Scientific enquiry. The nature and place of experimentation: a review
Investigación científica. La naturaleza y el papel del experimento en clases: una revisión

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Abstract

Most school syllabuses, even those for primary stages, specify aims that relate to the use of experimental work in gaining evidence. It can be argued that this is a key aspect of the nature and role of science. Nonetheless, evidence that such aims are attainable is sparse. Indeed, there is little evidence that such aims are actively required by teachers and they are rarely the focus of assessment. The skills are explored and evidence is discussed that suggests that such aims might be difficult to attain with younger secondary school pupils simply on grounds of cognitive development.

Key words: *Empirical, critical experiment, developmental levels, role of experimental, scientific thinking, scientific literacy.*

Resumen

La mayoría de currículos de la escuela, incluso para etapas iniciales de estudio, especifica los objetivos del uso del trabajo experimental para adquirir pruebas. Se puede argumentar que éste es un aspecto clave de la naturaleza y el papel de la ciencia. No obstante, las pruebas de que tales objetivos son alcanzables, son escasas, porque hay pocas pruebas de que tales datos son activamente pedidos por profesores y que raramente son la base de la valoración de los conocimientos. Estas habilidades son exploradas y discutidas y muestran que tales objetivos podrían ser difíciles de lograr en alumnos de escuela secundaria, sólo sobre los fundamentos del desarrollo cognitivo.

Palabras clave: *experimento empírico, crítico, niveles del desarrollo, papel del experimento, pensamiento científico, alfabetización científica.*

SCIENCE AND ENQUIRY

OSBORNE and COLLINS (2000, p. 23) pose a fundamental question when they ask,

> "What kind of scientific knowledge, skills or understanding do they (pupils) think they need for dealing with everyday life?"

In England, they showed that pupils found chemistry, as an aspect of science, uninteresting, with most of the content as unrelated to their everyday life. They suggested that the concentration on theoretical aspects appeared *"to too many pupils to be abstruse and far removed from their daily concerns"* (*ibid*., p. 25).

GRAY (1999) considered similar questions looking particularly at the developing world countries. According to GRAY, there has been a noticeable decline in the quality of science education in most developing world countries in the past few decades. He attributed this development to the fact that, historically, the structure and the nature of science curricula in the developing world countries has followed that of their colonial forebears despite the great differences in their needs.

Perhaps science education at school for all can be regarded as meeting three main needs:

1. Science as a *method of enquiry*: it seeks answers to questions by experimentation.
2. Science as *culture*: young people need to know the place of science in our society.
3. Science as a *body of knowledge*: some of the outcomes of science are important.

The relative weighting of these will vary according to age and sector (primary, secondary, tertiary) of education. At the moment, science syllabuses (and textbooks) tend to be designed around:

a) The logic and content of the science discipline;
b) The needs of minorities (what is needed for those who go further);
c) What worked in the past;

What tends to be ignored is:

i) The cultural side of science;
ii) Science as enquiry;
iii) The needs of majorities (those who do not go further);
iv) The psychology of the learners.

Science as a method of enquiry is the focus of the discussion here.

THE NATURE OF SCIENCE

LINSAY (1963) has argued that science, as a method that is used to describe human experience, involves firstly defining the problem clearly and accurately. Secondly, it involves designing experiments, considered the most important element in science as a method. SIZMUR and ASHBY (1997) emphasized the purpose of science as being the development of ways to conceptualize, understand and, perhaps, control the world.

The Scottish Consultative Council on the Curriculum (SCCC) Science Review Group (1994 - 1996) stated that science is "a distinct form of creative human activity which involves one way of seeing, exploring and understanding reality".

This is rather vague but points to investigation based on empiricism. Empiricism is the key to the scientific method of enquiry and this implies experimental work, perhaps in a laboratory.

> "Real laboratories for science and science instruction exist almost anywhere. Classical science almost anywhere begins outside, in nature. As knowledge and ideas grow, many are brought inside, for controlled investigation, analysis and discussion. So it should be for students." (PENICK and YAGER, 1986, p. 5).

According to this view school science laboratories should be places where students go to test the validity of their already existing explanations of objects, events, and ideas they encounter in their everyday life. It is the hope of PENICK and YAGER that through this approach a new breed of citizen will be produced, who no longer perceive science as "(...) an enigma to be avoided", but "(...) a mystery, rich in adventure and excitement waiting to be explored, understood and used".

The Science Curriculum Development Committee (SCDC, 1987), reporting on a two phase science curriculum review project (1981-1986) for England, Wales and Northern Ireland suggests two types of approaches:

1) learning to work as scientists or problem solving, that is, investigating phenomena in a systematic way and finding solutions to scientific problems,

2) relating science to out-of-school context through investigations of socially related problems or concerns.

Figure 1 is an illustration of a simplified version of what actually happens in a problem solving situation. The scientific process usually is more complex than this.

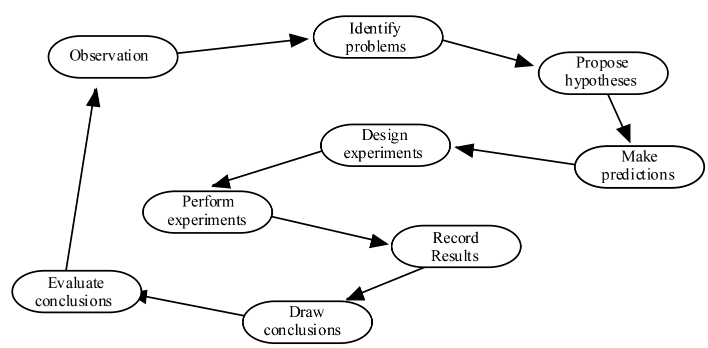

FIGURE 1. Basic Steps of the Scientific Process adapted from YIP *et al*., 1998, quoted in AL-SHUAILI, 2000

EMPIRICISM AND SCIENTIFIC LITERACY

Empiricism became the 'touchstone' in differentiating science and 'non-science' during the Enlightenment period in European history. The idea of using observable data to verify a theory dominated the human ways of understanding nature and natural phenomena from then onward. The success of science in explaining and predicting the natural world, thereafter, could not be ignored by educators. The study of science at that time strongly focused on the need to *understand* nature through the scientific method.

The empirical studies of nature, believed to have been pioneered by Sir Francis Bacon (1561-1626), inspired some educators to want to teach a science that will "(...) put the records straight concerning human experiences of the world for the benefit of future generations" (Cowley, 1661). However, there was little formal education at the time, and no science education in the whole of Europe. Public school education in England and Wales, during the time of Cowley, did not exist. In Scotland, however, many schools did exist for public access from the late seventeenth century (Cockburn, 2002). However, the place of formal science developed very slowly. It was not until the late 19th and early 20th century that the teaching of science with a strong empirical dimensions started to take hold (Armstrong, 1925).

In England and Wales, limitations found in courses led to new science courses like the Nuffield Science courses of the 1960s (Kerr, 1966; Jenkins, 2001). Nuffield Science courses were primarily concerned with teaching science as a process of enquiry (Kerr, 1966) rather than a body of information or content to master (Solomon, 2001). Adey (2001) pointed out that guided discovery or the enquiry process lacked evidence to validate its legitimacy as an effective method of teaching science. Indeed, Nuffield was much less effective than expected (Jenkins, 2001) and was costly in terms of facilities and equipment as well as teacher training.

The Scottish developments did not reflect Nuffield developments in terms of the strong emphasis on scientific processes. Nonetheless, the Scottish curriculum involved large amounts of pupil practical work and this tended to be based on a general principle of guided discovery. The Scottish syllabuses proved to be highly successful and were maintained, with repeated minor revisions, until the curriculum changes of the early 1990s. Nonetheless, the laboratory work was largely used to *illustrate* ideas taught rather than as an opportunity to develop scientific thinking.

Scientific literacy as an idea started to emerge, being defined in a variety of ways (eg. Jenkins, 1990; Hazen and Trefil, 1990; Solomon, 2001; Ryder, 2001). According to Hazen and Trefil, scientific literacy should enable one to understand everyday instances as they relate to science and vice versa. Solomon (2001) suggested that scientific literacy emphasizes five major outcomes. However, neither Hazen and Trefil nor Solomon laid much emphasis on the method of science. Indeed, Hazen and Trefil (1990) presented scientific literacy in terms of public issues, understanding the few general laws of nature, and an appreciation of scientific knowledge as a trend setter of human thinking. Scientific findings influence change in human thinking and eventually the thinking context of other subjects areas (Layton, 1995).

In Scotland, justifying the commitment towards developing new science knowledge and skills, Seed (1999) stated that:

> "All young people, not just those intending to follow careers in science, must be scientifically literate. They need to have a good knowledge and understanding of science and scientific ways of thinking in order to function effectively in a global and evolving technological society." (p. 2)

Although much of this similarly emphasizes knowledge and appreciation, there is a mention of 'scientific ways of thinking' although these are not defined. Generally, the emphasis is on the need for people to attain some basic understanding of science and its implications to everyday situations.

It is argued (Hadden and Johnstone, 1983; Hodson, 1990; Woolnough, 1991; Osbourne, 1997) that, through practical work, learners get the opportunity to work in groups, engage in a thinking process of discussion, compare their ideas to those advanced by other pupils and eventually develop a critical mind. However, most laboratory courses pay lip service to the development of such skills.

EMPIRICISM AND LABORATORY WORK

Osborne (1997) notes a decline in positive attitudes to laboratory work at school level and attributes this to the failure on the part of science educators and policy makers to differentiate between 'doing science' and 'learning science'. Doing science refers to practical activities meant to "... discover and establish new knowledge of natural and living world". On the other hand, learning science involves a number of learning strategies of which practical work is a part. These views by Osborne are reinforced by Hodson (1990), who makes an observation that practical work as conducted in schools does not "(...) engage them (pupils) in 'doing science', in any meaningful sense".

In Scotland, policy documents refer to the scientific process of enquiry (Soed, 1994, p. 6) but do not deal with how school science teaching should be organized and conducted in order for it to achieve this kind of aim? Indeed, is it achievable? It is asserted that meaningful science involves pupils actively investigating everyday problems using the scientific approach (SCDC, 1987; SCCC, 1996; Seed, 1999). This includes identifying and defining a problem, making hypotheses and deciding on variables to be manipulated, planning and setting up experiments to collect data, analyzing the data and making conclusions. The question to be answered here is whether pupils, at early secondary stages, have developed cognitive strategies that can enable them to plan and carry out experiments capable of providing a tenable solution to a scientific investigation.

There are questions about what scientific skills should be taught and at what stages as well as the possible methods to develop such skills. Of even greater importance is the question about the stage in a child's cognitive development when such skills can be developed. Millar talks about science that "(...) involves acts of 'showing' and 'telling" (Millar, 1998). On the whole, practical work, which is primarily the 'showing' aspect of science teaching and learning, is considered an essential mode of instruction in the teaching of school science (Woolnough and Allsop, 1985; Woolnough, 1991; Tamir, 1991; Millar, 1998).

Does the kind of practical experiences provided in school science result in the acquisition of desirable scientific skills? The educational effectiveness of practical work has always been questioned in some developed countries, countries which are normally characterized by good supplies of laboratory facilities, sizeable amount of time allotted for practical activities, enough staff for teaching and technical assistance in laboratories, small class sizes and adequate inclusion of assessment of practical skills by the examination systems (Woolnough, 1991; Wellington *et al*., 1994). Lack of these factors is assumed, particularly in developing countries, to be the cause of failure by planned practical activities in school science to fulfill their purposes (Zesaguli, 1988; Prophet, 1988). In fact, the ineffectiveness of practical work is to a large extent associated with the nature of the practical activity planned for the lesson (Osborne, 1997).

Based on a series of investigations conducted in schools and tertiary institutions in Scotland, it was found that the emphasis on doing "(...) much practical work does not transmit to students the outcomes intended by the designers." (Johnstone and Wham, 1982). The greatest learning occurs when there is a combination of formal skills teaching and miniature projects which place demands on students to design and conduct "their own experiments using the skills taught" (Johnstone and Wham, 1982).

In a recent study (Shah, 2004), 229 first year university students in chemistry were offered eight possible reasons for undertaking laboratory work in chemistry courses. They were asked to select the three which they considered most important. It is worth noting that the two reasons they considered most important were related to 'illustrating theory' and 'experimental skills'. The idea of laboratories being places where 'ideas can be tested' was seventh out of the 8 reasons offered to them. Clearly, this group, early in their university career, and arguably drawn from the more able school population, had not grasped the strong importance of the empirical approach as a key feature of their science education and did not see laboratories as a place where that approach might be developed. This will largely reflect their school experience in a context where school chemistry has a large and well developed laboratory component.

Research evidence demonstrates that equipping teachers with more skills for handling practical work in schools, on its own, simply does very little in ensuring a more authentic presentation of science practice (Matthews, 1994). Even a positive attitude towards scientific inquiry is not an assurance that such a teacher will consistently plan practical work in accordance with his/her views (Hodson, 1998). The immediate need to cover much of the syllabus content, to drill pupils to pass the examinations (Nott, 1997 quoted in Hodson, 1998) and general lack of control on the curriculum by the teacher simply dictate the purpose of practical activity planned.

Woolnough and Allsop (1985) challenge the notion that practical work done in school science can be equated to real scientific investigation. They acknowledge that indeed practical work in school science is practical in its nature, but question its authenticity as a science. Jenkins (1998) captures this doubt beautifully when he says that, "the theory was announced and then practical illustrations were paraded in its honour".

The first years of secondary school science education are perceived by many curriculum designers and educators as suitable for orientation of pupils into the science world (National Commission on Education, 1993; Science Council of Canada, 1984; SCCC, 1996; SEED, 1999) but can this involve the methods of science?

The SEED (1999) reports that experimental work in most schools visited still takes on the form of the 'cook book recipe' approach.

> "Pupils were given too few opportunities to develop skills of investigating, including planning, collecting evidence, recording and presenting and interpreting and evaluating." (SEED, 1999, p. 14).

However, how do teachers do this when current pressures almost seem to preclude it?

There are, perhaps, two main issues here. Firstly, given the pressures arising from overcrowded curricula and assessment demands, teachers simply have enormous difficulty in making their laboratories places of genuine enquiry. Secondly, even if teachers have the time and inclination, is the development of scientific enquiry *possible* for pupils in secondary education? Are pupils *cognitively* equipped to handle the abstract reasoning that scientific enquiry requires?

STAGES OF COGNITIVE DEVELOPMENT

PIAGET's asserted that intellectual growth or cognitive development is a logical series of successive equilibrations of schemata and that each schema is constructed from the existing one (FLAVELL, 1963). PIAGET identified three kinds of knowledge constructed by individuals through their continued interaction with the environment: physical knowledge, logic-mathematical knowledge and social knowledge (WADSWORTH, 1978; GALLAGHER and REID, 1981; WADSWORTH, 1989).

It has been observed in real life that some people have unique natural abilities to construct 'reliable' knowledge of reality without interacting with all of its aspects. This unique human characteristic has been associated mostly with scientists and engineers. One of the advocates of this notion is WHEATLEY who argues that "objects do not lie around ready made in the world but are mental constructs" (WHEATLEY, 1991).

The stage of concrete operations (7-11 years) is characterized by the development of the ability to apply logical thinking to concrete problems. However, the reasoning is still not perfect. The stage of formal (logical) operations ($11\text{-}15^{+}$) is characterized by the child's ability to handle abstract logic which is not restricted to the concrete world. According to WADSWORTH (1989), the reasoning at this stage is "content free and concrete free". The young person at this stage develops several cognitive structures which enables him or her to reason about the possible and the real world, deduce conclusions from hypothetical premises, reason from the specific to the general and derive new knowledge from existing knowledge through reflective thinking (PIAGET, 1967). While it has been argued, however, that not all adolescents and adults develop formal operations fully (GALLAGHER and REID, 1981), PIAGET insisted that more or less all have the *potential* to develop formal operations fully (PIAGET, 1967). BROWN and DESFORGES report on several studies casting doubt on the correlation between formal operational thinking and the developmental stages associated with it in line with Piagetian thinking.

Furthermore, PIAGET is said to attribute an insufficient role to the teacher, parent and peer since it stresses more the role of the individual in the process of knowledge construction (BLISS, 1995). This view is shared by many other psychologists who now consider the theories advanced by Vygotsky, AUSUBEL and BRUNER much more relevant to contemporary learning and teaching (LOVELL, 1974; KUBLI, 1979; ROWELL, 1984; BLISS, 1995). Nonetheless, although a majority of the psychologists and educators note some of the inadequacies in PIAGET's theory on cognitive development, they still regard his views as fundamental to modern day teaching and learning.

In response to BRUNER's ideas on discovery learning (BRUNER, 1966), many countries introduced a spiral system of curriculum design and an emphasis on group work (BLISS, 1995). In the 1960s, for example, the Scottish science curriculum involved extensive practical work which was apparently based on a general principle of guided discovery.

BRUNER's influence in the design of science curriculum has been on the emphasis to use guided discovery learning as a general method of teaching. AUSUBEL (1968) on the other hand, believes that people acquire knowledge primarily through reception. He advocates a more organized presentation of concepts instead of discovery.

AUSUBEL (1968) notes that, under normal conditions of didactic teaching in schools, the pupils are not engaged in any tenable independent discovery learning since all they need to know about the material to be learned is given to them by the teacher. An assessment of this way of acquiring knowledge requires that pupils have to recall only that which they have been taught in the specified lesson.

AUSUBEL's model is considered by many educators more sensible and consistent with what is mostly happening in reality (eg. TOULMIN, 1972; ENNIS, 1975; NOVAK, 1978; JOHNSTONE and MOYNIHAN, 1985; JOHNSTONE, 1987). On the other hand, ENNIS (1975) and TOULMIN (1972) are convinced that PIAGET's concept of cognitive stages presents some serious problems in as far as explaining the performance of both young children and adults on abstract and concrete reasoning is concerned.

IS COGNITIVE ACCELERATION POSSIBLE?

A look at the developmental psychology of young adolescents would certainly suggest that, at the early stages of secondary education, pupils may not be cognitively equipped to handle scientific reasoning. The ideas of hypothesis formation, planning and developing experimental situations to test such hypotheses and the concept of the critical experiment results from which offer clear evidence related to an hypothesis are all highly abstract ideas. Nonetheless, there might exist the possibility that pupils could be taught in such a way that such skills might be developed.

Cognitive Acceleration through Science Education (CASE) is a new teaching approach developed out of research into cognitive development based primarily on the works of JEAN PIAGET and encompassing some of the main principles of Lev Semyonovich Vygotsky's theories of learning (ADEY, 1999). The principal focus of the programme is to improve children's thinking processes by accelerating progress towards high-order thinking skills (SHAYER, 1999; ADEY, 1999).

One major aspect of human behaviour that PIAGET's model of cognitive development failed to address is the asynchronous appearances of variations of the same cognitive structure (*horizontal decalage)*: passing and failing tasks of the same logical structure. Neo-Piagetians have realised that knowledge construction is domain specific rather than dependent on the general operational schemes proposed by PIAGET (CASE, 1974a; PASCUAL-LEONE, 1974; SCARDAMALIA, 1977; CAREY, 1985; KEIL, 1986). Even highly educated adults perform badly on tasks involving abstract hypothetical thinking.

SCARDAMALIA (1977) indicates that the information processing demand of the task presented to the learner forms a significant aspect of the phenomenon of horizontal decalage. Numerous versions of the information processing models have been proposed to explain cognition (eg. JOHNSTONE, 1993; CHILD, 1993; ASHCRAFT, 1994). Studies by PASCUAL-LEONE (1974) and CASE (1974a) have provided a basis for the development of the information processing models proposed in the past 30 years.

COGNITIVE ACCELERATION AND INFORMATION PROCESSING

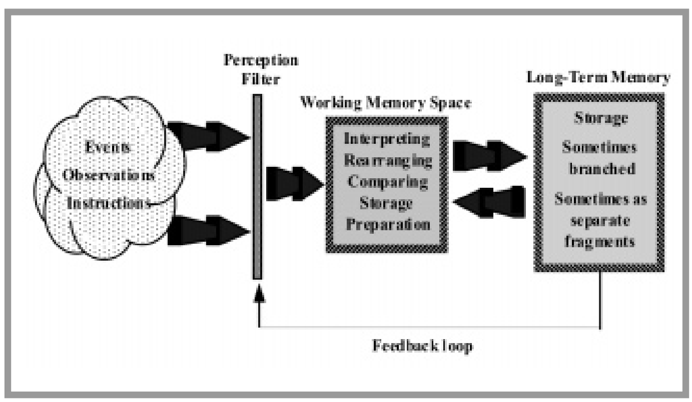

FIGURE 2. An Information Processing Model (after JOHNSTONE, 1993)

According to JOHNSTONE (1993), the sensory memory receives events, observations, and instructions through the influence of the long-term memory. The long-term memory provides a mechanism through which the sensory memory or the 'perception filter' selects information. BOURNE *et al.* (1986) suggest that, for any event, observation, or instruction to have meaning and to be retained beyond simple sensory, it must be recognized and encoded through processes of pattern recognition and pattern encoding.

One significant nature of the working memory is its delicateness, symbolized by a rapid decay of the input whenever a learner's attention is diverted from what is to be remembered (BRUNING *et al*., 1995). The other limitation of the working memory described by BRUNING *et al*. relates to its capacity, observed to be limited to only a few chunks of information.

Working memory is considered by most researchers as the part of information processing that people are conscious of at any given moment (BOURNE *et al*., 1986). It is the active part of the memory holding information that has just been encoded and some which has been retrieved from the long-term memory stores. JOHNSTONE (1993) presents a model of information processing that depict short-term memory as having the function of interpreting, rearranging, comparing, storing and preparing for durability. He acknowledges the active nature of the working memory and calls it the 'working memory space'.

The measure of how many pieces of information an individual can retain in a given time and be able to recall accurately is believed to be the brain child of Sir WILLIAM HAMILTON (MILLER, 1956). According to MILLER, HAMILTON made the proposition following his experiment with a handful of marbles. From the experiment, he concluded that, if one throws a handful of marbles on the floor, one would realize that it is difficult to "view at once" (MILLER, 1956) more than six or at most seven marbles without getting confused.

Subsequent studies of the mental capacity do confirm HAMILTON's speculation. The digit span is said to be the number of digits individuals can recall when given a series of them (BRUNING *et al*., 1995). MILLER in 1956 showed that the average capacity or the span of the short-term memory of an adult person is equal to seven plus or minus two items. Anything above this incurs errors during recall (MILLER, 1956).

The working memory is defined by BADDELEY (1986) as a system that holds information temporarily and manipulates it during some cognitive activities that include comprehending, learning and reasoning. A problem solving situation which requires the learner to manipulate tasks less than the working memory span is perceived easy to do by the learner. If the tasks are more than the working memory capacity can handle, then specific strategies ought to be use to rearrange the tasks into manageable chunks. JOHNSTONE and WHAM (1982) demonstrated that when students are presented with a quantity of information containing the number of units beyond their working memory capacity, the students gradually lose concentration and attain what they referred to as the "state of unstable overload".

It is clear that the number of units of information the individual can handle and manipulate at a time in order to produce the correct response is dependent on the individual's cognitive stage, which is a function of maturity (ie. developmental). SHAYER and ADEY (2002), on the other hand, are concerned with the belief that people's cognitive abilities can be increased beyond their developmental stage. However, their theory has been unsuccessful in resolving the issue of *why* the strategic learning is inapplicable to other individuals. Also, individuals employ different strategies to arrive at the same solution.

The information processing models can be used to explain *why* PIAGET's developmental stages happen. Through the information processing models, it may also be possible to explain why cognitive acceleration through strategic learning is possible. Perhaps cognitive acceleration is offering pupils enhanced ways of chunking and, therefore, using a limited working memory more efficiently.

The worldwide desire by science educators and policy makers to promote scientific literacy is central to the search for effective approaches required for teaching and learning science in schools. Emphasis by some curricula to engage pupils at lower secondary school levels in pupil-planned and pupil-designed investigations raises some concerns about the cognitive ability of those pupils to handle such exercises and produce expected outcomes.

FINAL THOUGHTS

Curriculum planners have, from time to time, added in aims related to scientific reasoning and, in particular to the place of the empirical as a method for gaining evidence related to hypotheses. The suggestion appears to be that pupils should be taught how to hypothesize and plan and conduct experiments which test these hypotheses. In other words, their laboratory experience should introduce to them the empirical approach as a method for gaining answers.

From the review of the literature, it is clear that there is little or no emphasis on this approach in schools. Curricula are overcrowded and no assessment 'reward' is offered for success in this area. Indeed, the way experimental work is often prescribed and seen as illustrative more or less precludes its use in developing scientific thinking.

Of greater concern, there has to be considerable doubt if scientific thinking skills are attainable at early secondary stages of education and it is most unlikely that they can be attained at primary stages. The latter makes the aims of the Scottish 5-14 document highly unrealistic (SEED, 1999). Indeed, the observations by SHAH (2004) would seem to suggest that few (drawn from the more able pupils) have grasped such aims as a part of their school laboratory experiences.

The development of such skills may be a great importance in developing a scientifically literate society. They are rarely assessed in typical school examinations and are not part of the assessment procedures for typical university laboratory courses, with no incentive for teachers to place much emphasis on such outcomes even if they had the time to do so in overcrowded curricula.

However, the cognitive development of pupils may the ***critical issue*** and this is an area where empirical evidence is much needed. The aims of school syllabuses must reflect not only what is possible in terms of time and resources but also reflect what is possible in terms of the cognitive development of pupils. Teaching the nature and place of experimentation may be highly desirable. Is it cognitively possible?

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