task, yet show memory for the location of hidden objects in a nonsearch task? *Developmental Psychology, 34*, 441-453.

Al-Fakhri, S. (1977). The development of the concept of speed among Iraqi children. In P. R. Dasen (Ed.), *Piagetian psychology: Cross-cultural contributions* (pp. 203-215). New York, NY: Gardner Press.

Alonso-Tapia, J. (2002). Knowledge assessment and conceptual understanding. In M. Limon & L. Mason (Eds.), *Reconsidering conceptual change: Issues in theory and practice* (pp. 389-414). Dordrecht: Kluwer Academic.

Alvermann, D. E., & Hague, S. A. (1989). Comprehension of counterintuitive science text: Effects of prior knowledge and text structure. *The Journal of Educational Research, 82*, 197-202.

Andaloro, G., Bellomonte, L., & Sperandeo-Mineo, R. M. (1997). A computer based learning environment in the field of Newtonian mechanics. *International Journal of Science Education, 19*, 661-680.

Anderson, N. H. (1981). *Foundations of information integration theory*. New York, NY: Academic Press.

Aristotle (2008). *Physics* (R. Waterfield, Trans.). Oxford: Oxford University Press.

Arons, A. B. (1997). *Teaching introductory physics*. New York, NY: John Wiley & Sons.

Asimov, I. (1975). *The left hand of the electron*. London: White Lion.

Ausubel, D. P. (1968). *Educational psychology: A cognitive view*. New York, NY: Holt, Rinehart and Winston.

Baillargeon, R. (1993). The object concept revisited: New directions in the investigation of infants' physical knowledge. In C. E. Granrud (Ed.), *Visual perception and cognition in infancy* (pp. 265-316). Hillsdale, NJ: Lawrence Erlbaum Associates.

Baillargeon, R. (1994). How do infants learn about the physical world? *Current Directions in Psychological Science, 3*, 133-140.

Baillargeon, R. (1995). A model of physical reasoning in infancy. In C. Rovee-Collier & L. P. Lipsitt (Eds.), *Advances in infancy research* (Vol. 9, pp. 305-371). Norwood, NJ: Ablex.

Baillargeon, R. (2001). Infants' physical knowledge: Of acquired expectations and core knowledge. In E. Dupoux (Ed.), *Language, brain, and cognitive development: Essays in honor of Jacques Mehler* (pp. 341-361). Norwood, NJ: Ablex.

Baillargeon, R. (2004). Can 12 large clowns fit in a Mini Cooper? Or when are beliefs and reasoning explicit and conscious? *Developmental Science, 7*, 422–424.

Baillargeon, R., & Hanko-Summers, S. (1990). Is the top object adequately supported by the bottom object? Young infants' understanding of support relations. *Cognitive Development, 5*, 29-53.

Baillargeon, R., Kotovsky, L., & Needham, A. (1995). The acquisition of physical knowledge in infancy. In D. Sperber, D. Premack, & J. Premack (Eds.), *Causal cognition: A multidisciplinary debate* (pp. 79-116). Oxford: Clarendon Press.

Baillargeon, R., Needham, A., & DeVos, J. (1992). The development of young infants' intuitions about support. *Early Development and Parenting, 1*, 69-78.

Baillargeon, R., Spelke, E. S., & Wasserman, S. (1985). Object permanence in five-month-old infants. *Cognition, 20,* 191-208.

Baird, A. A., Kagan, J., Gaudette, T., Walz, K. A., Hershlag, N., & Boas, D. A. (2002). Frontal lobe activation during object permanence: Data from near-infrared spectroscopy. *NeuroImage, 16*, 1120-1126.

Baker, S. T., Gjersoe, N. L., Sibielska-Woch, K., Leslie, A. M., & Hood, B. M. (in press). Inhibitory control interacts with core knowledge in toddlers' manual search for an occluded object. *Developmental Science.*

Baker, S. T., Murray, K., & Hood, B. M. (2009, April). *Children's expectations about weight and speed in falling objects: The younger the judge, the better?* Poster presented at the biennial meeting of the Society for Research in Child Development, Denver, CO.

Barker, R., & Gardiner, J. (2007). E-education and e-skills. In V. Avery, E. Chamberlain, C. Summerfield, & L. Zealey (Eds.), *Focus on the digital age* (pp. 15-22). New York, NY: Palgrave Macmillan.

Barton, R. (2004). *Teaching secondary science with ICT*. Maidenhead: Open University Press.

Bentley, A. M. (1986). The development of Swazi children's understanding of duration: The influence of speed and distance. *International Journal of Psychology, 21*, 353-361.

Berry, D. C., & Broadbent, D. E. (1988). Interactive tasks and the implicit-explicit distinction. *British Journal of Psychology, 79,* 251-272.

Berthier, N. E., Bertenthal, B. I., Seaks, J. D., Sylvia, M., Johnson, R., & Clifton, R. K. (2001). Using object knowledge in visual tracking and reaching. *Infancy, 2*, 257-284.

Berthier, N. E., DeBlois, S., Poirier, C. R., Novak, M. A., & Clifton, R. K. (2000). What's behind the door? Two- and three-year-olds reason about unseen events. *Developmental Psychology, 36*, 394-401.

Biemans, H. J. A., & Simons, P. R. J. (1999). Computer-assisted instructional strategies for promoting conceptual change. In W. Schnotz, S. Vosniadou, & M. Carretero (Eds.), *New perspectives on conceptual change* (pp. 247-262). Amsterdam: Pergamon.

Bingham, N. E., & West, J. Y. (1948). Aims and Purposes of Science Teaching. *Review of Educational Research, 18*, 297-314.

Bliss, J. (1995). Piaget and after: The case of learning science. *Studies in Science Education, 25*, 139-172.

Bliss, J., & Ogborn, J. (1989). Tools for exploratory learning. *Journal of Computer Assisted Learning, 5*, 37-50.

Bloom, P., & Weisberg, D. S. (2007). Childhood origins of adult resistance to science. *Science, 316*, 996-997.

Bogartz, R. S., Shinskey, J. L., & Schilling, T. H. (2000). Object permanence in five-and-a-half-month-old infants? *Infancy, 1*, 403-428.

Bogartz, R. S., Shinskey, J. L., & Speaker, C. J. (1997). Interpreting infant looking: The event set x event set design. *Developmental Psychology, 33*, 408-422.

Bovet, M., & Othenin-Girard, C. (1975). Étude piagétienne de quelques notions spatio-temporelles dans un milieu africain [Piagetian study of some spatiotemporal concepts in an African environment]. *International Journal of Psychology, 10*, 1-17.

Bowers, K. S., Regehr, G., Balthazard, C., & Parker, K. (1990). Intuition in the context of discovery. *Cognitive Psychology, 22,* 72-110.

British Educational Suppliers Association (2009). *ICT provision and use in 2009/10.* London: BESA.

Broaders, S. C., Cook, S. W., Mitchell, Z., & Goldin-Meadow, S. (2007). Making children gesture brings out implicit knowledge and leads to learning. *Journal of Experimental Psychology: General, 136*, 539-550.

Brown, D. E., & Hammer, D. (2008). Conceptual change in physics. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 127-154). London: Routledge.

Brown, J. R. (1986). Though experiments since the scientific revolution. *International Studies in the Philosophy of Science, 1*, 1-15.

Buckingham, D., & Shultz, T. R. (2000). The developmental course of distance, time, and velocity concepts: A generative connectionist model. *Journal of Cognition and Development, 1*, 305-345.

Butler, S. C., Berthier, N. E., & Clifton, R. K. (2002). Two-year-olds' search strategies and visual tracking in a hidden displacement task. *Developmental Psychology, 38*, 581-590.

Cahyadi, M. V., & Butler, P. H. (2004). Undergraduate students' understanding of falling bodies in idealized and real-world situations. *Journal of Research in Science Teaching, 41*, 569-583.

Cantlon, J. F., & Brannon, E. M. (2005). Semantic congruity affects numerical judgments similarly in monkeys and humans. *Proceedings of the National Academy of Sciences, 102*, 16507-16511.

Caramazza, A., McCloskey, M., & Green, B. (1981). Naive beliefs in "sophisticated" subjects: Misconceptions about trajectories of objects. *Cognition, 9*, 117-123.

Carey, S. (1985). *Conceptual change in childhood*. Cambridge, MA: MIT Press.

Carey, S. (1986). Cognitive science and science education. *American Psychologist, 41*, 1123-1130.

Carey, S. (1987). Theory change in childhood. In B. Inhelder, D. de Caprona, & A. Cornu-Wells (Eds.), *Piaget today* (pp. 141-163). London: Erlbaum.

Carey, S. (1988). Conceptual differences between children and adults. *Mind & Language, 3*, 167-181.

Carey, S. (1991). Knowledge acquisition: Enrichment or conceptual change? In S. Carey & R. Gelman (Eds.), *The epigenesis of mind: Essays on biology and cognition* (pp. 257-292). Hillsdale, NJ: Lawrence Erlbaum Associates.

Carey, S. (1992). The origin and evolution of everyday concepts. In R. Giere (Ed.), *Cognitive models of science* (pp. 89-128). Minneapolis, MN: University of Minnesota Press.

Carey, S. (1999). Sources of conceptual change. In E. K. Scholnick, K. Nelson, S. A. Gelman, & P. H. Miller (Eds.), *Conceptual development: Piaget's legacy* (pp. 293-326). Mahwah, NJ: Lawrence Erlbaum Associates.

Carey, S. (2000a). Science education as conceptual change. *Journal of Applied Developmental Psychology, 21*, 13-19.

Carey, S. (2000b). The origin of concepts. *Journal of Cognition and Development, 1*, 37-41.

Carey, S. (2004, Winter). Bootstrapping & the origin of concepts. *Daedalus*, 59-68.

Carey, S. (2009). *The origin of concepts*. New York, NY: Oxford University Press.

Carey, S., & Sarnecka, B. W. (2006). The development of human conceptual representations: A case study. In Y. Munakata & M. H. Johnson (Eds.), *Processes of change in brain and cognitive development: Attention and Performance XXI* (pp. 473-496). Oxford: Oxford University Press.

Carey, S., & Spelke, E. (1994). Domain-specific knowledge and conceptual change. In L. A. Hirschfeld & S. A. Gelman (Eds.), *Mapping the mind: Domain specificity in cognition and culture* (pp. 169-200). Cambridge: Cambridge University Press.

Carey, S., & Spelke, E. (1996). Science and core knowledge. *Philosophy of Science, 63*, 515-533.

Casati, R., & Pasquinelli, E. (2007). How can you be surprised? The case for volatile expectations. *Phenomenology and the Cognitive Sciences, 6*, 171-183.

Cashon, C. H., & Cohen, L. B. (2000). Eight-month-old infants' perception of possible and impossible events. *Infancy, 1*, 429-446.

Champagne, A. B., Gunstone, R. F., & Klopfer, L. E. (1983). Naive knowledge and science learning. *Research in Science & Technological Education, 1*, 173-183.

Champagne, A. B., Klopfer, L. E., & Anderson, J. H. (1980). Factors influencing the learning of classical mechanics. *American Journal of Physics, 48*, 1074-1079.

Chi, M. T. H. (2005). Commonsense conceptions of emergent processes: Why some misconceptions are robust. *The Journal of the Learning Sciences, 14*, 161-199.

Chi, M. T. H. (2008). Three types of conceptual change: Belief revision, mental model transformation, and categorical shift. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 61-82). London: Routledge.

Chi, M. T. H., Feltovich, P. J., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science, 5*, 121-152.

Chi, M. T. H., & Roscoe, R. D. (2002). The processes and challenges of conceptual change. In M. Limon & L. Mason (Eds.), *Reconsidering conceptual change: Issues in theory and practice* (pp. 3-27). Dordrecht: Kluwer Academic.

Chinn, C. A., & Malhotra, B. A. (2002). Children's responses to anomalous scientific data: How is conceptual change impeded? *Journal of Educational Psychology, 94*, 327-343.

Chiu, M.-J., Hua, M.-S., Chen, T.-F., Hwu, H.-G., Kao, C.-H., & Chen, C.-H. (2006). Brain responses of explicit and implicit memory: An event-related potential study. *NeuroReport, 17*, 1483-1486.

Chomsky, N. (1965). *Aspects of the theory of syntax*. Cambridge, MA: MIT Press.

Claxton, G. (1991). *Educating the inquiring mind: The challenge for school science*. New York, NY: Harvester Wheatsheaf.

Clement, J. (1982). Students' preconceptions in introductory mechanics. *American Journal of Physics, 50*, 66-71.

Clement, J. (1983). A conceptual model discussed by Galileo and used intuitively by physics students. In D. Gentner & A. L. Stevens (Eds.), *Mental models* (pp. 325-340). Hillsdale, NJ: Lawrence Erlbaum Associates.

Clement, J., Brown, D. E., & Zietsman, A. (1989). Not all preconceptions are misconceptions: Finding 'anchoring conceptions' for grounding instruction on students' intuitions. *International Journal of Science Education, 11*, 554-565.

Clements, W. A., & Perner, J. (1994). Implicit understanding of belief. *Cognitive Development, 9*, 377-395.

Collins, H. M. (2001). What is tacit knowledge? In T. R. Schatzki, K. Knorr-Cetina, & E. von Savigny (Eds.), *The practice turn in contemporary theory* (pp. 107-119). London: Routledge.

Confrey, J., & Doerr, H. M. (1994). Student modelers. *Interactive Learning Environments, 4*, 199-217.

Cooper, L. (1935). *Aristotle, Galileo, and the tower of Pisa*. Ithaca, NY: Cornell University Press.

Cox, M., Webb, M., Abbott, C. Blakely, B., Beauchamp, T., & Rhodes, V. (2003). *ICT and pedagogy: A review of the research literature*. London: Department for Education and Skills.

Craik, K. J. W. (1943). *The nature of explanation*. Cambridge: Cambridge University Press.

Cross, R. T., & Mehegan, J. (1988). Young children's conception of speed: Possible implications for pedestrian safety. *International Journal of Science Education, 10*, 253-265.

Csibra, G., Tucker, L. A., & Johnson, M. H. (1998). Neural correlates of saccade planning in infants: A high-density ERP study. *International Journal of Psychophysiology, 29*, 201-215.

Darwin, C. (1859). *On the origin of species by means of natural selection, or the preservation of favoured races in the struggle for life*. London: John Murray.

Davidson, M. C., Amso, D., Anderson, L. C., & Diamond, A. (2006). Development of cognitive control and executive functions from 4 to 13 years: Evidence from manipulations of memory, inhibition, and task switching. *Neuropsychologia, 44*, 2037-2078.

Délorme, A., & Pinard, A. (1970). Le développement de la notion de la vitesse relative [The development of the concept of relative speed]. *Canadian Journal of Behavioural Science, 2*, 91-104.

Department for Education and Employment (1999). *The National Curriculum for England: Science*. London: HMSO.

Department for Education and Skills (2004). *Information and communications technology in schools in England: 2004*. London: HMSO.

Diamond, A. (1988). Abilities and neural mechanisms underlying AB performance. *Child Development, 59*, 523-527.

Diamond, A. (1991). Neuropsychological insight into the meaning of object concept development. In S. Carey & R. Gelman (Eds.), *The epigenesis of mind: Essays on biology and cognition* (pp. 67-110). Hillsdale, NJ: Lawrence Erlbaum Associates.

Diamond, A. (2006). The early development of executive functions. In E. Bialystok & F. I. M. Craik (Eds.), *Lifespan cognition: Mechanisms of change* (pp. 70-95). Oxford: Oxford University Press.

Dienes, Z. (2008). Subjective measures of unconscious knowledge. *Progress in Brain Research*, 168, 49-64.

Dienes, Z., & Perner, J. (1999). A theory of implicit and explicit knowledge. *Behavioral and Brain Sciences, 22*, 735-808.

Dienes, Z., & Scott, R. B. (2005). Measuring unconscious knowledge: Distinguishing structural knowledge and judgement knowledge. *Psychological Research, 69*, 338-351.

Dijksterhuis, A., Bos, M. W., Nordgren, L. F., & van Baaren, R. B. (2006). On making the right choice: The deliberation-without-attention effect. *Science, 311*, 1005-1007.

Dijksterhuis, E. J. (1961). *The mechanization of the world picture*. Oxford: Clarendon Press.

diSessa, A. A. (1982). Unlearning Aristotelian physics: A study of knowledge-based learning. *Cognitive Science, 6*, 37-75.

diSessa, A. A. (1983). Phenomenology and evolution of intuition. In D. Gentner & A. L. Stevens (Eds.), *Mental models* (pp. 15-33). Hillsdale, NJ: Lawrence Erlbaum Associates.

diSessa, A. A. (1986). Artificial worlds and real experience. *Instructional Science, 14*, 207-227.

diSessa, A. A. (1993). Toward an epistemology of physics. *Cognition and Instruction, 10*, 105-225.

diSessa, A. A. (1996). What do 'just plain folk' know about physics? In D. R. Olson & N. Torrance (Eds.), *The handbook of education and human development: New models of learning, teaching and schooling* (pp. 709-730). Cambridge, MA: Blackwell.

diSessa, A. A. (2002). Why conceptual ecology is a good idea. In M. Limon & L. Mason (Eds.), *Reconsidering conceptual change: Issues in theory and practice* (pp. 29-60). Dordrecht: Kluwer Academic.

diSessa, A. A. (2006). A history of conceptual change research: Threads and fault lines. In R. K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences* (pp. 265-281). Cambridge: Cambridge University Press.

diSessa, A. A. (2008). A bird's-eye-view of the "pieces" vs. "coherence" controversy (from the "pieces" side of the fence). In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 35-60). London: Routledge.

Doerr, H. M. (1997). Experiment, simulation and analysis: An integrated instructional approach to the concept of force. *International Journal of Science Education, 19*, 265-282.

Dole, J. A., & Sinatra, G. M. (1998). Reconceptualizing change in the cognitive construction of knowledge. *Educational Psychologist*, 33, 109-128.

Dorfman, J., Shames, V. A., & Kihlstrom, J. F. (2002). Intuition, incubation, and insight: Implicit cognition in problem solving. In G. D. M. Underwood (Ed.), *Implicit cognition* (pp. 257-296). Oxford: Oxford University Press.

Driver, R. (1981). Pupils' alternative frameworks in science. *European Journal of Science Education, 3*, 93-101.

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

Driver, R., & Easley, J. (1978). Pupils and paradigms: A review of literature related to concept development in adolescent science students. *Studies in Science Education, 5*, 61-84.

Driver, R., & Erickson, G. (1983). Theories-in-action: Some theoretical and empirical issues in the study of students' conceptual frameworks in science. *Studies in Science Education, 10*, 37-60.

Duit, R. (1999). Conceptual change approaches in science education. In W. Schnotz, S. Vosniadou, & M. Carretero (Eds.), *New perspectives on conceptual change* (pp. 263-282). Amsterdam: Pergamon.

Duit, R. (2009). *Bibliography: Students' and teachers' conceptions and science education*. Retrieved October 23, 2009, from http://www.ipn.uni-kiel.de/aktuell/stcse/stcse.html

Duit, R., & Treagust, D. F. (2003). Conceptual change: A powerful framework for improving science teaching and learning. *International Journal of Science Education, 25*, 671-688.

Duit, R., Treagust, D. F., & Widodo, A. (2008). Teaching science for conceptual change: theory and practice. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 629-646). London: Routledge.

Dykstra, D. I., Jr., Boyle, C. F., & Monarch, I. A. (1992). Studying conceptual change in learning physics. *Science Education, 76*, 615-652.

Einstein, A. (1950). *Out of my later years*. London: Thames and Hudson.

Einstein, A., & Infeld, L. (1938). *Evolution of physics: The growth of ideas from the early concepts to relativity and quanta.* Cambridge: Cambridge University Press.

Elby, A. (2001). Helping physics students learn how to learn. *American Journal of Physics, 69*, S54-S64.

Evans, J. St. B. T. (2003). In two minds: Dual-process accounts of reasoning. *TRENDS in Cognitive Sciences, 7*, 454-459.

Fabiani, M., & Wee, E. (2001). Age-related changes in working memory function: A review. In C. Nelson & M. Luciana (Eds.), *The handbook of developmental cognitive neuroscience* (pp. 473-488). Cambridge, MA: MIT Press.

Ferrari, M., & Chi, M. T. H. (1998). The nature of naïve explanations of natural selection. *International Journal of Science Education, 20*, 1231-1256.

Finegold, M., & Gorsky, P. (1991). Students' concepts of force as applied to related physical systems: A search for consistency. *International Journal of Science Education, 13*, 97-113.

Fischbein, E. (1987). *Intuition in science and mathematics: An educational approach*. Dordrecht: D. Reidel.

Fodor, J. A. (1985). Précis of the modularity of mind. *The Behavioral and Brain Sciences, 8*, 1-42.

Forbus, K. (1983). Reasoning about space and motion. In D. Gentner & A. L. Stevens (Eds.), *Mental models* (pp. 53-74). Hillsdale, NJ: Lawrence Erlbaum Associates.

Forster, K. I., & Forster, J. C. (2003). DMDX: A Windows display program with millisecond accuracy. *Behavior Research Methods, Instruments, & Computers, 35*, 116-124.

Frederiksen, J. R., & White, B. Y. (1998). Teaching and learning generic modeling and reasoning skills. *Journal of Interactive Learning Environments, 55,* 33-51.

Fu, Q., Dienes, Z., & Fu, X. (2010a). Can unconscious knowledge allow control in sequence learning? *Consciousness and Cognition, 19*, 462-474.

Fu, Q., Dienes, Z., & Fu, X. (2010b). The distinction between intuition and guessing in the SRT task generation: A reply to Norman and Price. *Consciousness and Cognition, 19*, 478-480.

Galilei, G. (1632). *Dialogo sopra i due massimi sistemi del mondo* [Dialogue concerning the two chief world systems]. Florence: Battista Landini.

Galilei, G. (1638). *Discorsi e dimonstrazioni matematiche, intorno a due nuove scienze* [Discourses and mathematical demonstrations relating to two new sciences]. Leyden: Elsevirii.

Galili, I. (2001). Weight versus gravitational force: Historical and educational perspectives. *International Journal of Science Education, 23*, 1073-1093.

Ganea, P. A., Shutts, K., Spelke, E. S., & DeLoache, J. S. (2007). Thinking of things unseen: Infants' use of language to update mental representations. *Psychological Science, 18*, 734-739.

Garnham, W. A., & Ruffman, T. (2001). Doesn't see, doesn't know: Is anticipatory looking really related to understanding of belief? *Developmental Science, 4*, 94-100.

Gibson, E. J. (1969). *Principles of perceptual learning and development*. New York, NY: Appleton Century Crofts.

Gigerenzer, G. (2004). Fast and frugal heuristics: The tools of bounded rationality. In D. J. Koehler & N. Harvey (Eds.), *Blackwell handbook of judgment and decision making* (pp. 62-88). Malden, MA: Blackwell Publishing.

Gigerenzer, G. (2007). *Gut feelings: The intelligence of the unconscious*. London: Allen Lane.

Gilbert, J., & Swift, D. (1985). Towards a Lakatosian analysis of the Piagetian and alternative conceptions research programs. *Science Education, 69*, 681-696.

Gilbert, J. K., Osborne, R. J., & Fensham, P. J. (1982). Children's science and its consequences for teaching. *Science Education, 66*, 623-633.

Gilbert, J. K., & Watts, M. (1983). Concepts, misconceptions and alternative conceptions: Changing perspectives in science education. *Studies in Science Education, 10*, 61-98.

Gleitman, L. R., Cassidy, K., Nappa, R., Papafragou, A., & Trueswell, J. C. (2005). Hard words. *Language Learning and Development, 1*, 23-64.

Glover, D., Miller, D., Averis, D., & Door, V. (2005). The interactive whiteboard: A literature survey. *Technology, Pedagogy & Education, 14*, 155-170.

Goldin-Meadow, S., & Alibali, M. W. (1999). Does the hand reflect implicit knowledge? Yes and no. *Behavioral and Brain Sciences, 22*, 766-767.

Gopnik, A. (1996). The scientist as child. *Philosophy of Science, 63*, 485-514.

Gopnik, A., Meltzoff, A. N., & Kuhl, P. K. (2001). *The scientist in the crib: What early learning tells us about the mind*. New York, NY: HarperCollins.

Gould, H., Tobochnik, J., & Christian, W. (2006). *An introduction to computer simulation methods: Applications to physical systems* (3rd ed.). Boston, MA: Addison-Wesley.

Gourlay, S. (2004, April). *'Tacit knowledge': The variety of meanings in empirical research*. Paper presented at the 5th European Organizational Knowledge, Learning and Capabilities conference, Innsbruck, Austria.

Gunstone, R. (1988). Learners in science education. In P. J. Fensham (Ed.), *Development and dilemmas in science education* (pp. 282-305). London: Falmer Press.

Gunstone, R., & Watts, M. (1985). Force and motion. In R. Driver, E. Guesne, & A. Tiberghien (Eds.), *Children's ideas in science* (pp. 85-104). Milton Keynes: Open University Press.

Gunstone, R. F., & White, R. T. (1981). Understanding of gravity. *Science Education, 65*, 291-299.

Guzzetti, B. J., Snyder, T. E., Glass, G. V., & Gamas, W. S. (1993). Promoting conceptual change in science: A comparative meta-analysis of instructional interventions from reading education and science education. *Reading Research Quarterly, 28*, 117-159.

Haddad, J. M., Kloos, H., & Keen, R. K. (2008). Conflicting cues in a dynamic search task are reflected in children's eye movements and search errors. *Developmental Science, 11*, 504-515.

Haertel, H., Kires, M., Jeskova, Z., Degro, J., Senichenkov, Y. B., & Zamarro, J.-M. (2003, September). *Aristotle still wins over Newton: An evaluation report of a new, simulation-supported approach to teach the concepts of inertia and gravity.* Paper presented at EUROCON, Ljubljana, Slovenia.

Halloun, I. A., & Hestenes, D. (1985). Common sense concepts about motion. *American Journal of Physics, 53*, 1056-1065.

Hammer, D. (1996). More than misconception: Multiple perspectives on student knowledge and reasoning, and an appropriate role for education research. *American Journal of Physics, 64*, 1316-1325.

Hammer, D. (2000). Student resources for learning introductory physics. *American Journal of Physics, 68*, S52-S59.

Harris, P. L. (1983). Infant cognition. In P. H. Mussen (Ed.), *Handbook of child psychology* (Vol. 2, pp. 689-782). New York, NY: John Wiley & Sons.

Harris, P. L. (2002). What do children learn from testimony? In P. Carruthers, S. Stich, & M. Siegal (Eds.), *The cognitive basis of science* (pp. 316-334). Cambridge: Cambridge University Press.

Hatano, G. (1990). The nature of everyday science: A brief introduction. *British Journal of Developmental Psychology, 8*, 245-250.

Hayes, P. J. (1979). The naïve physics manifesto. In D. Michie (Ed.), *Expert systems in the micro-electronic age* (pp. 242-270). Edinburgh: Edinburgh University Press.

Helm, H., Gilbert, J., & Watts, D. M. (1985). Thought experiments and physics education. *Physics Education, 20*, 211-217.

Hennessy, S. (2006). Integrating technology into teaching and learning of school science: A situated perspective on pedagogical issues in research. *Studies in Science Education, 42*, 1-48.

Hennessy, S., & O'Shea, T. (1993). Learner perceptions of realism and magic in computer simulations. *British Journal of Educational Technology, 24*, 125-138.

Hennessy, S., Twigger, D., Driver, R., O'Shea, T., O'Malley, C. E., Byard, M., et al. (1995a). A classroom intervention using a computer-augmented curriculum for mechanics. *International Journal of Science Education, 17*, 189-206.

Hennessy, S., Twigger, D., Driver, R., O'Shea, T., O'Malley, C. E., Byard, M., et al. (1995b). Design of a computer-augmented curriculum for mechanics. *International Journal of Science Education, 17*, 75-92.

Hennessy, S., Wishart, J., Whitelock, D., Deaney, R., Brawn, R., la Velle, L., et al. (2007). Pedagogical approaches for technology-integrated science teaching. *Computers & Education, 48*, 137-152.

Heron, P. R. L., & Meltzer, D. E. (2005). The future of physics education research: Intellectual challenges and practical concerns. *American Journal of Physics, 73*, 390-394.

Heuer, D., & Wilhelm, T. (1997). Aristoteles siegt immer noch über Newton [Aristotle still wins over Newton]. *Der Mathematische und Naturwissenschaftliche Unterricht, 50*, 280-285.

Hewson, P. W., & A'Beckett Hewson, M. G. (1984). The role of conceptual conflict in conceptual change and the design of science instruction. *Instructional Science, 13*, 1-13.

Hofstadter, M., & Reznick, J. S. (1996). Response modality affects human infant delayed-response performance. *Child Development, 67*, 646-658.

Hogarth, R. M. (2001). *Educating intuition*. Chicago, IL: University of Chicago Press.

Holliman, R., & Scanlon, E. (2004). *Mediating science learning through information and communications technology*. London: RoutledgeFalmer.

Hood, B. (2001). Guest editorial. *Perception, 30*, 1281-1284.

Hood, B., Carey, S., & Prasada, S. (2000). Predicting the outcomes of physical events: Two-year-olds fail to reveal knowledge of solidity and support. *Child Development, 71*, 1540-1554.

Hood, B., Cole-Davies, V., & Dias, M. (2003). Looking and search measures of object knowledge in preschool children. *Developmental Psychology, 39*, 61-70.

Hood, B. M. (1995). Gravity rules for 2- to 4-year-olds? *Cognitive Development, 10*, 577-598.

Hood, B. M. (1998). Gravity does rule for falling events. *Developmental Science, 1*, 59-63.

Hood, B. M., Santos, L., & Fieselman, S. (2000). Two-year-olds' naïve predictions for horizontal trajectories. *Developmental Science, 3*, 328-332.

Hood, B. M., Wilson, A., & Dyson, S. (2006). The effect of divided attention on inhibiting the gravity error. *Developmental Science, 9*, 303-308.

Howe, C., Nunes, T., & Bryant, P. (2010). Intensive quantities: Why they matter to developmental research. *British Journal of Developmental Psychology, 28,* 307-330.

Howe, C., Taylor Tavares, J., & Devine, A. (2010a). *Children's conceptions about physical events: Explicit and tacit understanding of horizontal motion.* Manuscript in preparation.

Howe, C., Taylor Tavares, J., & Devine, A. (2010b). *Everyday conceptions of object fall: Explicit and tacit understanding in middle childhood.* Manuscript in preparation.

Howe, C., Taylor Tavares, J., & Devine, A. (2010c). *Teaching software*. Retrieved June 8, 2010, from http://www.educ.cam.ac.uk/research/projects/objectmotion/teachingsoftware/

Howe, C., Tolmie, A., & Anderson, A. (1991). Information Technology and group work in physics. *Journal of Computer Assisted Learning, 7*, 133-143.

Howe, C., Tolmie, A., Anderson, A., & Mackenzie, M. (1992). Conceptual knowledge in physics: The role of group interaction in computer-supported teaching. *Learning and Instruction, 2*, 161-183.

Howe, C., Tolmie, A., & Rodgers, C. (1992). The acquisition of conceptual knowledge in science by primary school children: Group interaction and the understanding of motion down an incline. *British Journal of Developmental Psychology, 10*, 113-130.

Howe, C. J. (1998). *Conceptual structure in childhood and adolescence: The case of everyday physics*. London: Routledge.

Hugens, C. (1669). Regulæ de motu corporum ex mutuo impulsu [Laws of motion on the impact of bodies]. *Philosophical Transactions, 4*, 927-928.

Huntley-Fenner, G., Carey, S., & Solimando, A. (2002). Objects are individuals but stuff doesn't count: Perceived rigidity and cohesiveness influence infants' representations of small groups of discrete entities. *Cognition, 85*, 203-221.

Inhelder, B., & Piaget, J. (1958). *The growth of logical thinking from childhood to adolescence* (A. Parsons & S. Milgram, Trans.). London: Routledge & Kegan Paul.

Isaacs, S. (1930). *Intellectual growth in young children*. London: Routledge.

Jackson, I., & Sirois, S. (2009). Infant cognition: Going full factorial with pupil dilation. *Developmental Science, 12*, 670-679.

James, W. (1890). *Principles of psychology*. London: Macmillan.

Johnson, K. (2004). Tacit beliefs, semantics and grammar. *Linguistics and Philosophy, 27*, 57-91.

Johnson, M. H. (2005). Developmental cognitive neuroscience (2nd ed.). Malden, MA: Blackwell.

Johnson, M. H., Tucker, L. A., Stiles, J., & Trauner, D. (1998). Visual attention in infants with perinatal brain damage: Evidence of the importance of anterior lesions. *Developmental Science, 1*, 53-58.

Johnson-Laird, P. N. (1983). *Mental models*. Cambridge: Cambridge University Press.

Jonassen, D. (2004). Model building for conceptual change: Using computers as cognitive tools. In M. Gregoriadou, A. Rapti, S. Vosniadou, & C. Kynigos (Eds.), *Information and communication technologies in education* (pp. 3-17). Athens: New Technologies Publications.

Jonassen, D. H. (2003). Using cognitive tools to represent problems. *Journal of Research on Technology in Education, 35,* 362-381.

Jones, A. T. (1983). Investigation of students' understanding of speed, velocity and acceleration. *Research in Science Education, 13*, 95-104.

Jordan, K. E., & Brannon, E. M. (2009). A comparative approach to understanding human numerical cognition. In B. M. Hood & L. R. Santos (Eds.), *The origins of object knowledge* (pp. 53-84). Oxford: Oxford University Press.

Kaiser, M. K., Jonides, J., & Alexander, J. (1986). Intuitive reasoning about abstract and familiar physics problems. *Memory & Cognition, 14*, 308-312.

Kaiser, M. K., McCloskey, M., & Proffitt, D. R. (1986). Development of intuitive theories of motion: Curvilinear motion in the absence of external forces. *Developmental Psychology, 22*, 67-71.

Kaiser, M. K., & Proffitt, D. R. (1984). The development of sensitivity to causally relevant dynamic information. *Child Development, 55*, 1614-1624.

Kaiser, M. K., Proffitt, D. R., & McCloskey, M. (1985). The development of beliefs about falling objects. *Perception & Psychophysics, 38*, 533-539.

Kaiser, M. K., Profitt, D. R., Whelan, S. M., & Hecht, H. (1992). Influence of animation on dynamical judgments. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 669-690.

Kannass, K. N., Oakes, L. M., & Wiese, D. (1999). The development of infants' perception of object movement along inclines. *Cognitive Development, 14*, 215-240.

Karmiloff-Smith, A. (1984). Children's problem solving. In M. E. Lamb, A. L. Brown, & B. Rogoff (Eds.), *Advances in developmental psychology* (Vol. 3, pp. 39-90). Hillsdale, NJ: Lawrence Erlbaum.

Karmiloff-Smith, A. (1986). From meta-processes to conscious access: Evidence from children's metalinguistic and repair data. *Cognition, 23,* 95-147.

Karmiloff-Smith, A. (1988). The child is a theoretician, not an inductivist. *Mind & Language, 3*, 183-195.

Karmiloff-Smith, A. (1992). *Beyond modularity: A developmental perspective on cognitive science*. Cambridge, MA: MIT Press.

Karmiloff-Smith, A. & Inhelder, B. (1974/1975). "If you want to get ahead, get a theory". *Cognition, 3*, 195-212.

Keen, R. K., Berthier, N. E., Sylvia, M. R., Butler, S., Prunty, P. K., & Baker, R. K. (2008). Toddlers' use of cues in a search task. *Infant and Child Development, 17*, 249-267.

Keysers, C., Boyd, R., Cohen, J., Donald, M., Güth, W., Johnson, E., et al. (2008). Explicit and implicit strategies in decision making. In C. Engel & W. Singer (Eds.), *Better than conscious? Decision making, the human mind, and implications for institutions* (pp. 225-258). Cambridge, MA: MIT Press.

Kim, I. K., & Spelke, E. (1992). Infants' sensitivity to effects of gravity on visible object motion. *Journal of Experimental Psychology: Human Behaviour and Performance, 18*, 385-393.

Kim, I.-K., & Spelke, E. S. (1999). Perception and understanding of effects of gravity and inertia on object motion. *Developmental Science, 2*, 339-362.

King, W. H. (1960). The development of scientific concepts in children. *British Journal of Educational Psychology, 31*, 1-20.

Kinzler, K. D., & Spelke, E. S. (2007). Core systems in human cognition. In C. von Hofsten & K. Rosander (Eds.), *Progress in brain research* (Vol. 164, pp. 257-264). Amsterdam: Elsevier.

Kirby, S. (2008). Syntax and semantics: Argument mapping and maturation in child passives. *Proceedings of the Thirty-Eighth Western Conference on Linguistics, 19*, 126-135.

Klaassen, K. (2005). The concept of force as a constitutive element of understanding the world. In K. Boersma, M. Goedhart, O. de Jong, & H. Eijkelhof (Eds.), *Research and the quality of science education* (pp. 447-457). Dordrecht: Springer.

Klaczynski, P. A., & Narasimham, G. (1998). Development of scientific reasoning biases: Cognitive versus ego-protective explanations. *Developmental Psychology, 34*, 175-187.

Kozhevnikov, M., & Hegarty, M. (2001). Impetus belief as default heuristics: Dissociation between explicit and implicit knowledge about motion. *Psychonomic Bulletin & Review, 8*, 439-453.

Krist, H., Fieberg, E. L., & Wilkening, F. (1993). Intuitive physics in action and judgement: The development of knowledge about projectile motion. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 19*, 952-966.

Kuczaj, S. A. (1975). On the acquisition of a semantic system. *Journal of Verbal Learning and Verbal Behavior, 14*, 340-358.

Kuczaj, S. A. (1982). The acquisition of word meaning in the context of the development of the semantic system. In C. J. Brainerd & M. Pressley (Eds.), *Verbal processes in children: Progress in cognitive development research* (pp. 95-123). New York, NY: Springer.

Kuczaj, S. A. (1999). The world of words: Thoughts on the development of a lexicon. In M. Barrett (Ed.), *The development of language* (pp. 133-160). Hove: Psychology Press.

Kuczaj, S. A., & Hill, H. M. (2003). The development of language. In A. Slater & G. Bremner (Eds.), *An introduction to developmental psychology* (pp. 211-236). Malden, MA: Blackwell Publishing.

Kuhn, D. (1989). Children and adults as intuitive scientists. *Psychological Review, 96*, 674-689.

Kuhn, T. S. (1962). *The structure of scientific revolutions*. Chicago, IL: University of Chicago Press.

Kuhn, T. S. (1977). *The essential tension: Selected studies in scientific tradition and change*. Chicago, IL: University of Chicago Press.

Kurzban, R. (2008). The evolution of implicit and explicit decision making. In C. Engel & W. Singer (Eds.), *Better than conscious? Decision making, the human mind, and implications for institutions* (pp. 155-172). Cambridge, MA: MIT Press.

Leboutet-Barrell, L. (1976). Concepts of mechanics among young people. *Physics Education, 11*, 462-466.

Lehrer, R., & Schauble, L. (2000). Modeling in mathematics and science. In R. Glaser (Ed.), *Advances in instructional psychology* (Vol. 5, pp. 101-159). Mahwah, NJ: Lawrence Erlbaum Associates.

Lehrer, R., & Schauble, L. (2003). Origins and evolution of model-based reasoning in mathematics and science. In R. Lesh & H. M. Doerr (Eds.), *Beyond constructivism: A models and modeling perspective on mathematics problem-solving, learning, and teaching*. (pp. 59-70). Mahwah, NJ: Lawrence Erlbaum Associates.

Lemer, C., Dehaene, S., Spelke, E., & Cohen, L. (2003). Approximate quantities and exact number words: Dissociable systems. *Neuropsychologia, 41*, 1942-1958.

Lesh, R., & Doerr, H. M. (2003). Foundations of a model and modeling perspective on mathematics teaching, learning, and problem solving. In R. Lesh & H. M. Doerr (Eds.), *Beyond constructivism: Models and modeling perspectives on mathematics problem solving, teaching, and learning* (pp. 3-33). Mahwah, NJ: Lawrence Erlbaum Associates.

Leslie, A. M. (1994). ToMM, ToBy, and Agency: Core architecture and domain specificity. In L. A. Hirschfeld & S. A. Gelman (Eds.), *Mapping the mind: Domain specificity in cognition and culture* (pp. 119-148). Cambridge: Cambridge University Press.

Leslie, A. M., Xu, F., Tremoulet, P., & Scholl, B. J. (1998). Indexing and the object concept: Developing what and where systems. *TRENDS in Cognitive Sciences, 2*, 10-18.

Levin, I. (1977). The development of time concepts in young children: Reasoning about duration. *Child Development, 48*, 435-444.

Levin, I. (1979). Interference of time-related and unrelated cues with duration comparisons of young children: Analysis of Piaget's formulation of the relation of time and speed. *Child Development, 50*, 469-477.

Levin, I., Israeli, E., & Darom, E. (1978). The development of time concepts in young children: The relations between duration and succession. *Child Development, 49*, 755-764.

Levin, I., Wilkening, F., & Dembo, Y. (1984). Development of time quantification, integration and nonintegration of beginnings and endings in comparing durations. *Child Development, 55*, 2160-2172.

Light, P., Foot,T., Colbourn, C., & McClelland, I. (1987). Collaborative interactions at the microcomputer keyboard. *Educational Psychology, 7*, 13-21.

Lindström, B., Ekeblad, E., & Neuman, D. (1987). Using the computer to promote conceptual change: The case of elementary arithmetics. *Education & Computing, 3*, 223-230.

Lourenço, O., & Marchado, A. (1996). In defense of Piaget's theory: A reply to 10 common criticisms. *Psychological Review, 103*, 143-164.

Lovell, K. (1961). *The growth of basic mathematical and scientific concepts in children.* London: University of London Press.

Low, J. (2010). Preschoolers' implicit and explicit false-belief understanding: Relations with complex syntactical mastery. *Child Development, 81*, 597-615.

Luciana, M. (2003). The neural and functional development of human prefrontal cortex. In M. de Haan & M. H. Johnson (Eds.), *The cognitive neuroscience of development* (pp. 157-174). Hove: Psychology Press.

Maloney, D. P. (1988). Novice rules for projectile motion. *Science Education, 72*, 501-513.

Mareschal, D., Johnson, M. H., & Grayson, A. (2004). Brain and cognitive development. In J. Oates & A. Grayson (Eds.), *Cognitive and language development in children* (pp. 113-161). Oxford: Blackwell Publishing.

Mash, C., Keen, R., & Berthier, N. E. (2003). Visual access and attention in two-year-olds' event reasoning and object search. *Infancy, 4*, 371-388.

Mayer, R. E. (2002). Understanding conceptual change: A commentary. In M. Limon & L. Mason (Eds.), *Reconsidering conceptual change: Issues in theory and practice* (pp. 101-114). Dordrecht: Kluwer Academic.

McCloskey, M. (1983a). Intuitive physics. *Scientific American, 24*, 114-122.

McCloskey, M. (1983b). Irrwege der Intuition in der Physik [Aberrations of intuition in physics]. *Spektrum der Wissenschaft, 6*, 88-99.

McCloskey, M. (1983c). Naïve theories of motion. In D. Gentner & A. L. Stevens (Eds.), *Mental models* (pp. 299-324). Hilsdale, NJ: Lawrence Erlbaum Associates.

McCloskey, M., Caramazza, A., & Green, B. (1980). Curvilinear motion in the absence of external forces: Naive beliefs about the motion of objects. *Science, 210*, 1139-1141.

McCloskey, M., & Kohl, D. (1983). Naive physics: The curvilinear impetus principle and its role in interaction with moving objects. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 9*, 146-156.

McCloskey, M., Washburn, A., & Felch, L. (1983). Intuitive Physics: The straight-down belief and its origin. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 9*, 636-649.

McDermott, L. C. (1984). Research on conceptual understanding in mechanics. *Physics Today, 37(7)*, 24-32.

McFarlane, A., & Sakellariou, S. (2002). The role of ICT in science education. *Cambridge Journal of Education, 32*, 219-232.

McLeod, P., & Dienes, Z. (1996). Do fielders know where to go to catch the ball or only how to get there? *Journal of Experimental Psychology: Human Perception and Performance, 22*, 531-543.

McLeod, P., Reed, N., Gilson, S., & Glennerster, A. (2008). How soccer players head the ball: A test of optic acceleration cancellation theory with virtual reality. *Vision Research, 48*, 1479-1487.

Meadows, S. (2006). *The child as thinker: The development and acquisition of cognition in childhood* (2nd ed.). Hove: Routledge.

Mestre, J. P. (1991). Learning and instruction in pre-college physical science. *Physics Today, 44*, 56-62.

Mildenhall, P. T., & Williams, J. S. (2001). Instability in students' use of intuitive and Newtonian models to predict motion: The critical effect of the parameters involved. *International Journal of Science Education, 23*, 643-660.

Miščević, N. (1992). Mental models and thought experiments. *International Studies in the Philosophy of Science, 6*, 215-226.

Miščević, N. (2007). Modelling intuitions and thought experiments. Croatian Journal of Philosophy, 20, 181-214.

Molina, M., & Jouen, F. (2002). Weight perception in 12-month-old infants. *Infant Behavior and Development, 26*, 49-63.

Montangero, J. (1979). Les relations du temps, de la vitesse et de l'espace parcouru chez le jeune enfant [The relationships of time, speed and distance travelled in the young child]. *L'Année Psychologique, 79*, 23-42.

Morgan, M. S. (1999). Learning from models. In M. S. Morgan & M. Morrison (Eds.), *Models as mediators: Perspectives on natural and social science* (pp. 347-388). Cambridge: Cambridge University Press.

Munakata, Y. (2000). Challenges to the violation-of-expectation paradigm: Throwing the conceptual baby out with the perceptual processing bathwater? *Infancy, 1*, 471-477.

Munakata, Y., McClelland, J. L., Johnson, M. H., & Siegler, R. S. (1997). Rethinking infant knowledge: Toward an adaptive process account of successes and failures in object permanence tasks. *Psychological Review, 104*, 686–713.

Murphy, C. (2003). *Literature review in primary science and ICT*. Bristol: NESTA Futurelab.

Nachtigall, D. (1982). Vorstellungen von Fünftkläßlern über den freien Fall [Fifth-grader's conceptions of free fall]. *Naturwissenschaften im Unterricht − Physik/Chemie, 30*, 91-97.

Needham, A., & Baillargeon, R. (1993). Intuitions about support in 4.5-month-old infants. *Cognition, 47*, 121-148.

Nersessian, N. J. (1992). How do scientists think? Capturing the dynamics of conceptual change in science. In R. N. Giere (Ed.), *Cognitive models of science* (pp. 3-44). Minneapolis, MN: University of Minnesota Press.

Nersessian, N. J. (1995). Should physicists preach what they practice? Constructive modeling in doing and learning physics. *Science & Education, 4*, 203-226.

Nersessian, N. J. (1998). Conceptual change. In W. Bechtel & G. Graham (Eds.), *A companion to cognitive science* (pp. 157-166). Malden, MA: Blackwell Publishing.

Nersessian, N. J. (1999). Model-based reasoning in conceptual change. In L. Magnani, N. J. Nersessian, & P. Thagard (Eds.), *Model-based reasoning in scientific discovery* (pp. 5-22). New York, NY: Plenum.

Nersessian, N. J. (2002a). Maxwell and "the method of physical analogy": Model-based reasoning, generic abstraction, and conceptual change. In D. B. Malament (Ed.), *Reading natural philosophy: Essays in the history and philosophy of science and mathematics* (pp. 129-166). Chicago, IL: Open Court Publishing.

Nersessian, N. J. (2002b). The cognitive basis of model-based reasoning in science. In P. Carruthers, S. Stich, & M. Siegal (Eds.), *The cognitive basis of science* (pp. 133-153). Cambridge: Cambridge University Press.

Nersessian, N. J. (2003). Kuhn, conceptual change, and cognitive science. In T. Nickles (Ed.), *Thomas Kuhn* (pp. 178-211). Cambridge: Cambridge University Press.

Nersessian, N. J. (2008a). *Creating scientific concepts*. Cambridge, MA: MIT Press.

Nersessian, N. J. (2008b). Mental modeling in conceptual change. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 391-416). London: Routledge.

Newton, I. (1687). *Philosophiæ naturalis principia mathematica* [Mathematical principles of natural philosophy]. London: S. Pepys.

Newton, I. (1728). *A treatise of the system of the world*. London: F. Fayram.

Newton, L. R. & Rogers, L. (2001). *Teaching science with ICT*. London: Continuum.

Nussbaum, J., & Novick, S. (1982). Alternative frameworks, conceptual conflict and accommodation: Toward a principled teaching strategy. *Instructional Science, 11*, 183-200.

Oakes, M. E. (1945a). Explanations of natural phenomena by adults. *Science Education, 29*, 137-142.

Oakes, M. E. (1945b). Explanations of natural phenomena by adults, II. *Science Education, 29*, 190-201.

Oakes, M. E. (1957). Explanations by college students. *Science Education, 41*, 425-428.

Osborne, R., & Freyberg, P. (1985). *Learning in science: The implications of children's science*. Auckland: Heinemann.

Özdemir, G., & Clark, D. B. (2007). An overview of conceptual change theories. *Eurasia Journal of Mathematics, Science & Technology Education, 3*, 351-361.

Papert, S. (1980). *Mindstorms: Children, computers and powerful ideas*. Brighton: Harvester.

Perkins, D. (1992). *Smart schools: Better thinking and learning for every child*. New York, NY: Free Press.

Piaget, J. (1952). *The origins of intelligence in children* (M. Cook, Trans.). London: Routledge & Kegan Paul.

Piaget, J. (1954). *The child's construction of reality* (M. Cook, Trans.). London: Routledge & Kegan Paul.

Piaget, J. (1969). *The child's conception of time* (A. J. Pomerans, Trans.). London: Routledge & Kegan Paul.

Piaget, J. (1970a). *The child's conception of movement and speed* (G. E. T. Holloway & M. J. MacKenzie, Trans.). London: Routledge & Kegan Paul.

Piaget, J. (1970b). *Genetic epistemology* (E. Duckworth, Trans.). New York, NY: Columbia University Press.

Piaget, J. (1972). Physical world of the child. *Physics Today, 25(6)*, 23-27

Piaget, J. (1977). *The grasp of consciousness: Action and concept in the young child* (S. Wedgwood, Trans.). London: Routledge & Kegan Paul.

Piaget, J. (1978). *The development of thought: Equilibration of cognitive structures* (A. Rosin, Trans.). Oxford: Basil Blackwell.

Piaget, J. (1985). *The equilibration of cognitive structures: The central problem of intellectual development* (T. Brown & J. T. Kishore, Trans.). Chicago, IL: University of Chicago Press.

Piaget, J., & Inhelder, B. (1974). *The child's conception of quantities: Conservation and atomism* (A. J. Pomerans, Trans.). London: Routledge & Kegan Paul.

Pine, K., Messer, D., & St. John, K. (2001). Children's misconceptions in primary science: A survey of teachers' views. *Research in Science & Technological Education, 19*, 79-96.

Pinker, S. (1984). *Language learnability and language development.* Cambridge, MA: Harvard University Press.

Pinker, S. (1989). *Learnability and cognition: The acquisition of argument structure*. Cambridge, MA: MIT Press.

Planinic, M., Boone, W. J., Krsnik, R., & Beilfuss, M. L. (2006). Exploring alternative conceptions from Newtonian dynamics and simple DC circuits: Links between item difficulty and item confidence. *Journal of Research in Science Teaching, 43*, 150-171.

Plato (2009). *Meno and other dialogues: Charmides, Laches, Lysis, Meno* (R. Waterfield, Trans.). Oxford: Oxford University Press.

Plessner, H., & Czenna, S. (2008). The benefits of intuition. In H. Plessner, C. Betsch, & T. Betsch (Eds.), *Intuition in judgement and decision making* (pp. 251-265). New York, NY: Lawrence Erlbaum Associates.

Polanyi, M. (1967). *The tacit dimension*. London: Routledge & Kegan Paul.

Poole, P. (2000). Information and communications technology in science education. In J. Sears & P. Sorensen (Eds.), *Issues in science teaching* (pp. 209-218). London: RoutledgeFalmer.

Posner, G. J., Strike, K. A., Hewson, P. W., & Gertzog, W. A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education, 66*, 211-227.

Raven, R. J. (1972). The development of the concept of acceleration in elementary school children. *Journal of Research in Science Teaching, 9*, 201-206.

Reber, A. S. (1989). Implicit learning and tacit knowledge. *Journal of Experimental Psychology: General, 118,* 219-235.

Reber, P. J., & Kotovsky, K. (1997). Implicit learning in problem solving: The role of working memory capacity. *Journal of Experimental Psychology: General, 126,* 178-203.

Reed, N., McLeod, P., & Dienes, Z. (2010). Implicit knowledge and motor skill: What people who know how to catch don't know. *Consciousness and Cognition, 19*, 63-76.

Reif, F. (2008). *Applying cognitive science to education: Thinking and learning in scientific and other complex domains*. Cambridge, MA: MIT Press.

Reif, F., & Larkin, J. H. (1991). Cognition in scientific and everyday domains: Comparison and learning implications. *Journal of Research in Science Teaching, 28*, 733-760.

Resnick, L. B. (1994). Situated rationalism: Biological and social preparation for learning. In L. A. Hirschfeld & S. A. Gelman (Eds.), *Mapping the mind: Domain specificity in cognition and culture* (pp. 474-493). Cambridge: Cambridge University Press.

Rogers, L. (2004). Integrating ICT into science education and the future. In R. Barton (Ed.), *Teaching secondary science with ICT* (pp. 139-154). Maidenhead: Open University Press.

Rosenberg, R. D., & Carey, S. (2006, June). *Infants' indexing of objects vs. non-cohesive entities*. Poster presented at the Biennial Meeting of the International Society on Infant Studies, Kyoto, Japan.

Rosenberg, R. D., & Carey, S. (2009). Infant's representations of material entities. In B. M. Hood & L. R. Santos (Eds.), *The origins of object knowledge* (pp. 165-188). Oxford: Oxford University Press.

Ruffman, T., Garnham, W., Import, A., & Connolly, D. (2001). Does eye gaze indicate implicit knowledge of false-belief? Charting transitions in knowledge. *Journal of Experimental Child Psychology, 80*, 201-224.

Ryle, G. (1949) *The concept of mind*. London: Hutchinson.

Santos, L. R., & Hood, B. M. (2009). Object representation as a central issue in cognitive science. In B. M. Hood & L. R. Santos (Eds.), *The origins of object knowledge* (pp. 1-23). Oxford: Oxford University Press.

Schauble, L. (1996). The development of scientific reasoning in knowledge-rich contexts. *Developmental Psychology, 32*, 102-119.

Scheuerecker, J., Frodl, T., Koutsouleris, N., Zetsche, T., Wiesmann, M., Kleemann, A. M., et al. (2007). Cerebral differences in explicit and implicit emotional processing – an fMRI study. *Neuropsychobiology, 56*, 32-39.

Scott, R. B., & Dienes, Z. (2010). Knowledge applied to new domains: The unconscious succeeds where the conscious fails. *Consciousness and Cognition, 19*, 391-398.

Sequeira, M., & Leite, L. (1991). Alternative conceptions and history of science in physics teacher education. *Science Education, 75*, 45-56.

Shanon, B. (1976). Aristotelianism, Newtonianism and the physics of the layman. *Perception, 5*, 241-243.

Shepard, R. A. (2008). The step to rationality: The efficacy of thought experiments in science, ethics, and free will. *Cognitive Science, 32*, 3–35.

Sherin, B. (2006). Common sense clarified: The role of intuitive knowledge in physics problem solving. *Journal of Research in Science Teaching, 43*, 535-555.

Schilling, T. H. (2000). Infants' looking at possible and impossible screen rotations: The role of familiarization. *Infancy, 1*, 389-402.

Siegler, R. S., & Crowley, K. (1994). Constraints on learning in nonprivileged domains. *Cognitive Psychology, 27,* 194-226.

Siegler, R. S., & Richards, D. D. (1979). Development of time, speed, and distance concepts. *Developmental Psychology, 15*, 288-298.

Siegler, R. S., & Stern, E. (1998). Conscious and unconscious strategy discoveries: A microgenetic analysis. *Journal of Experimental Psychology: General, 127,* 377-397.

Sinatra, G. M., & Pintrich, P. R. (2003). The role of intentions in conceptual change learning. In M. G. Sinatra & P. R. Pintrich (Eds.), *Intentional conceptual change* (pp. 1-18). Mahwah, NJ: Lawrence Erlbaum Associates.

Singh, C. (2001). Student understanding of quantum mechanics. *American Journal of Physics, 69*, 885-895.

Smith, C., Carey, S., & Wiser, M. (1985). On differentiation: A case study of the development of the concepts of size, weight, and density. *Cognition, 21*, 177-237.

Smith, C., Maclin, D., Grosslight, L., & Davis, H. (1997). Teaching for understanding: A study of student's preinstruction theories of matter and a comparison of the effectiveness of two approaches to teaching about matter and density. *Cognition and Instruction, 15*, 317-393.

Smith, H. J., Higgins, S., Wall, K., & Miller, J. (2005). Interactive whiteboards: Boon or bandwagon? A critical review of the literature. *Journal of Computer Assisted Learning, 21*, 91-101.

Spelke, E. S. (1985). Preferential looking methods as tools for the study of cognition in infancy. In G. Gottfried & N. Krasnegor (Eds.), *Measurement of audition and vision in the first year of postnatal life* (pp. 323-363). Norwood, NJ: Ablex.

Spelke, E. S. (1991). Physical knowledge in infancy: Reflections on Piaget's theory. In S. Carey & R. Gelman (Eds.), *The epigenesis of mind: Essays on biology and cognition* (pp. 133-169). Hillsdale, NJ: Lawrence Erlbaum Associates.

Spelke, E. S. (1994). Initial knowledge: Six suggestions. *Cognition, 50*, 431-445.

Spelke, E. S. (2000). Core knowledge. *American Psychologist, 55*, 1233-1243.

Spelke, E. S. (2003). What makes us smart? Core knowledge and natural language. In D. Gentner & S. Goldin-Meadow (Eds.), *Language in mind: Advances in the study of language and thought* (pp. 277-311). Cambridge, MA: MIT Press.

Spelke, E. S. (2004). Core knowledge. In N. Kanwisher & J. Duncan (Eds.), *Functional neuroimaging of visual cognition: Attention and performance XX* (pp. 29-56). Oxford: Oxford University Press.

Spelke, E. S., Breinlinger, K., Macomber, J., & Jacobson, K. (1992). Origins of knowledge. *Psychological Review, 99*, 605-632.

Spelke, E. S., & Kinzler, K. D. (2007). Core knowledge. *Developmental Science, 10*, 89-96.

Spelke, E. S., & Kinzler, K. D. (2009). Innateness, learning, and rationality. *Child Development Perspectives, 3*, 96-98.

Spelke, E. S., & Newport, E. L. (1998). Nativism, empiricism, and the development of knowledge. In R. M. Lerner (Ed.), *Handbook of child psychology* (Vol. 1, pp. 275-430). New York, NY: John Wiley & Sons.

Spelke, E. S., Phillips, A., & Woodward, A. L. (1995). Infants' knowledge of object motion and human action. In D. Sperber, D. Premack, & J. Premack (Eds.), *Causal cognition: A multidisciplinary debate* (pp. 44-78). Oxford: Clarendon Press.

Stanescu-Cosson, R., Pinel, P., van de Moortele, P.-F., Le Bihan, D., Cohen, L., & Dehaene, S. (2000). Understanding dissociations in dyscalculia: A brain imaging study of the impact of number size on the cerebral networks for exact and approximate calculation. *Brain, 123*, 2240-2255.

Stathopoulou, C., & Vosniadou, S. (2007). Conceptual change in physics and physics-related epistemological beliefs: A relationship under scrutiny. In S. Vosniadou, A. Baltas, & X. Vamvakoussi (Eds.), *Reframing the conceptual change approach in learning and instruction* (pp. 145-164). Oxford: Elsevier.

Stavy, R., & Tirosh, D. (2000). *How students (mis-)understand science and mathematics: Intuitive rules*. New York, NY: Teachers College Press.

Steinberg, R. N. (2000). Computers in teaching science: To simulate or not to simulate? *American Journal of Physics, 68*, S37-S41.

Stepans, J. I., Beiswanger, R. E., & Dyche, S. (1986). Misconceptions die hard. *The Science Teacher, 53(6)*, 65-69.

Stinner, A. (1994). The story of force: From Aristotle to Einstein. *Physics Education, 29*, 77-85.

Strauss, S. (1981). Cognitive development in school and out. *Cognition, 10*, 295-300.

Strike, K. A., & Posner, G. J. (1985). A conceptual change view of learning and understanding. In L. H. T. West & A. L. Pines (Eds.), *Cognitive structure and conceptual change* (pp. 211-231). Orlando, FL: Academic Press.

Sun, R., Mathews, R. C., & Lane, S. M. (2007). Implicit and explicit processes in the development of cognitive skills: A theoretical interpretation with some practical implications for science education. In E. M. Vargios (Ed.), *Educational psychology research focus* (pp. 1-26). New York, NY: Nova Science.

Suping, M. S. (2003). *Conceptual change among students in science*. Retrieved February 10, 2010, from http://www.stemworks.org/digests/EDO-SE-03-03.pdf

Tao, P.-K., & Gunstone, R. F. (1999). The process of conceptual change in force and motion during computer-supported physics instruction. *Journal of Research in Science Teaching, 36*, 859-882.

te Velde, A. F., van der Kamp, J., & Savelsbergh, G. J. P. (2008). Five- to twelve-year-olds' control of movement velocity in a dynamic collision avoidance task. *British Journal of Developmental Psychology, 26*, 33-50.

Thagard, P. (1992). *Conceptual revolutions*. Princeton, NJ: Princeton University Press.

Thatcher, R. W. (1992). Cyclic cortical reorganisation during early childhood. *Brain and Cognition, 20*, 24-50.

Tishman, S., & Perkins, D. N. (1997). The language of thinking. *Phi Delta Kappan, 78*, 368-374.

Trowbridge, D. E., & McDermott, L. C. (1980). Investigation of student understanding of the concept of velocity in one dimension. *American Journal of Physics, 48*, 1020-1028.

Trowbridge, D. E., & McDermott, L. C. (1981). Investigation of student understanding of the concept of acceleration in one dimension. *American Journal of Physics, 49*, 242-253.

Twigger, D., Byard, M., Draper, S., Driver, R., Hartley, R., Hennessy, S., et al. (1991). The 'conceptual change in science' project. *Journal of Computer Assisted Learning, 7*, 144-155.

Twigger, D., Byard, M., Driver, R., Draper, S., Hartley, R., Hennessy, S., et al. (1994). The conception of force and motion of students aged between 10 and 15 years: An interview study designed to guide instruction. *International Journal of Science Education, 16*, 215-229.

Tytler, R. (1998). The nature of students' informal science conceptions. *International Journal of Science Education, 20*, 901-927.

Tytler, R. (2000). A comparison of year 1 and year 6 students' conceptions of evaporation and condensation: Dimensions of conceptual progression. *International Journal of Science Education, 22*, 447-467.

van Hise, Y. A. (1988). Student misconceptions in mechanics: An international problem? *The Physics Teacher, 26*, 498-502.

Viennot, L. (1979). Spontaneous reasoning in elementary dynamics. *European Journal of Science Education, 1*, 205-221.

von Glasersfeld, E. (1989). Cognition, construction of knowledge and teaching. *Synthese, 80*, 121-140.

Vosniadou, S. (1994a). Capturing and modeling the process of conceptual change. *Learning and Instruction, 4*, 45-69.

Vosniadou, S. (1994b). Introduction. *Learning and Instruction, 4*, 3-6.

Vosniadou, S. (1999). Conceptual change research: State of the art and future directions. In W. Schnotz, S. Vosniadou, & M. Carretero (Eds.), *New perspectives on conceptual change* (pp. 3-13). Amsterdam: Pergamon.

Vosniadou, S. (2002a). Mental models in conceptual development. In L. Magnani & N. J. Nersessian (Eds.), *Model-based reasoning: Science, technology, values* (pp. 353-368). New York, NY: Kluwer Academic / Plenum.

Vosniadou, S. (2002b). On the nature of naive physics. In M. Limon & L. Mason (Eds.), *Reconsidering conceptual change: Issues in theory and practice* (pp. 61-76). Dordrecht: Kluwer Academic.

Vosniadou, S. (2003). Exploring the relationships between conceptual change and intentional learning. In G. M. Sinatra & P. R. Pintrich (Eds.), *Intentional conceptual change* (pp. 377-406). Mahwah, NJ: Lawrence Erlbaum Associates.

Vosniadou, S. (2007a). Conceptual change and education. *Human Development, 50(1)*, 47-54.

Vosniadou, S. (2007b). Personal epistemology and conceptual change: An introduction. In S. Vosniadou, A. Baltas, & X. Vamvakoussi (Eds.), *Reframing the conceptual change approach in learning and instruction* (pp. 99-104). Oxford: Elsevier.

Vosniadou, S. (2007c). The cognitive-situative divide and the problem of conceptual change. *Educational Psychologist, 42*, 55-66.

Vosniadou, S. (2008). Conceptual change research: An introduction. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. xiii-xxviii). London: Routledge.

Vosniadou, S., & Brewer, W. F. (1992). Mental models of the earth: A study of conceptual change in childhood. *Cognitive Psychology, 24*, 535-585.

Vosniadou, S., & Ioannides, C. (1998). From conceptual development to science education: A psychological point of view. *International Journal of Science Education, 20*, 1213-1230.

Vosniadou, S., Ioannides, C., Dimitrakopoulou, A., & Papademetriou, E. (2001). Designing learning environments to promote conceptual change in science. *Learning and Instruction, 11*, 381-419.

Vosniadou, S., Vamvakoussi, X., & Skopeliti, I. (2008). The framework theory approach to the problem of conceptual change. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 3-34). London: Routledge.

Vygotsky, L. S. (1978). *Mind in society: The development of higher psychological processes.* Cambridge, MA: Harvard University Press.

Vygostsky, L. S. (1986). *Thought and language*. Cambridge, MA: MIT Press.

Wagner, R. K., & Sternberg, R. J. (1985). Practical intelligence in real-world pursuits: The role of tacit knowledge. *Journal of Personality and Social Psychology, 49*, 436-458.

West, L. H. T., & Pines, A. L. (1986). Conceptual understanding and science learning: An interpretation of research within a sources-of-knowledge framework. *Science Education, 70*, 583-604.

Whitaker, R. J. (1983). Aristotle is not dead: Student understanding of trajectory motion. *American Journal of Physics, 51*, 352-357.

White, R. T., & Gunstone, R. F. (2008). The conceptual change approach and the teaching of science. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 619-628). London: Routledge.

Whittlesea, B. W. A., & Wright, R. L. (1997). Implicit (and explicit) learning: Acting adaptively without knowing the consequences. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 23*, 181-200.

Wieman, C., & Perkins, K. (2005). Transforming physics education. *Physics Today, 58(11)*, 36-41.

Wilde, O. (1999). *The picture of Dorian Gray*. New York, NY: Tom Doherty Associates. (Original work published 1891)

Wilkening, F. (1981). Integrating velocity, time, and distance information: A developmental study. *Cognitive Psychology, 13*, 231-247.

Wilkening, F. (1982). Children's knowledge about time, distance, and velocity interrelations. In W. J. Friedman (Ed.), *The developmental psychology of time* (pp. 87-112). New York, NY: Academic Press.

Wilkening, F., & Anderson, N. H. (1982). Comparison of two rule-assessment methodologies for studying cognitive development and knowledge structure. *Psychological Bulletin, 92*, 215-237.

Wilkening, F., & Huber, S. (2002). Children's intuitive physics. In U. Goswami (Ed.), *Blackwell handbook of childhood cognitive development* (pp. 349-370). Oxford: Blackwell Publishing.

Wilkening, F., Levin, I., & Druyan, S. (1987). Children's counting strategies for time quantification and integration. *Developmental Psychology, 23*, 823-831.

Wilkening, F., & Sodian, B. (2005). Scientific reasoning in young children: Introduction. *Swiss Journal of Psychology, 64*, 137-139.

Wiser, M., & Carey, S. (1983). When heat and temperature were one. In D. Gentner & A. L. Stevens (Eds.), *Mental models* (pp. 267-298). Hillsdale, NJ: Lawrence Erlbaum Associates.

Wood, J. N., & Grafman, J. (2003). Human prefrontal cortex: Processing and representational perspectives. *Nature Reviews Neuroscience, 4*, 139-147.

Yu, Q. (2002). Model-based reasoning and similarity in the world. In L. Magnani & N. J. Nersessian (Eds.), *Model-based reasoning: Science, technology, values* (pp. 275-286). New York, NY: Kluwer Academic / Plenum.

Za'rour, G. I., & Khuri, G. A. (1977). The development of concept of speed by Jordanian school children in Amman. In P. R. Dasen (Ed.), *Piagetian psychology: Cross-cultural contributions* (pp. 216-226). New York, NY: Gardner Press.

Zelazo, P. D. (2004). The development of conscious control in childhood. *TRENDS in Cognitive Sciences, 8*, 12-17.

Zelazo, P. D., Craik, F. I. M., & Booth, L. (2004). Executive function across the life span. *Acta Psychologica, 115*, 167-183.

Zelazo, P. D., Müller, U., Frye, D., & Marcovitch, S. (2003). The development of executive function in early childhood. *Monographs of the Society for Research in Child Development, 68(3, Serial No. 274)*.

Zietsman, A. I., & Hewson, P. W. (1986). Effect of instruction using microcomputer simulations and conceptual change strategies on science learning. *Journal of Research in Science Teaching, 23*, 27-39.

APPENDIX

A1 Summary of studies on the understanding of naturally induced object motion

Table A1 Summary of studies on the understanding of naturally induced object motion

Authors	Motion type	Age group	Task description	Findings
Baker et al. (2009)	Free fall	6-8 years	Objects dropped; predictions and observations compared.	After predicting what would happen if two canisters of different weights were dropped, children witnessed them fall and were required to report what happened. More association between weight and speed and more confirmation bias of observations as children get older.
Champagne et al. (1980, as cited in McDermott, 1984)	Free fall	High-school students	Objects dropped; predictions and observations compared.	Acknowledgement that speed increases with fall, but also thought speed is proportional to gravitational force. One third thought time of fall is shorter for heavier object.
Chinn & Malhotra (2002)	Free fall	Fourth grade students	Objects dropped; predictions and observations compared.	65% in prediction and precise-prediction groups predicted heavy rock would fall faster, 15% that light rock would hit first, and 20% that rocks would fall at same speed. 72% who expected rocks to fall same reported seeing them fall same; less than half who expected either to hit first reported observing them hit first.
Howe, Taylor Tavares, & Devine (2010a)	Horizontal	6-10 years	Computer task with billiard balls on a billiard table.	Predictions suggested friction is only slowly taken into account, as children get older. But judgements of motion imply acknowledgement of role of friction. Results imply that while older children may have some grasp of speed change along horizontals, younger children seemingly do not – younger children rarely acknowledged that speeds would be different

between two points.

Reference	Task	Age	Apparatus	Findings
Howe, Taylor Tavares, & Devine (2010b)	Free fall	6-10 years	Computer task with hot air balloon and balls of different sizes.	Predictive reasoning results show that children were generally unaware of influence of acceleration due to gravity. Tacit reasoning task, on the other hand, implied that children do display reasonably good tacit understanding that objects do accelerate through air.
Howe, Tolmie, & Rodgers (1992)	Incline	8-12 years	Toy cars rolling down slopes.	Level I: Variables like angle, friction, weight not considered or not understood correctly. Level II: Some understanding how variables interact. Weight important but not coordinated with other variables. Level III: Weight important and coordinated.
Inhelder & Piaget (1958)	Horizontal	5-15 years	Spring device launching balls of different sizes and weights.	Stage I: Children sometimes claimed light balls would go further because easier to set in motion, and sometimes heavier balls would go further because stronger. Stage IIA: Some attempt to eliminate these contradictions. Stage IIB: Children explained slowing down, but responses still comparable to Stage IIA. Stage IIIA: Children predicted large balls go further because heavier; friction and air resistance introduced. Stage IIIB: Children predicted heavier balls go further because more force.
Inhelder & Piaget (1958)	Incline	5-15 years	Adjustable plane; balls of different sizes and weights released.	Stage I (up to 7 years): Children responded intuitively based on experiences. Weight constantly assigned a role, but not always consistently. Stage II (7 to 11 years): Children were able to make correct formulations of correspondences, but not systematically. Stage IIIA:

Study	Type	Participants	Task	Findings
				Responses were made more readily; eventually hypothesising that height was relevant. Stage IIIB: The hypothesis was proposed and verified.
Kaiser & Proffitt (1984)	Horizontal	6-10 years, college students	Judgements of video recordings of dynamic collision events.	Both students and children could judge video recordings as natural or anomalous above chance levels, with only little improvement as age increased.
Kaiser, Proffitt, Whelan, & Hecht (1992)	Free fall	Undergraduate students	Predictions and judgements of trajectories.	Trajectories drawn were generally not consistent with physical principles. But when shown animations, more than 80 per cent of students preferred the trajectories that were more natural.
Kannass et al. (1999)	Incline	10-16 months	Events involving a computer-generated ball rolling up or down an incline.	In downward motion, only 16-month-olds reacted to the change in direction. In upward motion, 16-month-olds responded to featural changes; 10-month-olds did not differentiate between any of the scenarios. Over time, infants become more sophisticated in their responses to object speed and acceleration tasks.
Kim & Spelke (1992)	Incline	5-7 months	Events involving a computer-generated ball rolling up or down an incline, accelerating or decelerating.	5-month-olds looked longer at novel test trials where both variables changed; possibility of the scenario did not affect their behaviour. The possibility of the scenario did not violate expectations, and infants instead reacted on the basis of the amount of perceptual deviance from the familiar habituation event. 7-month-olds, however, looked longer at the impossible event, though less perceptual changes took place.

Study	Context	Age	Task	Findings
Nachtigall (1982)	Free fall	10-11 years	Theoretical predictions of balls falling.	Most thought the lead ball would reach the ground first, as it was heavier. When asked to predict whether the ball was faster when falling past B or past C, half thought the ball would be faster whilst falling past C, 47% believed there would be no acceleration, and 3% thought the ball would be slower when falling past C.
Piaget (1970a)	Incline	5-11 years	Judgements about acceleration of a ball rolling down a slope.	Stage I: Acceleration perceived as short and intensive effort. Stage II (6 years): Children have an intuitive conception of acceleration but it is not understood as continuous. Stage IIIa (7 to 8 years): Acceleration perceived as continuous, but children cannot relate successive speeds well. Stage IIIb (9 to 10 years): Children understand distances are travelled in shorter times as speed increases. Stage IV (11 years): Children can separate speed into distance-time relationships and make comparisons of successive speeds.
Raven (1972)	Incline	8-11 years	Judgements about acceleration of a car travelling down a slope.	A higher proportion of children solved tasks correctly as age increased (but only at 11 consistently high level). Less than half of 10-year-olds correct, but two thirds at 11 years.
Sequeira & Leite (1991)	Free fall	Undergraduate students	Theoretical predictions of balls falling.	More than half of the students predicted that the heaviest object would need the least time to fall in the air.
Shanon (1976)	Free fall	Undergraduate students	Theoretical predictions of objects falling and video recordings of motion, movement with constant acceleration was	A third to a half of predictions were Aristotelian. But when presented with

Study	Topic	Population	Task	Findings
				motion. identified as being natural, rather than the recordings of movement with constant velocity.
Trowbridge & McDermott (1980)	Incline	Undergraduate students	Predictions of relationship between distance travelled and elapsed time for a rolling ball.	The task posed no overall problem for any of the students because only qualitative relationships needed to be understood.
Trowbridge & McDermott (1981)	Incline	Undergraduates	Balls rolling down two inclines, accelerations to be compared.	Ten comparison approaches identified. Overall performance was poor; only about 40 per cent of introductory physics students showed some understanding of acceleration and used a correct approach to compare acceleration, even though they were aware of the theoretical concept.
van Hise (1988)	Free fall	4-adulthood	Theoretical predictions of balls falling.	4-6 years: Both reach the ground at the same time because thrown together. 6-7 years: Lighter one reaches ground first. 7-adulthood: Heavier ball will touch the ground first because of weight.

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A2 Questionnaire for teachers: Use of information and communication technology (ICT) in the classroom

Dear Teachers,

As part of my PhD research at the Faculty of Education, University of Cambridge, which looks at young children's explicit and tacit understanding of object motion, certain tasks are being carried out using a computer. As a sideline to this I would be interested to find out how much experience these children have in the use of ICT within the classroom, particularly in the context of science education. It would therefore be greatly appreciated if you could take the time to fill out this short questionnaire on your use of ICT in the classroom.

By completing and returning this questionnaire you will be giving your consent to participate in my research. Your responses will be collected anonymously and your data will be treated confidentially, and no identifying information will be used in publication. Should you wish your data to be withdrawn at any point, please let me know.

Kindly complete the questionnaire and return it to _____ by Monday, June 1st. In the meantime, if you have any further questions, please feel free to contact me at mh530@cam.ac.uk or at the Faculty of Education (see footer for address).

Many thanks

Michael Hast

Use of information and communication technology (ICT) in the classroom

Year: _____

1.   How many hours of your overall teaching, on average, incorporate the use of ICT?

_____ hours per week (out of _____ hours[*])

2.   Which ICT methods do you use in the classroom?

3.   With which of the above methods, if any, are your children given hands-on experience?

4.   How many hours a week, on average, do you spend on teaching science?

_____ hours per week (out of _____ hours[*])

5.   Do you incorporate ICT when teaching science?

YES / NO

6.   How much of your science teaching, on average, involves the use of ICT?

_____ hours per week (out of _____ hours[**])

7.   Which ICT methods do you use when teaching science?

---

[*] Total hours that your children are taught per week (not necessarily only by you), excluding breaks.
[**] Total hours of science teaching only.

A3 Consent form

Dear Parent or Guardian

I am currently carrying out research for my PhD at the Faculty of Education, University of Cambridge. My research is interested in seeing what pre-school and primary school children know about how fast objects move. There will be a range of tasks in which the children will simply be shown a range of everyday objects, either in real life or on a computer screen, and they will be asked questions about how fast these objects move.

Participation will be absolutely voluntary. If the children do not want to answer questions or if they want to stop at any point, they are free to do so, without needing to justify themselves. Also, any data that I collect will be treated confidentially, which means that if the results are published, there will be no way of identifying any data as that of your child's. If at any later point you wish your child's data to be withdrawn from the research, please let me know.

If you do **NOT** wish your child to participate in my research at all, please fill in the form below and return it to the school by Friday, May 2nd. If you require further information you are welcome to contact either the head teacher of your child's school, or you can contact me at the Faculty of Education (see footer for address).

Many thanks

Michael Hast

- -

I do not wish my child _____ (please give full

name), Year _____, to participate in your research.

A4 Sample questionnaire for Study 1

Initials: _____   **Gender: __**   **Year: __**   **Birthday: _____**

INCLINE

1. Do you think one of the two will **roll for longer**?

   Squash ball   Golf ball   Both the same

Because _____

2. Do you think one of the two will **roll faster**?

   Orange   Tennis ball   Both the same

Because _____

3. Do you think one of the two will **roll faster**?

   Tennis ball   Squash ball   Both the same

Because _____

4. Do you think one of the two will **roll for longer**?

   Orange   Golf ball   Both the same

Because _____

5. Do you think one of the two will **roll faster**?

   Squash ball   Orange   Both the same

Because _____

6. Do you think one of the two will **roll for longer**?

   Golf ball   Tennis ball   Both the same

Because _____

FALL

7. Do you think one of the two will **fall faster**?

   Hammer   Feather   Both the same

Because _____

8. Do you think one of the two will **fall faster**?

   Leaf   Stone   Both the same

Because _____

9. Do you think one of the two will **fall for longer**?

   Stone   Hammer   Both the same

Because _____

10. Do you think one of the two will **fall faster**?

      Feather   Stone   Both the same

Because _____

11. Do you think one of the two will **fall for longer**?

      Hammer   Leaf   Both the same

Because _____

12. Do you think one of the two will **fall for longer**?

      Leaf   Feather   Both the same

Because _____

<u>HORIZONTAL</u>

13. Do you think one of the two will **roll for longer**?

      Car   Truck   Both the same

Because _____

14. Do you think one of the two will **roll faster**?

      Marble   Car   Both the same

Because _____

15. Do you think one of the two will **roll for longer**?

      Truck   Marble   Both the same

Because _____

16. Do you think one of the two will **roll faster**?

      Billiard ball   Truck   Both the same

Because _____

17. Do you think one of the two will **roll for longer**?

      Marble   Billiard ball   Both the same

Because _____

18. Do you think one of the two will **roll faster**?

      Car   Billiard ball   Both the same

Because _____

A5 Sample questionnaire for Study 2

Initials: _____   **Gender: __**   **Year: __**   **Birthday: _____**

Light/Heavy

1.   Motion down an incline at 15 cm

a.   Control ball: what happens if you let it go? (correct or incorrect)

b.   Will the two balls take the same time, or will one take more, or less, to reach the end of the tube? Why?

c.   Do they both go as fast, or is one faster or slower? Why?

d.   How does the speed of the ball at Point A (0cm) compare with that at Point C (100cm); is it the same, or more, or less?

e.   How about Point A (0cm) and Point B (50cm)?

f.   How about Point B (50cm) and Point C (100cm)?

2.   Motion down an incline at 30 cm (incline comparison)

a.   Will the ball take the same time as before, more, or less, to reach the end of the tube? Why?

b.   Does it go as fast as before, or is it faster or slower? Why?

3. <u>Horizontal motion</u>

a. Control ball: what happens when it reaches the end of the tube? (correct or incorrect)

b. Will the two balls take the same time, or will one take more, or less, to stop? Why?

c. Do they both go as fast, or is one faster or slower? Why?

d. How does the speed of the ball at Point A (0cm) compare with that at Point C (100cm); is it the same, or more, or less?

e. How about Point A (0cm) and Point B (50cm)?

f. How about Point B (50cm) and Point C (100cm)?

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4. <u>Motion in free fall</u>

a. Control ball: what happens if you let it go? (correct or incorrect)

b. Will the two balls take the same time, or will one take more, or less, to reach the end of the tube? Why?

c. Do they both go as fast, or is one faster or slower? Why?

d. How does the speed of the ball at Point A (0cm) compare with that at Point C (100cm); is it the same, or more, or less?

e. How about Point A (0cm) and Point B (50cm)?

f. How about Point B (50cm) and Point C (100cm)?

A6 Addendum to 7.3.2.2 on repeated testing of same sample and order of tasks

In order to see whether the repeated testing of the same sample of children and the order of tasks had any effect on the children's performance on individual tasks, an additional sample of children was recruited. These children were tested on their performance in the Study 3 task (see Chapter 10) and on their performance in the Study 4 task (see Chapter 11).

1. Method

1.1 Participants

As noted in Chapter 7, the additional study sample consisted of 16 children (8 girls). The sample included 4 Year 1 children (2 girls; age M = 6.30 years, SD = 0.26), 4 Year 2 children (2 girls; age M = 7.01 years, SD = 0.30), 4 Year 4 children (2 girls; age M = 9.27, SD = 0.22) and 4 Year 6 children (2 girls; age M = 11.33, SD = 0.12). The children were recruited from the same school as the main sample. None of them had previously participated in any of the four pilot studies or any of the four main studies.

1.2 Materials

The materials used in the two tasks were the same as those in the main Study 3 (see Chapter 10) and as those used in the main Study 4 (see Chapter 11) respectively.

1.3 Design

The conditions for the two tasks were the same as in the main Study 3 (see Chapter 10) and as in the main Study 4 (see Chapter 11) respectively. One half of the children – two from each age group, one girl and one boy – performed the Study 3 task first and then the Study 4 task a few days later. The other half of the children performed the Study 4 task first and then the Study 3 task a few days later.

1.4 Procedure

The procedure and the instructions for the two tasks were the same as in the main Study 3 (see Chapter 10) and as in the main Study 4 (see Chapter 11) respectively.

2. Results

2.1 Methods of analysis

Analyses were conducted on two levels. On the first level, the additional sample children's responses to the Study 3 task were compared with each other, that is, the mean scores for children who performed the Study 3 task first were compared with the mean scores for children who performed the Study 3 task second. The same analyses were conducted for the Study 4 task. On the second level, the additional sample children's overall responses to the Study 3 task were compared with those of the main Study 3 sample, and the additional sample children's overall responses to the Study 4 task were compared with those of the main Study 4 sample. All analyses of mean score comparisons involved Mann-Whitney tests. Effects of gender were analysed with Mann-Whitney tests, and effects of conditions were analysed with Kruskal-Wallis tests and post hoc Jonckheere-Terpstra tests. No significant gender or condition effects were found, therefore these are not considered further. All data were analysed using PASW (Predictive Analytics Software, formerly SPSS) Statistics version 18.

2.2 Study 3 task

2.2.1 Mean scores

No significant differences for any of the mean scores for the Study 3 task were observed between the children who performed the Study 3 task first and the children who performed the Study 4 task first. This was the case for speed predictions, for speed change predictions, and for incline height comparison predictions.

2.2.2 Response times

No significant differences for any of the mean response times for the Study 3 task were observed between children who performed the Study 3 task first and those who performed the Study 4 task first.

2.3 Study 4 task

2.3.1 Judgements

No significant differences for any of the mean judgement scores for the Study 4 task were observed between children who performed the Study 4 task first and those who performed the Study 3 task first.

2.3.2 Response times

No significant differences for any of the mean response times for the Study 3 task were observed between children who performed the Study 4 task first and those who performed the Study 3 task first.

2.4 Additional sample versus main sample

2.4.1 Study 3 task

No significant differences for any of the mean scores for the Study 3 task were observed between the additional sample children and the main sample children. This was the case for speed predictions, for speed change predictions, and for incline height change predictions. Response times did not differ significantly between the two groups either.

2.4.1 Study 4 task

No significant differences for any of the mean scores for the Study 4 task were observed between the additional sample children and the main sample children. This was the case for speed predictions, for speed change predictions, and for incline height change predictions. Response times did not differ significantly between the two groups either.

3. Summary

The results suggest that repeated testing of the same children had no effect on mean scores, both for explicit predictions (Study 3 task) and for tacit judgements (Study 4 task). The results for children who performed either task first did not differ significantly from those for children who performed either task second. This also indicates that the order of presentation of tasks had no significant effect on scores either. The results obtained here further indicate that the Study 3 main sample results were not affected by having done Study 2 previously. The children in the additional sample, who had not done the Study 2 task at all, did not differ significantly from the main Study 3 sample in their mean scores for the Study 3 task. The results further imply that the main Study 4 sample judgements were not affected by exposure to prior tasks. The children in the additional sample did not differ significantly from the main Study 4 sample in their mean judgement scores for the Study 4 task. This was even the case if they performed the Study 4 task prior to the Study 3 task, therefore not having been exposed to any other tasks beforehand. It can therefore be assumed that any results obtained in the main studies were not affected by repeated testing or by order of tasks.

A7 Debrief information

Research on children's science

Dear _____,

I would like to take this opportunity to thank _____ School for helping me with my PhD research. Please find attached a summary of the work. If you or any other teachers or parents have any questions, feel free to contact me at mh530@cam.ac.uk or at the Faculty of Education (see footer for address).

Many thanks

Michael Hast

Young children's explicit and tacit understanding of object motion
Research summary

There seems to be much agreement in the research literature that children do not start school as blank slates, but that they bring with them ideas about how the world works (based on their experiences, on what they learn from their parents etc.). The problem in many areas of science is that the ideas children have beforehand do not comply with accepted scientific views and therefore, in the course of education, the children's beliefs need to be altered appropriately. In some subjects this seems to be easier to do, for example in chemistry or biology. But in physics, especially in dynamics, this is not the case, because children do have so much experience with the outside world, from the day they are born, and so their ideas are held very firmly.

My work was interested in exploring primary school children's beliefs about speed and acceleration of objects, and whether there are other ways of assessing their understanding. For this purpose, a distinction can be made between two kinds of knowledge. Explicit knowledge is the kind of knowledge that can be expressed verbally or in writing. Tacit knowledge, on the other hand, is a kind of knowledge that cannot be assessed through asking questions but it can be expressed in actions. For example, knowing how to ride a bicycle is tacit knowledge – you might know *how* to ride a bicycle, but you don't necessarily know *why* you can ride it or *what* exactly makes the bicycle move (because you may not know all the physical principles involved in making the bicycle move forward). I looked at children's explicit beliefs in three studies and compared it with their tacit understanding in a fourth study.

Study 1

In the first study I showed children a range of everyday objects and paired them together. The children had to make predictions about motion along a horizontal, down an incline, and in free fall, and they had to justify their answers. For example, they were shown a feather and a hammer and were asked whether one of the two would fall faster, or whether they would both fall as fast as each other. I was not interested in their choices, only in their justifications, and found that children used a range of justifications – weight, size, shape, texture, any other reasons – and that the use of justifications varied across ages and motion types. Younger children appeared to rely more on size than older children, and less on weight. When used as a justification, faster speed was, perhaps not unsurprisingly, almost always associated with roundness and smoothness of objects. In free fall, children mainly associated faster motion with heavier and bigger objects across all ages. Horizontal motion, on the other hand, was associated with lighter and smaller objects, again consistently across all ages. But while younger children predicted faster incline motion for lighter and smaller objects, older children predicted faster motion for heavier and bigger objects.

Study 2

In the second study I decided to further investigate the findings from Study 1 but using a more 'scientific' set-up. There were two balls – a heavy ball and a light ball – of similar sizes, and a tube. Consistent with Study 1, faster horizontal motion was usually associated with the

lighter ball, and faster motion in free fall was usually associated with the heavier ball. Faster incline motion predictions, on the other hand, changed with age. Younger children predicted faster motion for the lighter ball and older children for the heavier ball. This suggests that even though the changes go from one incorrect view to another incorrect view, there is little resistance to change in beliefs within the total age range. Concerning acceleration, children generally seemed to appreciate that there must be a change in speed between a starting point and any subsequent point. However, they did not always appreciate that there would be changes between two points when the balls were moving at both points. But in order to appreciate the naturalness of motion, children will need to understand that objects accelerate (or decelerate).

Study 3

Given the fairly extensive use and the recognised benefits of ICT in primary school teaching, the third study was a replication of Study 2 but using a computer. The children were shown pictures on a computer screen and they were given prediction options to choose from. The results of this study all show very similar results to those of Study 2. Even when all options were presented to children, including the correct one, children still made choices consistent with their predictions in Study 2.

Study 4

The fourth study, then, was concerned with trying to discover whether children are able to identify correct motion scenarios, even when these are different from their beliefs that they have shown in Studies 2 and 3. The children were shown short video clips where the balls were moving, either correctly or incorrectly. Over 75 per cent of same-speed trials were judged to be correct, whereas only just over 25 per cent of the different-speed trials were judged to be correct. Children can also seemingly identify inappropriate scenarios almost instantly; trials that are neither correct nor match their explicit beliefs (i.e. when the heavy ball is faster along the horizontal, or when the light ball is faster in free fall). Despite some unresolved questions it is clear that there is a mismatch between explicit reasoning and tacit judgement, with children recognising naturalness of motion.

Conclusion

Whether making use of tacit knowledge can facilitate change of beliefs in early science cannot be assumed on the basis of the current results alone, as no intervention study was conducted. The current work has merely looked at distinguishing explicit reasoning from tacit judgements in primary school children. Can tacit knowledge modify their existing explicit beliefs? The current research cannot offer any conclusive support, neither in favour of successful changes nor against it. However, what it does do is offer suggestions for the construction of conceptual change programmes.