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The role of practical work in science education

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> According to Plato, the world can be divided into the abstract world of ideas or thoughts and the concrete world of physical realities. He was not very successful in finding connections and relations between these two worlds. What Plato had forgotten was to include the laboratory, the missing link between the abstract world of thought and the concrete world of physical realities. The role of the laboratory is to connect the two worlds together. (Brodin, 1978, p. 4)

1.1 Introduction

Science education differs from almost all other subjects taught in school in that it involves practical lessons that are, generally speaking, undertaken in specifically designed and, in many cases, purpose built laboratories (White, 1988). We use the term ‘practical lesson’ to mean any lesson in which the students are involved in manipulating and/or observing real (as opposed to virtual) objects and materials, and it is this manipulation and observation that we will refer to as ‘practical work’. Practical work in this sense is a broad category that includes, for example, ‘recipe’ (Clackson & Wright, 1992) style tasks (sometimes referred to as ‘cook-book’ tasks), experiments, investigations and discovery style tasks. In characterizing such activities *not* on the basis of where they are undertaken but on what is undertaken, it seems more appropriate to refer to them as ‘practical work’, rather than ‘laboratory work’ (or ‘labwork’). That said, we recognize that in many countries, including England, most secondary school science practical work is undertaken in laboratories and so most of what we refer to as ‘practical work’ can also be thought of as being ‘laboratory work’.

1.2 Previous studies into the role of practical work

In 1960 Kerr undertook the first extensive survey in order to inquire into the nature and purpose of practical work within the framework of the teaching of biology, chemistry and physics within grammar schools in England and Wales. The findings, which basically involved the teachers arranging ten suggested aims (purposes) for practical work in order of their perceived importance, are summarized in Table 1.1.

Table 1.1 Teachers' ten suggested aims (purposes) for practical work in order of their perceived importance (from Kerr, 1964, p. 27)

Pooled order of importance of aims of practical work

Ten aims of practical work	Teachers' rank ordering, 1 being most important Biology–B Chemistry–C Physics–P								
	Ages 11–14			Ages 15–16			Ages 17–18		
	B	C	P	B	C	P	B	C	P
To encourage accurate observation and careful recording	2	2	5	1	1	4	1	1	1
To promote simple, common-sense, scientific methods of thought	4	4	4	3	2	3	4	4	4
To develop manipulative skills	8	7	7	9	8	8	5	5	6
To give training in problem solving	9	9	9	8	9	9	9	7	8
To fit the requirements of practical examination regulations	10	10	10	10	10	10	8	8	10
To elucidate the theoretical work so as to aid comprehension	6	6	6	4	4	2	2	2	2
To verify facts and principle already taught	7	8	8	7	7	7	7	6	5
To be an integral part of the process of finding facts by investigation and arriving at principles	5	5	3	6	3	1	3	3	3
To arouse and maintain interest in the subject	1	1	1	5	5	5	10	10	9
To make physical phenomena more real through actual experience	3	3	2	2	6	6	6	9	7

While a direct comparison between the findings of Kerr (1964) and a subsequent study by Beatty (1980) (students aged 11–13 in England and Wales) is not possible since the latter study used an expanded list of twenty aims, a cautious comparison between the two studies can be made by comparing the order of importance of only those aims proposed by Kerr (1964) that are common to both studies. Bennett (2003) has suggested that despite a certain degree of variation between the studies in terms of teachers, subjects and student ages, there is a general consensus that most teachers perceived the most important aims of practical work as being:

- to encourage accurate observation and description;
- to make scientific phenomena more real;
- to enhance understanding of scientific ideas;
- to arouse and maintain interest (particularly in younger pupils);
- to promote a scientific method of thought.

(Bennett, 2003, pp. 78–79)

While other alternative lists have been proposed (Hodson, 1990; Kerr, 1964; Thompson, 1975; Woolnough & Beatty, 1980), they frequently share the same, or broadly similar, generic aims. Hodson (1990), for example, suggests that there are five primary aims for practical work:

- to motivate, by stimulating interest and enjoyment;
- to teach laboratory skills;
- to enhance the learning of scientific knowledge;
- to give insight into scientific method, and develop expertise in using it;
- to develop certain ‘scientific attitudes’, such as open-mindedness, objectivity and willingness to suspend judgement.

(Hodson, 1990, pp. 30–33)

While the lists proposed by Hodson (1990) and Bennett (2003) are not identical, they are, broadly speaking, similar and while accepting the arbitrary nature of any particular list, that proposed by Hodson (1990) provides a useful framework within which to consider the justifications for the use of practical work.

1.3 Five generic aims for the use of practical work

Despite the aspirations and expectations of those who advocate a central role for practical work in the teaching of science, the limited research that has been undertaken in this area has found it to be, as commonly used, no more effective in achieving *most* of these generic aims than other non-practical methods of teaching. It is to that research, and its implications for the five generic aims suggested by Hodson (1990), that we now turn.

1.4 The role of practical work in enhancing the learning of scientific knowledge

Research findings into the role of practical work in enhancing the development of conceptual understanding is, at best, ambiguous. For example, while Hewson and Hewson (1983) report a significant enhancement of conceptual understanding amongst students who had received a primarily practical-based instruction, compared to those who received a traditional, non-practical instruction, Mulopo and Fowler (1987) reported no significant difference in the level of conceptual understanding amongst students whether they had been taught using practical or traditional, non-practical methods. Indeed, Mulopo and Fowler report that the most significant factor in determining the extent of conceptual development was not the method of instruction but rather the student's level of intellectual development.

Indeed, reviews relating specifically to practical work (Chang & Lederman, 1994; Hofstein & Lunetta, 1982; Lazarowitz & Tamir, 1994; Watson et al., 1995) have shown that when outcomes are measured using pen and paper tests, the use of practical work offers no significant advantage in the development of students' scientific conceptual understanding. Given the central role of the laboratory, its high financial cost and the high aspirations that many teachers have regarding its value, such non-significant findings are disappointing if the development of conceptual understanding is seen as a prime function of practical work. Clackson and Wright (1992), rather negatively, suggest that:

> Although practical work is commonly considered to be invaluable in science teaching, research shows that it is not necessarily so valuable in science *learning*. The evidence points to the uncomfortable conclusion that much laboratory work has been of little benefit in helping pupils and students understand concepts. (p. 40)

Yager et al. (1969) argue that some academically able students may in fact consider laboratory work to be wasteful of their time, serving only to delay their pursuit of new theories and concepts. In contrast, Van den Berg and Giddings (1992) argue that such beliefs, if held by the students, would be a criticism of the form of specific practical tasks rather than constituting a criticism of practical work per se.

However, these findings seem, generally speaking, to reinforce Ausubel's (1968) assertion that 'In dividing the labour of scientific instruction, the laboratory typically carries the burden of conveying the method and the spirit of science whereas the textbook and teachers assume the burden of transmitting subject matter and content' (p. 346).

Hodson (1992) has claimed that it is necessary to introduce students to the relevant scientific concepts *prior* to their undertaking any practical work if the task is to be effective as a means of enhancing the development of their conceptual understanding. More recently, Millar (1998) has questioned whether the observation of specific phenomena within the context of a practical task can, unaided, lead to the development of conceptual understanding. In this context it has been proposed (Millar et al., 1999) that the function of practical work might be better understood in terms of a link, or bridge, between previously taught scientific concepts and subsequent observations.

One explanation (Tamir, 1991) suggested for the lack of research evidence to support the use of practical work as an effective means for developing students' conceptual knowledge is that, in contrast to teacher demonstration, its use can generate cognitive overload. Cognitive overload occurs as a consequence of simultaneous demands made of the students by practical work in that they need to apply intellectual and practical skills as well as prior knowledge (Johnstone & Wham, 1982).

Therefore, despite the frequent claims that one of the aims of practical work is to provide an effective means of developing conceptual understanding, the research findings suggest, at least when the outcomes are measured using pen and paper tests, that there is no significant advantage to its use.

1.5 The role of practical work in motivating students

Abrahams (2009) has reported that what teachers frequently refer to as ‘motivation’ is, in a strict psychological sense, better understood as situational interest. The fact that situational interest is, unlike motivation or personal interest, unlikely to endure beyond the end of a particular lesson (Hidi & Harackiewicz, 2000; Murphy & Alexander, 2000) helps to explain why students need to be continuously re-stimulated by the frequent use of practical work. Once this fact is recognized, the reason why many pupils who claim to like practical work also claim to have little, if any, personal interest in science, or any intention of pursuing it once it is no longer compulsory (Abrahams, 2009) becomes clearer. For while these students *do* like practical work their reasons for doing so appear primarily to be that they see it as *preferable* to non-practical teaching techniques that they associate, in particular, with more writing (Edwards & Power, 1990; Gardner & Gould, 1990; Hodson, 1990; Hofstein & Lunetta, 1982). This helps to explain why, *despite* claims that students are said to prefer a laboratory-centred approach (Lazarowitz & Tamir, 1994; Pickering, 1987) and that its use encourages and motivates students to study science (Abrahams & Saglam, 2010; Arce & Betancourt, 1997; Kerr, 1964; Lazarowitz & Tamir, 1994), there is a broad consensus (House of Commons Science and Technology Committee, 2002; Millar & Osborne, 1998; Osborne & Collins, 2001; Osborne et al., 1998; Osborne et al., 2003) that far too many ‘young people are, at age 16, closing off the option of entering a career in science or engineering at a time when the UK is suffering from a shortage of scientists and engineers’ (House of Commons Science and Technology Committee, 2002, p. 23). Indeed, these issues are not limited to the UK and that ‘… it is obvious that the S&T sector in Europe (and other OECD countries) is facing a serious problem, [that is] the recruitment to the S&T sector’ (ROSE, p. 28). In fact, this is happening despite the devotion of a significant proportion of science teaching time to the pursuit of practical work. Indeed, Bennett (2003) argued that there is little reason to doubt that the amount of time spent on practical work in the UK has not changed appreciably since the studies by Beatty and Woolnough (1982) and Thompson (1975) in which it was found that one third of the time allocated to science education, during ‘A’ level study (post compulsory education age 17–18), is devoted to some form of practical work (Thompson, 1975) with this rising to one half of science teaching time for students in the 11–13 age range (Beatty & Woolnough, 1982).

A study by Windschitle and Andre (1998) into pupil motivation and the influence of epistemological beliefs on learning found that practical work was primarily effective in motivating epistemologically more mature students and that in contrast the epistemologically less mature students found non-practical teaching styles more motivating. Other studies (Arce & Betancourt, 1997; Berry et al., 1999; Watson & Fairbrother, 1993) report that students are more frequently motivated by practical work in which they are allowed to exercise some degree of control over its design and which they find both challenging and rewarding, although Lazarowitz and Tamir (1994) suggest that the motivational effectiveness of such tasks can be reduced if they are perceived as too difficult.

1.6 The role of practical work in teaching laboratory skills

One of the difficulties in reviewing the literature that relates to the effectiveness of practical work in the teaching of skills is that the term ‘skill’ has been used to mean different things to different people in different studies (Bennett, 2003). Hofstein and Lunetta (1982) argue that many studies take too narrow a view of laboratory skills and consequently neglect to measure development in skill areas such as creative thinking, problem solving, general intellectual development, observing and classifying. Hodson (1990) distinguishes between ‘craft skills’ which are content specific – learning to read a micrometre, carrying out a titration – and content independent skills such as observation and manual dexterity which are generalizable to other contexts or disciplines, while Gott and Duggan (1995) question the appropriateness of using the term ‘skill’ to describe *any* content-independent processes. Dawe (2003) argues that content-independent skills are, because of their generalizability, of more value to *all* students, while content-specific skills are of value primarily to future scientists or technicians. However, Ausubel (1968) argues, with regard to problem-solving skills, that there is no reason to believe that even if they could be taught, in the context of one subject, that they could be transferred to other contexts or disciplines. Heaney (1971) reports that while a heuristic approach – in this context any approach to learning that employs a practical method – leads to the development of problem-solving skills, a more traditional ‘didactic-with-demonstration’ approach is actually detrimental to the development of problem-solving skills, a finding that has not been confirmed in any other study. Indeed, Millar (1989) and Millar and Driver (1987) argue that content-independent processes cannot be taught but are rather innate abilities that we all have a natural propensity to develop. Relatedly, a study by Boud et al. (1980) into students’ perspectives about laboratory work reported that students themselves do not believe that their problem-solving skills improve as a consequence of undertaking practical work.

Similar uncertainty surrounds the effectiveness of practical work in the development of creative thinking. Hill (1976), using the Minnesota Test of Creative Thinking, reported an improvement in creativity after pupil involvement in practical work in chemistry. In contrast, Gangoli and Gurumurthy (1995), using an ‘objective-type’ test devised and standardized by Gurumurthy (1988), reported no evidence of improvement in creative thinking within their study.

Hofstein (1988) has pointed out that if the term ‘skill’ is interpreted narrowly to mean only ‘manipulative skill’, then practical work has, perhaps unsurprisingly, been found to have a measurable advantage over other non-practical types of instruction within science education (Gangoli & Gurumurthy, 1995; Kempa & Palmer, 1974). However, while not denying its relative effectiveness in this area, White (1996, 1979) and Clackson and Wright (1992) have questioned both the appropriateness and cost-effectiveness of its use as a means for developing content-independent manual dexterity, with White (1979) going so far as to claim that ‘if skill in manipulation *per se* is the aim, not merely skill with scientific apparatus, there are cheaper and probably more efficient and effective ways of developing it. Needlework and fine woodwork are instances' (p. 762). Such criticism echoes that made about sixty years earlier in the *British Association Report* (1917) in which it was suggested that some purposes for undertaking laboratory work are of an intrinsically lesser value than others and that 'In the laboratory the development of dexterity and skill is only a secondary consideration' (British Association Report, 1917; quoted in Connell, 1971, p. 138).

1.7 The role of practical work in developing scientific attitudes

The term 'scientific attitude' is both broad and weakly defined within the literature. Indeed, it has been pointed out (Abrahams, 2009) that the term 'attitude' has been appropriated by different researchers to describe on the one hand 'scientific attitudes' and on the other hand 'attitudes towards science'. Aiken and Aiken (1969), discussing traits such as intellectual honesty, open-mindedness and curiosity, referred to them as 'the more cognitive scientific attitudes' (p. 295). In contrast, Hofstein and Lunetta (1982) use the term 'attitude' when discussing the development of 'favourable attitudes toward science' (p. 210). There has been relatively little research (Hofstein & Lunetta, 1982) to evaluate the effectiveness of practical work as a means of developing scientific attitudes although, in marked contrast, it has been pointed out (Simon, 2000) that there have been in excess of 200 studies into attitudes towards science.

Part of the explanation for this is to be found in terms of differences between the generic aims for practical work used by different researchers. Thus, while Shulman and Tamir (1973) place both attitude and interest towards science in the same generic category, Hodson (1990) places them in different generic categories and, as such, the term 'attitude' relates only to scientific attitudes and not to attitudes towards science.

Yet even when the term 'attitude' is used only with regard to scientific attitudes there is little evidence within the literature as to what constitutes scientific attitudes or, more importantly, how these are determined. Thus, while Henry (1975) suggests that scientific attitudes include the need to be (i) observant, (ii) careful, (iii) patient and (iv) persistent, Lazarowitz and Tamir (1994) suggest a much expanded list of scientific attitudes that includes 'honesty, readiness to admit failure, critical assessment of the results and their limitations, curiosity, risk taking, objectivity, precision, confidence, perseverance, responsibility, collaboration, and readiness to reach consensus' (p. 98).

However, from a study of seventeen senior biology laboratories (USA, age 17–18) Fordham (1980) reported that the pursuit of scientifically correct results meant that honesty, far from being a scientific attitude that was developed through the use of practical work, was frequently its first casualty insofar as 'If the experiment doesn't work we go to somebody else and get their results … it looks better when you get the results that you are supposed to … it's pretty obvious you won't get as good a mark as someone who got it to work' (p. 114).

Despite differences as to what might, or might not, be considered an appropriate scientific attitude, Gauld and Hukins (1980) have pointed out that the majority of the scientific attitudes that appear in the literature fall into three generic categories: (i) general attitudes towards scientific ideas, (ii) attitudes towards the evaluation of scientific ideas and (iii) commitment to a particular set of beliefs about science. From a more fundamental perspective Bennett (2003) has argued that despite the difference between scientific attitudes and attitudes towards science both are inextricably linked with behaviours, dispositions and beliefs, rendering a clear-cut distinction between them highly problematic.

In conclusion, Gardner and Gould (1990) claim, with regard to the development of scientific attitudes, that 'While students generally enjoy hands-on experience and the opportunity to work individually or in small groups, we cannot conclude that such experiences will, by themselves, bring about major changes in styles of thinking' (p. 151).

1.8 The role of practical work in developing insights into and expertise of the scientific method

Lazarowitz and Tamir (1994) have claimed that by undertaking practical work students develop an understanding of the nature of science, the way scientists work and, in particular, 'the multiplicity of scientific methods' (p. 98). Yet such a multiplicity of methods is often overlooked given the strength of the prevailing view (Bennett, 2003) of the scientific enterprise that is firmly embedded within a hypothetico-deductive (Popper, 1989) view of science. Millar (1989) has pointed out that even if the hypothetico-deductive view of science *is* an appropriate model for the scientific enterprise it does not accurately represent the nature of practical work as it occurs within the school laboratory.

Indeed, it has been claimed (Martin, 1979) that a large proportion of practical work undertaken within the school laboratory has been reflective of 'dubious or discarded philosophies of science' (p. 331), a reference to the now widely discredited inductive view (Millar 2004) that seeks to derive natural laws from observations. In the same context Layton (1990) has questioned the extent to which any philosophy of science has been systematically used to guide the nature of practical work in the school laboratory, noting that 'the philosophy of science has rarely been used in a systematic and deliberate manner as a prime source of objectives for student laboratory work' (p. 37).

Hodson (1989) has argued that the perceptions about both the nature of science and scientific method are shaped by the distorted manner in which textbooks portray the relationship between experiment and theory in that 'The actual chronology of experiment and theory is rewritten in text-books. This helps to sustain the myth that the path of science is certain and assigns a simple clear cut role to experiments' (p. 57).

It might be worth pausing briefly simply to clarify the difference between two contrasting views of science. The first of these is referred to as the inductive view and is one in which the starting point is experimental observation within which a local pattern might be discerned. By undertaking further experimental observations, over a larger sample, the initial local pattern might be found to be a more general one in the sense that it also holds with regards all of the observations in the larger sample. Such a general pattern might then lead to the formulation of a tentative hypothesis about the behaviour that would be experimentally observed in an even larger sample that could then be explored by undertaking an even larger and more diverse set of observations. If these subsequent observations all support the tentative hypothesis, this might lead to a general conclusion in the form of a theory. In contrast, the deductive view is one in which the starting point is an existing theory from which one, or more, scientifically testable hypotheses can be derived. Any of these hypotheses can be tested by comparing the observable behaviour predicted by the hypothesis with actual experimental observations. These experimental observations have the potential to either support or refute the hypothesis that, in turn, results in either in the refutation of, or further support for, the theory from which the hypothesis was derived.

Interestingly for teachers, Matthews and Winchester (1989) suggest that only if students are allowed to see that science is often less than certain and that the relationship between experiment and theory is not always unambiguous will they develop an understanding of scientific method. Lazarowitz and Tamir (1994) point out that such an approach will mean that ‘the distorted image many students have of scientists (unusual persons wearing white gowns, working in isolation, and exhibiting extraordinary behaviour) may be discarded, and students may realize that scientists are ordinary persons’ (p. 109).

1.9 Current perspectives on the nature and purpose of practical work

An increasing scepticism as to the effectiveness of the laboratory-centred approach to science teaching has led many researchers (Abrahams & Millar, 2008; Gagné & White, 1978; Hodson, 1996; Van den Berg & Giddings, 1992; Woolnough & Allsop, 1985) to question both the nature and purpose of practical work and how best to make its use most effective.

The current debate has served to highlight the fact that there still remains, despite the long history of debate, a wide range of differing views as to the nature and purpose of practical work. Just how wide this range is, and how it changes over time, can be seen by presenting a few of those positions that serve to mark out the boundaries within which most current views can be found.

In this respect Kreitler and Kreitler (1974) propose that the purpose of practical work is to provide a means of enabling students to gain direct experience with scientific concepts that in turn generate episodes that serve to give those concepts meaning. They reject as wholly unrealistic the suggestion that its purpose, even in part, is to aid in either the development of problem-solving skills or the generation of both curiosity and interest in science. In marked contrast, Woolnough and Allsop (1985) argue that the purpose of practical work has nothing at all to do with the development of conceptual understanding and go so far as to suggest a need to 'deliberately and consciously separate practical work from the constraint of teaching scientific theory … We will make no progress until we have cut this Gordian Knot' (pp. 39–40). While supporting this separation Hofstein and Lunetta (1982) go on to suggest that a main purpose of practical work, and one frequently overlooked, is in the development of creative thinking, problem solving, scientific thinking and general intellectual development as well as the effect it can have on students' attitudes to science.

When all these issues are taken together, along with the higher cost of building and maintaining school laboratories, the *prima facie* case for practical work no longer appears quite as self-evident as it did when the National Science Teachers Association asserted that:

> The time is surely past when science teachers must plead the case for school laboratories. It is now widely recognised that science is a process and an activity as much as it is an organized body of knowledge and that, therefore, it cannot be learned in any deep and meaningful way by reading and discussion alone. (1970, p. 3)

Despite strong beliefs amongst teachers regarding the value of practical work, the empirical results to date indicate that, other than as a means for improving manual dexterity, its long-term value is, at best, uncertain. Such uncertainty, Bates (1978) suggests, means that the onus of proof therefore still remains firmly on those who believe in its value in areas other than improving manual dexterity to prove their case:

> Teachers who believe that the laboratory accomplishes something special for their students would do well to consider carefully what those outcomes might be, and then to find a way to measure them for the answer has not yet been conclusively found: What does the laboratory accomplish that could not be accomplished as well by less expensive and less time consuming alternatives? (p. 75)

Yet Millar et al. (1999) optimistically point out that, despite these widely divergent views, most science educators recognize the educational value of practical work and would agree that it should constitute a significant proportion of the time spent in teaching science at school provided, as White (1996) argues, that the term 'educational value' remains loosely defined.