



Improving science teachers' conceptions of nature of science: a critical review of the literature

Fouad Abd-El-Khalick & Norman G. Lederman

To cite this article: Fouad Abd-El-Khalick & Norman G. Lederman (2000) Improving science teachers' conceptions of nature of science: a critical review of the literature, International Journal of Science Education, 22:7, 665-701, DOI: [10.1080/09500690050044044](https://doi.org/10.1080/09500690050044044)

To link to this article: <http://dx.doi.org/10.1080/09500690050044044>



Published online: 16 Jul 2010.



Submit your article to this journal [↗](#)



Article views: 2691



View related articles [↗](#)



Citing articles: 316 View citing articles [↗](#)



RESEARCH REPORT

Improving science teachers' conceptions of nature of science: a critical review of the literature

Fouad Abd-El-Khalick, Science and Mathematics Education Center, American University of Beirut, Beirut, Lebanon, and Norman G. Lederman, Department of Science and Mathematics Education, Oregon State University, USA; e-mail: fa03@aub.edu.lb

This paper aimed to review, and assess the 'effectiveness' of the attempts undertaken to improve prospective and practising science teachers' conceptions of nature of science (NOS). The reviewed attempts could be categorized into two general approaches: implicit and explicit. *Implicit* attempts utilized science process-skills instruction or engagement in science-based inquiry activities to improve science teachers' conceptions of NOS. To achieve the same goal, *explicit* attempts used instruction geared towards various aspects of NOS and/or instruction that utilized elements from history and philosophy of science. To the extent that teachers' NOS conceptions were faithfully assessed by the instruments used in the reviewed studies, the explicit approach was relatively more effective in enhancing teachers' views. The relative ineffectiveness of the implicit approach could be attributed to two inherent assumptions. The first is that developing an understanding of NOS is an 'affective', as compared to a 'cognitive', learning outcome. The second ensuing assumption is that learners would *necessarily* develop understandings of NOS as a by-product of engaging in science-related activities. However, despite the relative 'effectiveness' of the explicit approach, much is still required in terms of fostering among science teachers 'desired' understandings of NOS. The paper emphasizes that explicitness and reflectiveness should be given prominence in any future attempts aimed at improving teachers' concepts of NOS.

Introduction

The preparation of scientifically literate students is a perennial goal of science education (American Association for the Advancement of Science [AAAS] 1990, 1993, Millar and Osborne 1998). Furthermore, an adequate understanding of nature of science (NOS) is a central component of scientific literacy (AAAS 1990, 1993, Klopfer 1969, National Science Teachers Association [NSTA] 1982). Indeed, the objective of helping students develop adequate understandings of NOS is 'one of the most commonly stated objectives for science education' (Kimball 1967-68: 110). This objective has been agreed upon by most scientists and science educators for the past 85 years, and has recently been reemphasized in the major reform efforts in science education (AAAS 1990, 1993, Millar and Osborne 1998, National Research Council [NRC] 1996).

NOS

The phrase 'nature of science' typically refers to the epistemology of science,

science as a way of knowing, or the values and beliefs inherent to the development of scientific knowledge (Lederman 1992). Beyond these general characterizations, no consensus presently exists among philosophers of science, historians of science, scientists, and science educators on a specific definition for NOS. The use of the phrase 'NOS' throughout this paper instead of the more stylistically appropriate 'the NOS', is intended to reflect the authors' lack of belief in the existence of a singular NOS or general agreement on what the phrase specifically means. This lack of agreement, however, should not be disconcerting or surprising given the multifaceted, complex, and dynamic nature of the scientific endeavour.

Conceptions of NOS have changed with developments in various scientific disciplines. A case in point is the 'leap' from a classical deterministic approach in physics to a quantum indeterministic conceptualization of the discipline. Concomitantly, conceptualizations of NOS have changed with developments in history, philosophy, and sociology of science: disciplines that systematically investigate the scientific endeavour. These developments have, in turn, resulted in changing the ways in which science educators and science education organizations have defined the phrase 'NOS' since the turn of the century.

Changes in philosophy, sociology, and history of science

Changes in conceptions of NOS have mirrored major shifts in focus and emphasis in the fields of philosophy, sociology, and history of science. An attempt to delineate these changes or trace their development is necessarily beyond the scope of the present paper. However, work in the philosophy and sociology of science in the twentieth century can be generally divided into two periods separated by Kuhn's (1962) *Structure of Scientific Revolutions* (Giere 1998). Pre-Kuhnian philosophy of science was dominated by the work of logical empiricists who erected the distinction between the 'context of discovery' and 'context of justification' and focused their efforts on the latter (Giere 1988). Philosophers in this tradition (e.g. Carnap 1937, Popper 1959, Reichenbach 1938, Russell 1914) were interested in developing a normative logical account to justify scientific claims rather than a descriptive account of how science actually works. As such, they attempted to outline the logical and epistemological foundations of science to the exclusion of psychological and sociological foundations that they considered 'external' to science. The reciprocity of this philosophical orientation with history of science was evident in an 'internalist' approach that dominated history of science in the first half of the twentieth century (Kuhn 1977). This historiographic tradition emphasized the history of scientific 'ideas' with undue regard to the contexts within which such ideas were developed.

The first half of the twentieth century also witnessed the emergence of the sociology of science as a field with the pioneering work of Robert Merton. He (e.g. Merton 1949), nonetheless, was interested in providing an account of the social structure of science rather than a social account of scientific knowledge.

Kuhn's (1962) paradigmatic and revolution approach marked a shift among philosophers (and historians) of science from emphasizing the context of justification to delving into the context of discovery. A variety of factors that were considered by empiricists to be 'irrational' or 'external' to science were brought into the mix. No longer were philosophers of science accused of committing what the logical empiricists labelled 'the sin of psychologism', or conflating logic with psy-

chology (Popper 1959), when they invoked sociological, psychological, or cultural elements in their attempts to provide accounts of the scientific endeavour. Kuhn's paradigmatic approach generated much controversy within philosophical circles. On the one hand, it was adopted and extended in a 'programmes and traditions' approach to the philosophy of science (e.g. Lakatos 1980, Laudan 1977). On the other hand, Kuhn was criticized (see, for example, Popper 1970, Popper 1994) for introducing all sorts of 'relativisms' (see, for example, Rorty 1991) and 'irrationalities' (see, for example, Feyerabend 1988) into accounts of the development of scientific knowledge. Indeed, dissatisfaction with the Kuhnian account is apparent in work that extends the legacy of logical empiricism (Giere 1988). Examples include the relatively recent work by van Fraassen in constructive empiricism (e.g. van Fraassen 1985).

Post-Kuhnian philosophy of science also witnessed the emergence of science studies (e.g. Collins 1985, Pinch 1986) and the 'Strong Program' in the sociology of scientific knowledge (especially Barnes 1974, Bloor 1976) that was inspired by general work in the sociology of knowledge (e.g. Habermas 1972). These efforts attempted to produce genuine *sociological* accounts of the production of scientific knowledge (e.g. Longino 1990). Moreover, it might be safe to say that the hallmark of post-Kuhnian philosophy of science was a preoccupation with reconciling accounts of science with 'actual' scientific practice. The orientation was accentuated by - and in turn legitimized - a plethora of *descriptive* accounts of science such as laboratory studies (e.g. Latour 1986, Latour and Woolgar 1986) and sociological analysis of scientists' discourse (e.g. Mulkay 1979, 1981). All these developments were reciprocally related to the general adoption of an 'externalist' approach to history of science (Kuhn 1977) that attempted to situate scientific issues, claims and practices within their larger social and cultural contexts (e.g. Shapin 1996).

Changes in science education organizations' conceptions of NOS

Changes in conceptualizing NOS within philosophical, sociological and historical circles are reflected in the ways the science education community has defined the phrase 'NOS' during the past 100 years. Without making any claims as to the exhaustiveness of the following summary, it could be noted that during the early 1900s, understanding NOS was equivalent to understanding 'The Scientific Method' (Central Association for Science and Mathematics Teachers, 1907). The 1960s witnessed an emphasis on enquiry and science process skills (e.g. observing, hypothesizing, inferring, interpreting data, and designing experiments). By the 1970s a shift in defining NOS was apparent. The Center of Unified Science Education at Ohio State University (1974) characterized scientific knowledge as being tentative (subject to change), public (shared), replicable, probabilistic (predictions based on scientific knowledge are never absolute), humanistic (reflects human attempts to impose order on nature), historic (past knowledge should be judged in its historical contexts and should not be compared to contemporary conceptions), unique (has its own set of rules and values), holistic (internally consistent), and empirical (based on and/or derived from observations of the natural world).

By the 1980s, psychological factors, such as the theory-laden nature of observation and the role of human creativity in developing scientific explanations, as well as sociological factors, such as the social structure of scientific organizations

and the role of social discourse in validating scientific claims, started to appear in definitions of NOS. The NSTA (1982) advanced that an adequate understanding of NOS entails an understanding of the empirical and tentative nature of scientific knowledge, and an appreciation of the central role of theory and inquiry in science. More recently, the California Department of Education (1990) emphasized that although science depends on evidence, scientific activities are theory-driven and scientists conduct their investigations from within certain frameworks of reference. *Science for All Americans* (AAAS 1990) outlined three basic components that underlie an adequate understanding of NOS. The first is viewing the world as understandable, and yet understanding that science cannot provide answers to all questions. The second component relates to the nature of scientific inquiry. It entails understanding that although inquiry in science relies on logic and is empirically based, it nevertheless involves imagination and the invention of explanations. The third component emphasizes an understanding of the social and political aspects of science. Most recently, the *National Science Education Standards* (NRC, 1996) have emphasized the historical, tentative, empirical, logical, and well-substantiated nature of scientific claims. Also emphasized were the values of scepticism and open communication, as well as the interaction between personal, societal and cultural beliefs in the generation of scientific knowledge.

Thus, a review of the research literature on NOS needs to be undertaken and 'read' from the standpoint that, much like scientific knowledge, conceptions of NOS are necessarily tentative and historical. In other words, one should realize that conceptions of NOS currently adopted by science educators and science education organizations are not 'inherently better' than, for instance, those emphasized during the 1960s. It is only with the advantage of hindsight that such normative comparisons could be made. Each of the aforementioned sets of NOS conceptions should be viewed from within the context of the systematic thinking about scientific knowledge and practice that predominated the period in which that set was adopted. The present review, as such, avoids adopting an evaluative stance towards conceptions of NOS espoused in the reviewed research efforts. Rather, an evaluative stance is embraced when examining the approaches that researchers undertook to convey to learners 'desired' conceptions of NOS and to assess those conceptions.

Research on NOS

Nos has been the subject of intensive research during the past 50 years. Lederman (1992) presented a comprehensive review of this research. He noted that research related to NOS was conducted along four related, but distinct, lines. These lines were:

- (a) Assessment of student conceptions of the nature of science; (b) development, use, and assessment of curricula designed to 'improve' student conceptions of the nature of science; (c) assessment of, and attempts to improve, teachers' conceptions of the nature of science; and (d) identifications of the relationship among teachers' conceptions, classroom practice, and students' conceptions.

(Lederman 1992: 332)

Given the interest in helping students develop adequate understandings of NOS, it was only natural that investigators, within the first line of research, started by assessing students' conceptions of the scientific enterprise. Results were consistent

regardless of the assessment instruments used in individual studies. Research has shown that students typically have not acquired valid understandings of NOS (e.g. Aikenhead 1973, Broadhurst 1970, Lederman and O'Mally 1990, Mackay 1971, Rubba 1977, Rubba *et al.* 1981, Tamir and Zohar 1991, Wilson 1954). Students' naive conceptions of NOS were attributed to a lack of knowledge of this aspect of science, even among the most capable students and those most interested in science. Researchers thus reasoned that curricula were not successful in imparting such knowledge, and this initiated the second line of research.

Reasearch efforts to design, implement, and test curricula aimed at conveying accurate conceptions of NOS began. Several units, courses, and curricula geared towards this end were shown to significantly increase students' scores on post-tests that assessed their conceptions of NOS. These curricula utilized history and philosophy of science and/or instruction that emphasized NOS to foster adequate conceptions among students. Such efforts, however, denied the importance of the teacher as a variable. Researchers concluded that students' gains were independent of the teachers' understandings of NOS. The assumption was that when given the curricula, the appropriate materials, and when shown how to use them, teachers would be successful in helping students develop conceptual understandings of NOS (Lederman 1992).

Later studies, however, came to the cast doubt on such results and conclusions. When variables such as pre-testing, teacher experience, and student prior knowledge were controlled for, confusing results emerged. The developed units and curricula seemed to give different results with different teachers. Researchers started to realize the role of teachers as the main intermediaries of the science curriculum (Brown and Clarke 1960). More studies came to support the claim that teachers' understandings, interests, attitudes, and classroom activities influence student learning to a large extent (Merill and Butts 1969; Ramsey and Howe 1969). This turned the attention towards teachers' conceptions of NOS and initiated the third line of research.

Studies were consistent in showing that teachers possessed inadequate conceptions of NOS (e.g. Abd-El-Khalick and BouJaoude 1997, Behnke 1950, Carey and Stauss 1970, Pomeroy 1993). A significant propotion of teachers, for example, believed that scientific knowledge is not tentative. Other teachers still held a positivistic, idealistic view of science (Lederman 1992). As such, science educators, within the third line of research, focused their efforts on improving science teachers' conceptions of NOS. These efforts are the focus of the present review.

Lederman (1992) noted that research concerned with improving teachers' conceptions of NOS was guided by the assumption that teachers' conceptions directly transfer into their classroom practices. In other words, it was assumed that improving teachers' NOS views is sufficient for promoting 'effective' NOS instructions in the classroom. The crucial role and possible influences of other contextual variables that typify the complex and multifaceted nature of teaching in the classroom (e.g. institutional and curriculum constraints, and teacher intentions and experiences), were disregarded. This assumption, however, was not explicitly tested. As such, Lederman continued, researches within the fourth line of research related to NOS attempted to elucidate the relationship between teachers' conceptions of NOS and their classroom practices. Exploring this latter line of research before turning to examine the attempts undertaken to improve teachers' concep-

tions of NOS is crucial for the purpose of the present paper. As will become evident below, this exploration has important implications for, and raises important questions regarding the fruitfulness of the present review.

The relationship between teachers' conceptions of NOS and classroom practice: necessary and sufficient conditions

The fourth line of research related to NOS has indicated that the relationship between teachers' conceptions of NOS and their classroom practice was more complex than originally assumed. Several variables have been shown to mediate and constrain the translation of teachers' NOS conceptions into practice. These variables include pressure to cover content (Abd-El-Khalick *et al.* 1988, Duschl and Wright 1989, Hodson 1993), classroom management and organizational principles (Hodson 1993, Lantz and Kass 1987, Lederman 1995), concerns for student abilities and motivation (Abd-El-Khalick *et al.* 1998, Brickhouse and Bodner 1992, Duschl and Wright 1989, Lederman 1999), institutional constraints (Brickhouse and Bodner, 1992), teaching experience (Brickhouse and Bodner, 1992, Lederman, 1999), discomfort with understandings of NOS, and the lack of resources and experiences for assessing understandings of NOS (Abd-El-Khalick *et al.* 1998).

It is safe to assume that teachers cannot possibly teach what they do not understand (Ball and McDiarmid 1990, Shulman 1987). To be able to convey to students 'appropriate' conceptions of NOS - as defined, for instance, in current reform documents in science education, such as *Benchmarks for Science Literacy* (AAAS 1993) and the *National Science Education Standards* (NRC 1996) - teachers themselves should possess 'adequate' conceptions of the scientific enterprise. However, research on the translation of teachers' conceptions into classroom practice indicates, and rightly so, that even though teachers' conceptions of NOS can be thought of as a *necessary* condition, these conceptions, nevertheless, should not be considered *sufficient* (Lederman 1992). At least one implication for research related to NOS is apparent. Research efforts, it is argued, should 'extend well beyond teachers' understandings of the nature of science, as the translation of these understandings into classroom practice is mediated by a complex set of situational variables' (*ibid.*: 351). Research efforts should, for instance, focus on situational factors, such as institutional support and curricular emphases, which might *facilitate* the translation of teachers' conceptions of NOS into actual instructional activities. This latter recommendation, however, is based on the assumption that the necessary condition has been sufficiently met.

If having 'adequate' conceptions of NOS is deemed necessary for the successful teaching of this valued aspect of science, then inferences about the role of situational variables (sufficient conditions) in hindering or facilitating the translation of teachers' conceptions of NOS into teaching practice will always be conflated with the role of the necessary condition unless the effect of this condition could be 'ruled out'. This possible conflation by the necessary condition (i.e. teachers' conceptions of NOS) could be ruled out if there are basis for believing that attempts to 'improve' teachers' conceptions of NOS have been 'successful'.

The present review aimed to (a) delineate the major approaches undertaken to improve prospective and practising science teachers' conceptions of NOS; and (b) assess the extent to which these attempts were successful. 'Successful', it should be noted, was considered in the sense that the resultant teachers' understanding of

NOS adequately met the conditions deemed necessary to enable teachers to convey 'appropriate' conceptions of the scientific enterprise to pre-college students.

Attempts to improve teachers' conceptions of NOS

The present review was concerned with attempts to improve prospective and practising science teachers' conceptions of NOS. This characterization included preservice and in-service science teachers as well as science majors and non-majors who are potential candidates for teacher preparations programs. As such, the review included attempts undertaken within the contexts of preservice and in-service teacher education programs and the various disciplinary departments. Conceptions of NOS were taken to refer to those aspects measured by one or more of the instruments designed to assess learners' understandings of NOS as compiled in the comprehensive review of those instruments by Lederman *et al.* (1998).

Attempts to enhance science teachers' conceptions of the scientific enterprise started in the early 1960s with an examination of the effects of extant programmes such as summer institutes and Academic Year Institutes funded by the National Science Foundation on teachers' NOS conceptions. These assessment studies undertaken by Gruber (1960, 1963) and Welch and Walberg (1967-68) indicated that participant science teachers made very little progress in their understandings of NOS as a result of participating in those institutes.

Following these initial studies, Carey and Stauss (1969), Kimball (1967-68), and Wood (1972) examined the background and academic variables related to teachers' understandings of NOS. This undertaking was also part of many intervention studies that aimed to improve teachers' conceptions of NOS (e.g. Billeh and Hasan 1975, Carey and Stauss 1968, 1970, Lavach 1969, Olstad 1969) and was pursued well into the recent past (e.g. Scharmann 1988a, 1988b). These studies indicated that teachers' conceptions of NOS were independent of virtually all the investigated variables including teachers' high school and college science content knowledge, science achievement, and academic achievement (Billeh and Hasen 1975, Carey and Stauss 1968, 1969, 1970, Olstad 1969, Scharman 1988a, 1988b, Wood 1972). Teachers' conceptions of NOS were also not related to other cognitive variables such as logical thinking ability, quantitative aptitude, and verbal aptitude (Scharmann 1988a, 1988b); social-personal variables such as locus of control orientation (Scharmann 1988b); and personal attributes such as gender (Wood 1972). Conceptions of NOS were likewise independent of the teaching level (elementary versus secondary) (Wood 1972), science subject taught, in-service professional training (Billeh and Hasan 1975, Lavach 1969), field-based teaching experiences (Scharmann 1988b), and years of teaching experience (Billeh and Hasen 1975, Kimball 1967-68, Lavach 1969).

Learning science content in undergraduate courses and in-service institutes, and participating in the activities of science in undergraduate science courses or through professional practice did not seem to contribute to science teachers' understanding of NOS (Billeh and Hasen 1975, Carey and Stauss 1968, 1969, 1970, Gruber 1960, 1963, Kimball 1967-68, Olstad 1969). Thus science educators turned their attention to the use of alternative approaches to address potential, prospective, and practising science teachers' understandings of NOS.

Intervention studies aimed at improving preservice science teachers' conceptions of NOS included those by Akindehin (1988), Barufaldi *et al.* (1977), Carey

Table 1. Standardized instruments used to assess participants' NOS views in the reviewed studies.

| <i>Study</i> | <i>Instrument</i> | <i>Developer(s)</i> | <i>NOS topics</i> | <i>Number and type of items</i> |
|--|--|--|---|---|
| Trembath (1972) | Untitled | Author | Hypothesis testing, structure of theories and laws, nature of explanations | 18 multiple-choice items |
| Jones (1969), Lavach (1969) Olstad (1969), Riley (1979) | <i>Test on Understanding Science</i> (TOUS) | Cooley and Klopfer (1961) | Scientific enterprise, scientists, and methods and aims of science | 60 four-alternative multiple-choice items |
| Carey and Stauss (1968, 1970) | <i>Wisconsin Inventory of Science Processes</i> (WISP) | Scientific Literary Research Center (1967) | Assumptions of science (36 items), and operations of science (57 items) including activities, objectives, and products of science | 93 "agree/disagree" analogous statements |
| Spears and Zollman (1977) Haukoos and Penick (1983, 1985) | <i>Science Process Inventory</i> (SPI) Form D | Welch and Pella (1967-68) | Assumptions, activities, nature of outcomes, and ethics and goals of the scientific enterprise | 135 forced-choice (agree/disagree) statements |
| Ogunniyi (1983) Akindehin (1988) Scharmann and Harris (1992) | <i>Nature of Science Scale</i> (NOSS) | Kimball (1967-68) | Tentative and dynamic nature of science, assumptions and values of science, and lack of a single "Scientific Method" | 29 three-point Likert-type items |
| Billeh and Hassan (1975) | <i>Nature of Science Test</i> (NOST) | Authors | Assumptions (8 items), products (22 items), processes (25 items), and ethics (5 items) of science | 60 multiple-choice items |
| Barufaldi, Bethel, and Lamb (1977) | <i>Views of Science Test</i> (VOST) | Hillis (1975) | Tentative nature of science | 40 five-point Likert-type |
| Scharmann (1990) Scharmann and Harris (1992) | Untitled | Johnson and Peeples (1987) | Methods of science | 20 five-point Likert-type items |
| Ogunniyi (1983) | <i>Language of Science</i> (LOS) | Ogunniyi (1982) | Categories related to language of science including: definition, characteristics, functions, and formation | 64 forced-choice (agree/disagree) statements |

and Stauss (1968, 1970), Ogunniyi (1983), Olstad (1969), Riley (1979), Shapiro (1996) and Trembath (1972). Interventions undertaken within in-service programmes included studies by Billeh and Hasan (1975), Lavach (1969), and Scharmann and Harris (1992). Similar attempts were also undertaken in undergraduate science content courses and included studies by Haukoos and Penick (1983, 1985), Jones (1969), Scharmann (1990), and Spears and Zollman (1977).

Generally speaking, these studies used one of two approaches. The first approach was advocated by science educators such as Gabel, Rubba, and Franz (1977), Haukoos and Penick (1983, 1985), Lawson (1982), and Rowe (1974). This approach, labelled in the present review as an *implicit* approach, suggests that an understanding of NOS is a learning outcome that can be facilitated through process skill instruction, science content coursework, and 'doing science'. Researchers who adopted this implicit approach utilized science process skills instruction and/or scientific inquiry activities (Barufaldi *et al.* 1977, Riley 1979, Trembath 1972) or manipulated certain aspects of the learning environment (Haukoos and Penick 1983, 1985, Scharmann 1990, Scharmann and Harris 1992, Spears and Zollman 1977) in their attempts to enhance teachers' NOS conceptions. Researchers who adopted the second approach to enhancing teachers' understandings of NOS (Akindehin 1988, Billeh and Hasan 1975, Carey and Stauss 1968, 1970, Jones 1969, Lavach 1969, Ogunniyi 1983) utilized elements from history and philosophy of science and/or instruction geared towards the various aspects of NOS to improve science teachers' conceptions. This approach, labelled in the present review as an *explicit* approach to improving teachers' understanding of NOS, was advanced by educators such as Billeh and Hasan (1975), Hodson (1985), Kimball (1967-68), Klopfer (1964), Lavach (1969), Robinson (1965), and Rutherford (1964).

Instruments used to assess participants' conceptions of NOS

Before turning to examine the individual studies that attempted to enhance science teachers' conceptions of NOS, it is crucial to elucidate some points regarding the assessment instruments that were used in these studies to gauge participants' NOS views. With the exception of Shapiro (1996), researchers in the reviewed studies used standardized paper-and-pencil instruments to assess participants' conceptions of NOS. These instruments comprised forced-choice, such as agree/disagree, Likert-type or multiple-choice items. Table 1 presents a list of these instruments, their developers, NOS aspects or topics they purported to assess, and the number and type of items that each employed.

Many criticisms have been levelled against the use of standardized instruments to assess learners' NOS views. Two major criticisms were related to these instruments' validity. First, Aikenhead, Ryan, and Desautels (1989) argued that such instruments were all based on a problematic assumption. These instruments *assumed* that respondents perceive and interpret an instrument's items in a manner similar to that of the instrument developers. Aikenhead *et al.* argued that ambiguities result from assuming that respondents understand a certain statement in the same manner that the researchers or instrument developers would, and agree or disagree with that statement for reasons that coincide with those of the researchers or instrument developers. Such ambiguities seriously threaten the validity of such instruments.

Second, Lederman *et al.* (1998) noted that these standardized instruments usually reflected their developers' views and biases related to NOS. Being of the forced-choice, Likert-type or multiple-choice category, these instruments ended up imposing the researchers'/developers' own views on the respondents. Additionally, responses to instrument items were usually designed with various philosophical stances in mind. As such, irrespective of the choices the respondents made, they often ended up being stamped with labels that indicated that they firmly held coherent, consistent philosophic stances such as inductivist, verificationist or hypothetico-deductivist. Thus, the views that ended up being ascribed to respondents were more of an artefact of the instrument in use than a faithful representation of the respondents' conceptions of NOS.

In addition to validity issues, the use of standardized instruments severely limits the feasibility of drawing conclusions regarding the meaningfulness and importance of the gains in understanding NOS achieved by participants in the studies presently reviewed. Standardized instruments were mainly intended to label participants' NOS views as 'adequate' or 'inadequate' - mostly by assigning those views certain numerical values - rather than elucidating and clarifying such views. This was the case in almost all the studies presently reviewed, which were mainly 'quantitative' in nature. With the exception of Shapiro (1996) who adopted an 'interpretive' stance, researchers often limited their 'results' section to reporting participants' pre- and/or post-test means scores or gain scores for the instruments in use. These researchers did not elucidate participants' NOS views prior to, or at the conclusion of the treatment. Moreover, researchers did not describe those areas in which participants achieved 'important' gains in their NOS understandings or the nature of those gains. Additionally, those researchers who reported 'gains' in participants' NOS understandings noted that those gains were 'statistically significant'. None, however, commented on the 'practical significance' of such gains. Drawing conclusions in this regard was also difficult given that standard deviations and adjusted mean scores were often not included in the reviewed reports. These features of the reviewed studies made it very difficult to assess the 'meaningfulness' and 'importance' of the reported gains. As will later become evident, the reviewers found it necessary to make several nested assumptions on a number of occasions in the attempt to gauge the importance of the gains in understanding NOS reported in some studies.

The study by Shapiro (1996) was an exception in this regard. Instead of using a standardized instrument, Shapiro used repertory grids (described later) in conjunction with individual interviews to assess participants' conceptions of NOS. Lederman and O'Malley (1990) and Lederman (1992) emphasized the usefulness of individualized interviews in generating faithful representations of learners' NOS views. Interviews allow respondents to express their own reviews on issues related to NOS thus alleviating concerns related to imposing a particular view of the scientific enterprise on respondents. Moreover, by asking respondents to elaborate and/or justify their answers, interviews allow researchers to assess not only respondents' positions on certain issues related to NOS, but the respondents' reasons for adopting those positions as well. Thus, ambiguities can be avoided and the likelihood of misinterpreting respondents' views is greatly reduced.

Additionally, the use of interpretive tools such as individual interviews often reflects the researcher's interest in elucidating and clarifying participants' NOS views rather than simply labelling or judging them. Data generated from inter-

views could be used, as was the case in Shapiro's (1996) study, to generate descriptive profiles of participants' NOS views. Such profiles greatly facilitate gauging the practical importance of any claimed gains in participants' understandings of NOS.

A final note regarding instrumentation relates to the substantive 'adequacy' of the instruments used in some of the reviewed studies. It was argued earlier that passing evaluative judgements on conceptions of NOS adopted within a certain period should be avoided. This argument was based on the premise that NOS understandings emphasized at one point in time necessarily reflect that time's scholarship on understanding the scientific enterprise. However, such assumption would not hold when a standardized instrument developed in the mid-1960s is used to assess learners' NOS views two or three decades later when marked changes in conceptualizing NOS have been well documented and disseminated. This was the case with three of the reviewed studies. An examination of table 1 indicates that Ogunniyi (1983) and Scharmman and Harris (1992) used the NOSS developed by Kimball in 1967 (Kimball 1967-68), and that Haukoos and Penick (1983, 1985) used the SPI developed by Welch and Pella in 1967 (Welch and Pella 1967-68) to assess their participants' conceptions of NOS. As such, the results of these studies should be viewed with added caution.

Improving teachers' conceptions: implicit attempts

Table 2 presents a summary of the design, participants, and context and duration of treatment of studies that adopted an implicit approach to enhancing science teachers' NOS views. Also reported in table 2 are the mean gain scores for treatment groups and the percentage that the treatment post-test scores represent relative to the total scores of NOS instruments used in these studies. The following discussion focuses on the rationale and nature of the interventions undertaken by the various researchers and the meaningfulness of the gains, if any, in NOS understandings reported for participant science teachers.

Trembath (1972) aimed to assess the influence of a 'small' curriculum project on prospective elementary teachers' views of NOS. The curriculum project, developed at Frankston Teachers' College, Australia, aimed to enhance participants' understandings of the ways in which hypotheses are developed and tested, the logical structure of theories and laws, and the ways in which theories and laws can be used to make different types of explanations. These broad goals were translated into 24 behavioral objectives. Participants, however, were not presented with these objectives at the outset of the programme.

The programme, which took $2\frac{1}{2}$ hours to complete, presented prospective teachers with a set of narratives. Each narrative put forth a certain situation and was divided into a set of 'frames'. Each frame required students to read several paragraphs and provide a short answer in the form of a hypothesis, prediction, or inference. Students then compared their answers with those provided after each frame. If the two answers agreed, then students proceeded to the next frame. Otherwise, students were asked to re-read the frame and attempt to reconcile their answers with the suggested ones. On completing the frames, students were asked to provide a short answer that would serve as a section review.

It should be emphasized that participants were not made aware of the goals or specific objectives of the programme. Moreover, the report did not indicate that the participants were debriefed on completing a set of frames or that they were

Table 2. Studies that adopted an implicit approach to improving science teachers' views of NOS.

| <i>Study</i> | <i>Design</i> | <i>Participants</i> | <i>Context</i> | <i>Duration of treatment</i> | <i>Treatment group significant gain score</i> | <i>Post-treatment scores relative to total score for instrument(s) used</i> |
|------------------------------------|---|--|---|--|--|---|
| Trembath (1972) | Pre-test-post-test control group; random assignment | Preservice elementary teachers; 24 experimental, 24 control | Elementary teacher preparation programme | 2½ hours | 20.5% | 59% |
| Barufaldi, Bethel, and Lamb (1977) | Pre-test-post-test equivalent control group; non-randomized | Elementary education majors; 56 experimental (three science methods courses), 32 control (one math methods course) | Elementary science and math methods courses | Integrated into course (2½ hour per week for 14 weeks) | 3.5 to 6.0% (estimated) | 75% |
| Spears and Zollman (1977) | Pre-test-post-test two-treatment; random assignment | 171 non-science majors | Physics course (four sections) | Integrated into course | None (on 3 SPI components) 2.5% (on the 4th) | 76% |
| Riley (1979) | 3 × 3 factorial; random assignment | 90 undergraduate preservice elementary teachers | Elementary methods programme | Four 1½ hour-sessions | None | - |
| Haukoos and Penick (1983) | Pre-test-post-test two-treatment | 78 two-year, comprehensive, community college students | Biology course (four intact sections) | Integrated into course | 8.0% | 79% |
| Haukoos and Penick (1985) | Pre-test-post-test two-treatment | 61 two-year, comprehensive, community college students | Biology course (two intact sections) | Integrated into course | None | 72% (estimated) |
| Scharmann (1990) | Non-equivalent control-group | Freshmen non-science majors; 13 experimental, 17 control | Three-week summer-session biology course (two sections) | 4½ hours | Estimate not possible due to lack of data | - |
| Scharmann and Harris (1992) | One-group pre-test-post-test | 19 inservice secondary science teachers | Three-week NSF-sponsored summer institute | Six hours per day for 15 days | None for NOSS; 1.5% (for Johnson and Peoples 1987) | 63% (for Johnson and Peoples, 1987) |

encouraged to explicitly discuss their responses or the reasoning through which such responses were derived. Trembath (1972) seemed to have assumed that participants would develop adequate understandings of the targeted NOS aspects by simply 'going through' the programme activities. Trembath reported a statistically significant difference between the mean pre-test and post-test score for the experimental group, but noted that this score only increased from 7.0 to 10.7 points out of 18 possible points.

Barufaldi *et al.* argued that 'a major *affective* goal [italics added] of science teacher education should be the enhancement of the philosophical viewpoint that science is a tentative enterprise and that scientific knowledge is not absolute' (1977: 289). It is noteworthy that Barufaldi *et al.* explicitly labelled attaining an understanding of NOS or, at least, of the tentativeness of science as an 'affective' goal. In the studies presently reviewed, researchers often did not delineate the domain (cognitive versus affective) to which they believed understandings of NOS belong.

The study assessed the influence of elementary science methods courses at the University of Texas at Austin on junior and senior elementary education majors' understandings of the tentativeness of science. The courses had no components that were specifically geared towards enhancing participants' views of the tentative NOS. Rather, consistent with the authors' view of NOS as an 'affective' outcome, an implicit approach was used. Thus, Barufaldi *et al.* noted, in these courses:

Students were presented with numerous hands-on, activity-centered, inquiry-oriented science experiences ... [and] ... many problems-centered science activities ... The uniqueness and the variety of the learning experiences in the courses provided the students with many opportunities to understand the tentativeness of scientific findings. (1977: 291)

Pair-wise comparisons between treatment groups and the control group as well as comparisons between pairs of treatment groups and the control group (see table 2) were statistically significant. Barufaldi *et al.* thus concluded that a methods course which 'stresses inquiry methods and procedures, emphasizing a hands-on approach integrated with individual problem solving, develops, alters, and enhances ... preservice teachers' ... philosophical view ... toward the tentative nature of scientific knowledge' (149 *ibid.*: 293).

The authors, however, did not present enough evidence to support this rather sweeping generalization. Barufaldi *et al.* did not report the pre-test mean VOST scores or the mean gain scores for the various groups. However, if we assume that the groups did not differ appreciably on their pre-test VOST scores and that the control group mean score did not change appreciably from the pre-test to the post-test, then the gains achieved can be assessed. The mean post-test VOST score for the control group was 141. The corresponding scores for the three treatment groups were 153, 149, and 148. As such, the approximate gains achieved were very small and ranged between 3.5 and 6 percentage points. Given that there are 200 possible points on the VOST instrument and that respondents could score 120 points by simply choosing neutral responses, it is difficult to ascertain that the above gains reflect a meaningful improvement in participants' understanding of the tentative nature of scientific knowledge.

Spears and Zollman (1977) assessed the influence of engagement in some degree of scientific inquiry on students' understandings of the process of science.

Participants were randomly assigned to the four lecture sections and associated laboratory sections of a physics course offered at Kansas State University. Some students did not complete or missed either the pre-test or post-test. As such, data from only about 50% of the original sample were used in the final analysis. The authors, however, did not provide any data to indicate that the remaining participants were representative of the original population.

Two types of laboratory instructional strategies, structured and unstructured, served as the treatments. The 'structured' approach emphasized verification whereas the 'unstructured' approach stressed inquiry or discovery. Both approaches asked students to investigate problems related to physical principles discussed in the lectures and informed them about the available equipment. Beyond this point the two approaches differed in a major way. In the 'structured' laboratory, students were provided with explicit procedures with which they attempted to verify the physical principles concerned. Students in the 'unstructured' laboratory, however, were free to investigate the problem in whichever way they deemed appropriate. They made their own decisions regarding what data to collect, how to collect this data, how to treat the data, and how to interpret and present their results.

Data analyses controlled for the participants' major, years in college, and course lecture and laboratory grades as well as the type of lecture presentation in each of the four sections. These analyses indicated that there were no statistically significant differences between the adjusted scores of the two groups on the Assumptions, Nature of Outcomes, and Ethics and Goals components of the SPI Form D (Welch and Pella 1967-68). There was a significant difference in the mean scores on the Activities component. The mean post-test score of students in the 'structured' laboratory (46.3) was higher than that of students in the 'unstructured' laboratory (45.0). The difference, however, could not have amounted to more than 2.5 percentage points. And even though the authors did not discuss the practical significance of this result, the observed difference was very small to be of any practical importance. As such, compared to students in the structured laboratory group, students in the unstructured group did not demonstrate better understanding of NOS as measured by the SPI. 'Doing science', either within a structured, traditional environment or within the more advocated inquiry or discovery approach, did not seem to improve college students' understanding of NOS (see also Carey and Stauss 1968, Kimball 1967-68).

Riley (1979) argued that there is a growing belief among science educators, though *not* empirically tested, that teachers' understandings of, and attitudes toward science would improve as a result of first-hand, manipulative experiences and enhanced proficiency in the processes of science. Riley, like Barufaldi *et al.* (1977), explicitly labelled an understanding of NOS as an 'affective' outcome and adopted an implicit approach to teaching about NOS through involving teachers in 'doing science'.

The study investigated the influence of hands-on versus non-manipulative training in science process skills on, among other things, preservice elementary teachers' understandings of NOS. The study had 3×3 factorial design with the treatment and science grade point average as independent variables. The treatment had three levels: active-inquiry (hands-on), vicarious-inquiry (non-manipulative), and control. Participants were divided into three groups according to their grade

point average (high, medium, or low) and 30 students from each group were randomly selected and assigned to one of three treatment levels.

The four $1\frac{1}{2}$ hour-session treatment involved activities that focused on various science process skills, such as observing, classifying, inferring, predicting, communicating, measuring and the metric system, and using space/time relationships. The only difference between the aforementioned levels of treatment was student involvement. In the active-inquiry treatment, participants were trained in science process skills using a hands-on, manipulative approach. Participants in the vicarious-inquiry treatment group did not manipulate any materials. They were trained in science process skills using a demonstration approach where the instructor exclusively manipulated all materials. The control group participants viewed science related films for approximately the same amount of time.

Data analyses indicated that there were no significant differences between the groups mean TOUS (Cooley and Klopfer 1961) scores related to the treatments. As such, participants in the active-inquiry, vicarious-inquiry, and control groups did not differ in their understandings of NOS. The author thus concluded that prospective elementary teachers' understandings of NOS were not significantly improved through hands-on, manipulative instruction in the processes of science. Thus, the conclusions of Riley's (1979) study stand in contrast with those of Barufaldi *et al.* (1977) who concluded that 'doing science' within the context of methods courses could enhance prospective elementary teachers' conceptions of NOS.

Haukoos and Penick (1983) investigated the effects of classroom climate on community college students' learning of science process skills and content achievement. The authors replicated their study two years later (Haukoos and Penick 1985). They argued that gains in the development of students' inquiry skills and science process skills might be related to aspects of the classroom environment such as the extent to which instruction is directive or non-directive. Implicit to this argument is the assumption that students learn about the nature of scientific inquiry implicitly through certain aspects related to the classroom environment.

The studies features two treatments: Discovery Classroom Climate (DCC) treatment and a Non-discovery Classroom Climate (NDCC) treatment. In both studies, participants were enrolled in intact sections of an introductory biology course. Throughout the duration of the course, students in both groups received instruction on the same content. The only difference between the two treatments was the classroom climate that was determined by the extent to which the instructor used direct or indirect verbal behaviours. In the lecture/discussion sessions, students in the NDCC group were presented with the content in a manner 'that conveyed the impression that science was complete and final, and seldom did the students question it' (Haukoos and Penick 1983: 631). With the DCC group, the instructor assumed a low profile, elicited student questions, and encouraged discussion of the lecture material. All student responses and interpretations were accepted and were not judged as right or wrong.

In the laboratory portion of the course, students carried out the same experiments using the same materials. However, during laboratory sessions, students in the NDCC group were exactly told how to manipulate materials. Their results were either accepted or rejected by the instructor. Students in the DCC laboratory were alternatively encouraged to select and explore their own questions, and to manipulate the available materials in whichever ways they deemed fit in answering their questions. The instructor kept explicit directions and judgments to a mini-

mum. In this regard, the two laboratory environments were similar to the 'structured' and 'unstructured' or traditional and inquiry based treatments that were employed by Spears and Zollman (1977).

To ensure the fidelity of the treatments, student-teacher interactions were audio-taped and analysed using the Science Laboratory Interaction Categories (SLIC) (Shymansky and Penick 1979). Student-teacher interactions were coded and then compared with established DCC and NDCC criteria. The percentage of total class time spent on each of the coded behaviours was calculated and used to produce a Learning Condition Index (LCI) for each treatment. The LCI values reported for each section of the investigated course in *both* studies indicated that classroom environments were consistent with the respective treatments.

Data analyses in the first study (Haukoos and Penick 1983) indicated that the DCC group had a significantly higher mean SPI score than the NDCC group. The reported difference was on the order of about 8 percentage points. The authors concluded that the classroom climate influenced students' learning of science processes. However, Haukoos and Penick (1985) were not able to replicate these results. Analyses in the second study revealed no statistically significant differences, at any acceptable level, between the DCC and NDCC groups. These latter results, it should be noted, are consistent with the findings of Spears and Zollman (1977).

The authors resorted to several factors to explain why students in the DCC class did not demonstrate better understandings of the processes of scientific inquiry as compared to students in the NDCC class. They noted that in the replication study, the instructor might have developed subtle ways to render the classroom climate in both treatments less distinct. The reported LCI scores, however, do not support this interpretation. Haukoos and Penick also noted that they were 'not able to truly match students in the original study with those in replication. Students *may* [italics added] have been older, brighter, more motivated, or different in other ways' (1985: 166). It should be noted that the authors did not limit the conclusions of their first study to the sample investigated. They made rather a sweeping generalization. Now that the expected results were not obtained, possible effects due to the participants' characteristics were called upon. The authors did not provide any data or conduct any systematic analysis to support any of these speculative interpretations.

Moreover, Haukoos and Penick noted that 'we have two choices; we can question the new data or we can question the old' (ibid.: 165). They nevertheless decided only to question the new study. They did not choose even to speculate about another, probably more plausible, interpretation: namely, that classroom climate might not be related to developing students' understandings of NOS. The fact that the authors did not even consider the alternative interpretations indicates an inherent bias in favour of the DCC treatment. Given that the initial results were not replicated and that the authors insisted that some factors other than the treatment was responsible for the new results, serious doubts could be raised regarding the claimed influence of the classroom climate that specifically derives from instructors' verbal behaviours on college students' NOS views.

Scharmann (1990) aimed to assess the effects of a diversified instructional strategy (versus a traditional lecture approach) on freshmen college students' understandings of the nature of scientific theories, among other things. The strategy was implemented over the course of $4\frac{1}{2}$ hours. Participants were first given 30

minutes to individually respond in writing to four questions that asked about their feelings and beliefs concerning the evolution/creation controversy. Next, students were randomly assigned to discussion groups of 3-5 students. They were asked to share their responses to the above questions and then respond to four new questions. These latter questions asked each group to provide reasons that would support teaching only evolution, teaching creation origins in addition to evolution, and teaching neither evolution nor creation origins in science classes. Students were also asked to decide whether, and explain why one set of reasons was more compelling than another set. Ninety minutes were allocated for this phase of the treatment during which the author did not interfere in the course of the discussions. For the next 30 minutes, spokespersons shared their groups' concerns, differences, and points of agreement with the whole class. Following a break, the author led a 90-minute interactive lecture/discussion that aimed to resolve any misconceptions that arose as a result of the group discussions and were evident in their presentations. Finally, during the last 30 minutes participants were given the opportunity to reflect on the discussion activity.

It should be noted that, while discussing the rationale behind the expected effectiveness of a diversified instructional strategy in enhancing students' NOS conceptions, Scharmann (1990) argued that students should be guided to use empirical, logical, historical, and sociological criteria when attempting to establish the validity of scientific theories. There were no indications that the experimental group received instruction about any of these criteria in the course of the treatment. It seemed that Scharmann assumed that students would implicitly learn about these criteria and other NOS aspects just by participating in the aforementioned discussions.

Scharmann (1990) reported a significant difference between the pre-test and post-test scores for both the experimental and the control group. Students in both groups achieved statistically significant gains in their understandings of NOS. Scharmann concluded that both classes provided students with opportunities to grow in their understandings of NOS but that the diversified instructional strategy was superior in this respect. The author, however, did not provide any evidence to support this claim. Given that both groups demonstrated gains in their understandings of NOS and given the lack of data to indicate otherwise, the effectiveness of the treatment should be considered with extreme caution.

Scharmann and Harris aimed to assess the influences of a 3-week NSF-sponsored summer institute on, among other things, participants' understandings of NOS. The authors noted that 'changes in an understanding of the nature of science can be . . . enhanced through a more indirect and applied context . . . and through a variety of readings and activities' that help participants to discuss their NOS views (1992: 379). As such, similar to Scharmann (1990), the authors adopted an implicit approach to improving science teachers' conceptions of NOS.

The NOSS (Kimball 1967-68) was used to assess participants' understandings of the 'philosophical' NOS, and an instrument developed by Johnson and Peeples (1987) was used to assess participants' 'applied' understandings of NOS. The authors did not elucidate the distinction between 'philosophical' and 'applied' understandings of NOS.

During the first two weeks of the institute the participants were presented with biological and geological content relevant to evolutionary theory. In addition, vari-

ous instructional methods and teaching approaches including lectures, small-group and peer discussions, field trips, and other inquiry-based approaches were taught and modelled by the authors. The authors noted that the 'theme' of promoting participants' conceptions of NOS pervaded all the aforementioned activities. However, no direct or explicit NOS instruction was used. The final week of the institute was used to provide the participants with an opportunity to integrate what they had learned by designing and presenting instructional units on evolution utilizing the various approaches and activities experienced at the institute.

Data analyses did not reveal significant differences between pre-test and post-test mean NOSS scores. However, statistically significant differences were obtained in the case of the Johnson and Peeples (1987) instrument. The authors thus concluded that even though participants' conceptions of the 'philosophical' NOS were not changed, their understandings of the 'applied' NOS were significantly improved. Scharmann and Harris (1992), however, did not comment on the practical significance of the gain achieved by the participants. Out of 100 possible points for the latter instrument, the pre-test and post-test mean scores were 61.74 and 63.26, respectively. The mean gain only amounted to about $1\frac{1}{2}$ percentage points.

Improving teachers' conceptions: explicit attempts

Almost all studies that adopted an explicit approach, similar to those that adopted an implicit approach, were quantitative in nature. Shapiro's (1996) interpretive study was the only exception. Table 3 presents a summary of studies that utilized an explicit approach to enhancing science teachers' NOS views.

In two separate but similar studies, Carey and Stauss (1968, 1970) investigated whether a secondary science methods course at the University of Georgia could significantly improve prospective and practising secondary science teachers' conceptions of NOS, respectively. NOS was an underlying theme in the science methods courses investigated in the two studies. Participants were introduced to NOS through lectures and discussions and read articles and books related to history and philosophy of science. Throughout the courses and irrespective of the activity or topic discussed (writing objectives, planning, teaching methods, evaluation, etc.) participants were always asked to discuss whether the activities or topics were compatible with the image of NOS presented in the courses.

Carey and Stauss (1968) reported that participants made statistically significant gains in their understandings of NOS. The reported mean gain amounted to about 4.5 percentage points on the WISP (Scientific Literacy Research Centre 1967). However, assessing the practical significance of such a gain was not possible given that the authors failed to report standard deviations for participants' pre- and post-test mean scores.

Data analyses for the second study (Carey and Stauss 1970) indicated that the WISP post-test scores, total and subsets, were significantly higher than the pre-test scores. The mean gains were on the order of about 11 percentage points and were in all cases greater than the variances of the corresponding pre- and post-test mean scores. Additionally, out of 93 possible points on the WISP, the mean post-test score was 78.61 indicating about 85% agreement with the instrument's model for NOS. It should be noted that the gains achieved in the present study were among the highest reported in the studies reviewed in the present paper. As such,

Table 3. Studies that adopted an explicit approach to improving science teachers' views of NOS.

| <i>Study</i> | <i>Design</i> | <i>Participants</i> | <i>Context</i> | <i>Duration of treatment</i> | <i>Treatment group significant gain score</i> | <i>Post-treatment scores relative to total score for instrument used</i> |
|-------------------------|---|--|--|-----------------------------------|---|--|
| Carey and Stauss (1968) | One-group pre-test-post-test | 17 preservice secondary science teachers | Science methods courses | Integrated into course | 4.5% | 78% |
| Carey and Stauss (1970) | One-group pre-test-post-test | 31 in-service secondary science teachers | Science methods courses | Integrated into course | 11% | 85% |
| Jones (1969) | Pre-test-post-test control-group, non-randomized | Non-science majors; 87 experimental, 55 control | General education vs. professional science courses | Integrated into education course | 11% | 73% |
| Lavach (1969) | Pre-test-post-test control-group (no pretest for control group) | Inservice science teachers; 11 experimental, 15 control | Historically oriented science programme | Three hours per week for 11 weeks | 6% | 60% |
| Olstad (1969) | One group pre-test-post-test | 69 preservice elementary teachers (46 in replication study) | Elementary science methods course | Integrated into course | 4.5% | 75% (average) |
| Billie and Hasan (1975) | Pre-test-post-test control group | 171 inservice secondary science teachers | Four-week summer methods course | Integrated into course | 3 to 10% | 59% (average) |
| Ogunniyi (1983) | One-group pre-test-post-test | 54 student teachers | Science education course | Integrated into course | 3% (on NOSS) 4.5% (on LOS) | 18% (for NOSS) 60% (for LOS) |
| Akindehin (1988) | Pre-test-post-test group | Preservice secondary science teachers; 65 experimental, 80 control | <i>Introductory Service Teacher Education</i> (ISTE) package | One hour per week for 12 weeks | Estimate not possible due to lack of data | 90% |
| Shapiro (1996) | Interpretive (case study) | Jan: a preservice elementary teacher (21 teachers in cohort) | Science methods course | Integrated into course | - | - |

Carey and Stauss (1968, 1970) were the first researchers to present evidence in support of the notion that instruction in history and philosophy of science may positively contribute to science teachers' understandings of NOS.

Jones (1969) investigated whether non-science majors enrolled in a general education physical science course at the University of Tulsa achieved better understandings of science and scientists compared to students enrolled in professionally oriented courses. Three professional courses in general chemistry, general physics, and engineering physics, offered at the same university, were chosen for comparison. Each course was concerned with a particular scientific discipline and mainly focused on the facts, vocabulary, discoveries, and quantitative procedures of the discipline concerned, as well as on problem solving within the discipline. The general education physical science course, which included topics from astronomy, physics, chemistry, and geology, served as the experimental treatment. The course was concerned with some facts and principles from the aforementioned four disciplines but placed greater emphasis on historical development, philosophy of science, and science-related societal issues.

Data analyses, which controlled for participants' predicted college achievement, actual achievements in the investigated courses, and pre-test TOUS scores, indicated a statistically significant difference between the mean TOUS post-test scores for the experimental and control groups. The mean gain score for the experimental group was +5.79 points, whereas that for the comparison group was -0.45. Thus, the difference in the gain scores for the two groups amounted to a substantial increase of about 11 percentage points.

Lavach (1969) assessed the influence of a historically oriented science programme - that he developed and conducted - on practising science teachers' understandings of science, scientists, the scientific enterprise, and the aims and methods of science as measured by the TOUS. Lavach claimed that the study had a pre-test-post-test control-group design. The author, however, did not pre-test the control group and thus impregnated the study with a variety of extraneous variables, such as testing effect and history, any of which could have contributed to any gains demonstrated by the experimental group.

Teachers in the experimental group met for 3-hour sessions per week over 11 weeks. Each session consisted of a 2-hour lecture/demonstration followed by a one-hour laboratory. In the laboratory session, teachers replicated some of the experiments that were conducted by the scientist under discussion. The nature of the control group experiences (or lack thereof) was not elucidated.

Data analyses revealed a statistically significant difference between the mean pre- and post-test TOUS scores for the experimental group (35.27 and 38.91, respectively). Out of 60 possible points on the TOUS, the mean gain amounted to 6 percentage points. The author also reported statistically significant differences between the experimental and control group mean post-test TOUS scores. It should be noted, however, that this latter comparison was not valid given that teachers in the experimental group achieved a higher mean pre-test score on the TOUS (35.27) than that achieved by teachers in the control group on the post-test (30.06). Relative to the difference between the two groups mean post-test scores that achieved statistical significance, the difference between the control group mean post-test score and the experimental group mean pre-test score would have achieved a similar level of statistical significance. These initial differences between the two groups were not taken into account when the comparison was

made. Lavach (1969), nevertheless, concluded that as a result of participating in the programme, the teachers achieved significant gains in their understandings of NOS.

Olstad (1969) aimed to assess the influence on prospective elementary teachers' NOS views of an elementary science methods course offered at the University of Washington during Fall term, 1965-66. The study was replicated during Winter term of the same year. The course, entitled *Science in the Elementary School*, addressed several topics which included 'the nature of science, scientific "method" and attitude, scientific models, science as a social force, [and] inductive and deductive processes' (p. 10). These topics and their methodological implications in terms of equipment, curricular materials, and evaluation were explored. The lectures in the course were supplemented with laboratory sessions. The activities in these sessions aimed to familiarize the participants with the various aspects of process-oriented science teaching such as generating models, interpreting data, designing experiments, and inductive thinking.

Data analyses revealed significant gains in mean TOUS scores for the original and replication groups. The author concluded that participants achieved substantial gains in their understandings of NOS as a result of participating in the course. The gains achieved, however, were on the order of 4.5 percentage points on the 60-point TOUS scale.

Billeh and Hasan (1975) assessed the influence of a 4-week summer training methods course on in-service science teachers' understandings of NOS. All 186 secondary science teachers in Jordan were invited to attend the course that was designed and conducted by the investigators. The 171 teachers (92%) who participated were divided into four groups according to subject matter taught (biology, chemistry, physical science, and physics). The experimental group comprised teachers in the chemistry, physical science, and physics groups. Biology teachers served as the comparison group.

Participant teachers attended lectures/demonstrations on science teaching methods and basic science concepts, and were involved in laboratory investigations that emphasized a guided discovery approach. Participants' understandings of the target science concepts were reinforced with outside readings and viewing science-related films. In addition to these activities, teachers in experimental group (chemistry, physical science, and physics teachers) received:

Twelve 50-minute lectures in the nature of science. These lectures covered the following topics: What is science?; Science and common sense; science and technology; art of scientific investigation; nature of scientific knowledge (characteristics, classification, scientific theories, and models); growth and development of scientific knowledge; and sociological aspects of science.

(Billeh and Hasan, 1975: 211)

It should be noted that this was the first reported attempt to improve science teachers' understandings of NOS by employing formal and direct instruction about this aspect of science. There were no indications that the participants were instructed in or assigned readings from history or philosophy of science.

While the pre-test mean NOST scores for the four teacher groups were not significantly different, the post-test mean scores were. The physical science and chemistry groups achieved significantly better than the biology and the physics groups. The mean gain scores of the chemistry (4.15), physical science (5.66), and

physics (2.00) groups were statistically significant. The biology group mean gain score (1.67) did not achieve statistical significance. These mean gains ranged between about 3 percentage points for the physics group to about 10 percentage points for the physical science group. The authors thus concluded that formal instruction on NOS contributed to significant gains in teachers' NOS understandings. The authors, however, did not comment on the practical significance or meaningfulness of the achieved gains. However, irrespective of whether the gains could be considered important or not, the post-test mean NOST scores achieved by the chemistry (36.51), physical science (36.02), and physics (33.64) groups were not high. Given that there are 60 possible points on the NOST, these latter scores might be indicative of inadequate understandings of, at least, some aspects of NOS addressed in the training course.

Ogunniyi (1983) assessed the influence of a science education course that presented integrated topics in history and philosophy of science on student teachers' conceptions of NOS and language of sciences measured by the NOSS (Kimball 1967-68) and LOS (Ogunniyi 1982), respectively. The course, developed by the author, covered several topics, including 'Origin of scientific thought; . . . significant scientific revolutions and their consequences; nature of scientific inquiry; epistemological foundations of science; science and superstition; characteristics of scientific and traditional societies; [and] scientific literacy' (Ogunniyi 1983: 194). Lectures were augmented by discussions and outside readings.

Data analyses revealed statistically significant differences between participants' pre-test and post-test scores on both instruments used. However, given that there are 59 and 64 possible points on the NOSS and the LOS respectively, participants' mean *post-test* NOSS (10.72) and LOS scores (38.48) did not seem to reflect adequate understandings of nature and the language of science.

Akinedehin (1988) argued that attempts to help science teachers develop adequate conceptions of NOS need to be *explicit*. The author assessed the influence of an instructional package, the *Introductory Science Teacher Education* (ISTE) package, on prospective secondary science teachers' conceptions of NOS. The package comprised nine units that included lectures, discussions, and laboratory sessions.

The first unit introduced student teachers to the nature of knowledge and varying ways of knowing, while the second discussed various aspects of the scientific enterprise and scientific disciplines. The third unit presented participants with a model of scientific inquiry that emphasized generating and defining problems, generating hypotheses, and experimenting as well as interactions between these various aspects. The model also stressed the role of established theory, ethical and regulative mechanisms, logical and mathematical systems, and creativity in scientific investigation. The fourth unit was intended to reinforce student teachers' understandings of scientific inquiry through having them map similarities between Francesco Redi's work on refuting the notion of spontaneous generation and aspects of the inquiry model with which they were presented. The fifth unit presented participants with an overview of the state of knowledge before the Greeks. Broad developments in scientific thought were then traced all the way from the fourth up to the twentieth century. During the sixth unit, participants were provided with the opportunity to practise their understandings of scientific inquiry by conducting investigations to find answers to genuine problems in chemistry, biology, and physics. The seventh unit presented students with natural phenomena and various corresponding explanations and invited them to discuss

and compare scientific versus supernatural explanations of those phenomena. The eighth unit aimed to bring about a change in participants' attitudes toward science through persuasive communication, and the final unit presented them with the humane aspects of scientific work.

A statistically significant result was obtained for the experimental group. Out of 58 possible points on the NOSS, the grand mean score was 51.84. This mean score, it should be noted, was the highest reported NOSS score among the studies presently reviewed. The standard deviations from the mean for the experimental and control groups were 1.41 and -1.41, respectively. As such, the statistical significance was in favour of the experimental group. It should be noted, however, that the author did not report the mean pre-test and post-test scores. As such, it was difficult to assess the practical significance of the gains achieved by the student teachers.

Shapiro (1996) reported on the changes in one prospective elementary teacher's thinking about the nature of investigation in science during her involvement in designing a study to answer a simple research question. This case study emerged from a larger research project that investigated the ways in which elementary student teachers' thinking and feelings about the nature of investigation in science could be studied. The project also aimed to assess the changes in elementary student teachers' thinking and feelings about the nature of scientific investigation as a result of their involvement in independent investigations.

Data for the larger study were collected over the course of four years. More than 210 elementary student teachers in four cohorts were involved in the study. During their science methods class, each cohort of student teachers worked on an assignment intended to help them develop an in-depth understanding of science and scientific procedures of investigation. Over the course of about seven weeks devoted to the assignment, student teachers were asked to pose a simple genuine problem, generate a research question, and then design a systematic procedure to answer their question. The author and other research assistants helped the student teachers in defining their problems and refining their research questions. They encouraged students to think about relevant variables and how to define and control them during the study. Throughout the assignment, student teachers kept journals of the various stages of their investigations.

During the first three years of the study, a research tool, the repertory grid, was developed and refined. This tool aimed to assess participants' thinking and feelings about the nature of investigation in science. The repertory grid and individual interviews served as the main sources of data. Twenty-one (out of the 38) fourth cohort participants completed the repertory grid at the beginning of the science methods class and again after the conclusion of the investigation. Participants were interviewed following the second administration of the grid. The interviews focused on the changes that students made in their grids.

Several other data sources were employed in the study. At the beginning of the class the student teachers were asked to provide a written statement on their definition of science. This task was also completed at the conclusion of the methods class where students were asked to indicate whether and how their definitions of science had changed as result of participating in the investigation. Other sources of data included notes made by the researcher throughout the study, and the complete records of the student teachers' notes, journals, and reflections that they made throughout the investigations.

The repertory grid had two dimensions. The first comprised personal constructs and the second elements related to conducting scientific investigations. The fifteen personal constructs were related to scientific investigation and each represented a continuum between two opposite poles. Examples of these constructs included 'using the imagination-spontaneous ideas' versus 'recipe-like prescriptive work', 'creating new knowledge' versus 'discovering what exists - the way things are', and 'using the "scientific method" to solve the problem' versus 'not using any particular method'. The personal constructs were used to provide descriptive ratings for twelve elements along the second dimension of the grid. Like the constructs, participants were provided with these elements that represented typical experiences encountered in the course of conducting a scientific investigation, such as defining a problem for investigation, delineating relevant variables, and designing tests. For each of the 12 elements, the student teachers completed a grid or chart rating the elements on each of the aforementioned 15 personal constructs. The ratings were given along a five-point scale that ran between the opposite poles of each construct.

Changes in student teachers' thinking about the nature of scientific investigations were assessed by comparing the grids completed prior to and after conducting the independent investigations. Pronounced movements on the grids were focal points for discussion during the aforementioned interviews. The interviews were analysed in conjunction with other materials generated during the study. Changes in student teachers' thinking were coded and organized into categories. These categories were eventually organized into 'themes of change' about the nature of investigations in science as a result of involvement in independent inquiries. Twelve change themes were identified.

In the present report, Shapiro (1996) only reported in detail on three 'themes of change' that were evident in the case of one prospective elementary teacher, Jan, a student teacher selected from the fourth year cohort. In this regard, it should be noted that the idiosyncrasy of the changes in teachers' thinking and the possible uniqueness of the reported case place limits on the results of the present study. The first change theme was in Jan's ideas about the nature of the steps and procedures of investigations in science. Jan indicated that she often thought of doing science as being synonymous with following rules and checklists. After participating in the investigation, she came to appreciate the role of original thinking and imagination in devising ways to come up with answers to a research question. The second change theme was in Jan's thinking about what science is. At the beginning of the methods class, Jan indicated that science is a body of information that has been tested and re-tested that it now achieved the status of facts. After the completion of the investigation, Jan noted that she came to view science more as a process of inquiry and less as a mere collection of facts. She also indicated that her experience helped her to appreciate the complexity of inquiring into everyday occurrences and the difficulty of drawing conclusions from the generated data. Finally, in the third identified change theme, Jan shifted from an objectivist view of science to one that emphasized the role of researchers in creating new knowledge. It should be noted, however, that Shapiro (1996) did not explicate the areas in which Jan showed little or no change in her thinking about the nature of investigation in science. Thus, the reported case study represented an unbalanced treatment of the issue.

As far as all the participants in the present study were concerned, the author noted that the major change for most of them was the development of an appreciation for the complexity of the process of designing and conducting an investigation. Moreover, there was an apparent shift in participants' views towards thinking of science as a collaborative enterprise.

Probably the most important features of the present study were its emphasis on reflection and its explicitness. Shapiro (1996) noted that students were often encouraged to reflect on their experiences. Moreover, the author emphasized the reflective nature of the interviews that allowed student teachers to have insights into changes in their thinking about science. This was possible due to two reasons. The first was the participants' involvement in independent investigations, which provided them with specific examples when reflecting on and delineating how their experiences affected their thinking about NOS. The second reason was the fact that student teachers were provided with specific and relevant constructs and elements that they utilized to reflect on particular aspects of their investigations. This represented an explicit aspect of the approach used in the present study to enhance participants' views of NOS. In this respect Shapiro noted that 'the use of personal constructs allowed reflection on features of changes in thinking that were not immediately apparent to students' (ibid.: 554)

Appraisal, discussion and conclusions

Before assessing the 'success' of the reviewed attempts in enhancing science teachers' views of NOS, the assumptions inherent to the alternative approaches used in the reviewed studies will be examined.

Implicit and explicit approaches: a closer look at underlying assumptions

Before turning to address this issue, an important point should be clarified. It cannot be over-emphasized that the above delineation should not be taken to mean that implicit and explicit approaches differ in terms of 'kind'. That is, not every instructional sequence in history (or philosophy) of science is an explicit attempt to enhance learners' conceptions of NOS, nor is every science process-skills instructional sequence or science-based inquiry activity an implicit approach to achieve that end. For instance, Russell noted that 'if we wish to use the history of science to influence students' understanding of science, we must . . . treat [historical] material in ways which illuminate particular characteristics in science' (1981: 56). As such, an instructional sequence in history of science can be labelled as an implicit approach if it were devoid of any discussion of one or more aspects of NOS. Similarly, involving learners in science-based inquiry activities can be more of an explicit approach if the learners were provided with opportunities to reflect on their experiences from within a conceptual framework that explicates some aspects of NOS.

Shapiro (1996), for instance, involved prospective elementary teachers in independent 'scientific investigations'. In this sense, those student teachers were 'doing science', and such an approach could be labelled 'implicit'. Shapiro, however, provided prospective teachers with personal constructs to help them reflect on specific aspects of their investigations. Some of these constructs, as previously noted, were concerned with specific aspects of NOS. These constructs represented a concep-

tual framework or an explicit tool that guided students in their thinking about, and reflections on the activities in which they were involved.

The basic difference between implicit and explicit approaches, it follows, is not a matter of the 'kind' of activities used to promote NOS understandings. The difference lies in the extent to which learners are provided (or helped to come to grips) with the conceptual tools, such as some key aspects of NOS, that would enable them to think about and reflect on the activities in which they are engaged. This difference derives from the assumptions underlying the two approaches. First, it seems that advocates of an implicit approach assumed that learning about NOS would result as a 'by-product' of the learners' engagement in science-based activities. They expected science teachers to learn about NOS as a consequence of instruction in science process-skills and/or involvement in inquiry-based activities, or as a result of changes in the learning environment despite the absence of any direct references to NOS. For instance, Barufaldi *et al.* noted that 'students presented with numerous hands-on, activity-centered, inquiry-oriented science experiences . . . should have developed a more tentative view of science' (1977: 291). There were no indications that these activities were followed by any discussions of the notion that scientific knowledge is not certain. Similarly, under the implicit approach, changes in the learning environment were believed to engender among learners better understandings of NOS. For instance, Haukoos and Penick noted that if 'the instructor assumed a low profile by sitting at student eye level and stimulated discussion of the . . . materials with questions designed to elicit student ideas', then learners would develop an understanding of the notion that scientific knowledge is not complete or absolute (1983: 631). Again, the researchers did not attempt to make students aware of the facts that scientific knowledge is tentative. They assumed that the instructors' verbal behaviours would convey the latter notion to the learners.

Contrary to what was assumed under the implicit approach, advocates of an explicit approach argued that the goal of enhancing science teachers' conceptions of NOS 'should be planned for instead of being anticipated as a side effect or secondary product of . . . science content or science methods classes' (Akindehin 1988: 73). They advanced that certain aspects of NOS should be made explicit in any attempt aimed towards fostering adequate conceptions of NOS among learners. For instance, Billeh and Hasan (1975) presented in-service secondary science teachers with twelve lectures that dealt with, among other things, the nature of scientific investigations, the nature of scientific knowledge, and sociological aspects of science. Others used instruction in history and philosophy of science to help science teachers achieve better understandings of the scientific enterprise (e.g. Jones 1969, Ogunniyi 1983). Still others used a combination of these elements. For instance, in addition to instruction on NOS, Akindehin (1988) used Francesco Redi's work on refuting the notion of 'spontaneous generation' to illustrate aspects of a dynamic model of scientific investigation with which he presented preservice science teachers. Moreover, inquiry-based activities were sometimes used in addition to the aforementioned elements to enhance teachers' conceptions of NOS (e.g. Akindehin 1988, Olstad, 1969, Shapiro, 1996).

The aforementioned differences between implicit and explicit approaches seem to be rooted in yet another assumption. This second assumption may help to clarify why advocates of an implicit approach expected learners to develop certain understandings of NOS by participating in science-based activities or,

for instance, as a result of the instructor assuming a low profile during instruction when these approaches lacked any reflective elements or direct references to NOS. Advocates of an implicit approach, it seems, assumed learning about NOS to be an 'affective' goal. Barufaldi *et al.* (1977) and Riley (1979) explicitly labelled attaining an understanding of NOS an 'affective' learning outcome. As such, conceptions of NOS were thought of as 'attitudes' or 'dispositions' towards science. Consequently, attainment of better conceptions of NOS would, as would favourable attitudes towards science, be facilitated through successful experiences in 'doing science'. By comparison, those researchers who used an explicit approach seemed to consider developing and understanding of NOS to be a 'cognitive' learning outcome. And even though none of the latter researchers made explicit use of the label, it was rather plausible to infer this from the very fact that they presented science teachers with lectures that specifically addressed clearly delineated aspects of NOS (e.g. Akindehin 1988, Billeh and Hasan 1975, Carey and Stauss 1968, 1970, Olstad 1969). To sum up, two interrelated assumptions seemed to underlie the implicit approach. The first depicted attaining an understanding of NOS to be an 'affective' learning outcome. This assumption entailed a second one: the assumption that learning about NOS would result as a by-product of 'doing science'.

The assumptions underlying the implicit approach harbour some naive views about NOS. Under this approach, it is assumed that aspects of NOS can be *directly read* from the records of the scientific enterprise and its practices. In a sense, a one-to-one correspondence is assumed between the practice of science and NOS. As such, one can *discover* aspects of NOS by going through the motions of science. However, NOS as an 'enterprise', if you will, is a reflective endeavour. The varying images of science that have been constructed throughout the history of the scientific enterprise are, by and large, the result of the collective endeavours of historians of science, philosophers of science, sociologists of science, scientists turned historians or philosophers, and reflective scientists. Within a certain time frame, the various aspects that are taken to be representative of the scientific enterprise reflect the collective attempts of those individuals to *reconstruct* the history and activities of science in an attempt to understand its workings. The endeavour to delineate various aspects of NOS is not a matter of merely reading the 'book of science' or going through its motions, but rather a matter of putting questions to that book and reflecting on that practice. Kuhn (1970) noted that a shift in the 'kind' of questions that historians asked of the records of science has completely transformed the way science is viewed.

It follows that even though any attempt to foster better understandings of NOS among science teachers should be framed within the context of the content and activities of science, these attempts, nevertheless, should be explicit and reflective. It is essential that teachers be provided with conceptual frameworks that would help them to construct better understandings of certain aspects of NOS. These conceptual frameworks, as previously noted, are the products of a purposeful and elaborate endeavour by a collective of individuals who examined and continue to examine the scientific enterprise. It is unlikely that prospective or practising science teachers would be able to construct such elaborate conceptual frameworks through their relatively limited experiences with the various dimensions of the scientific enterprise, and enterprises that systematically study the scientific endeavour (i.e. history, philosophy, and sociology of science).

The underlying assumptions of the implicit approach seemed to have compromised its effectiveness in enhancing science teachers' understandings of NOS. If a more critical appraisal of the success of the implicit and explicit approaches is deferred for the moment, and if the reviewed studies are examined on the basis of the statistical models that were employed and the numerical gains that were reported, then it could be concluded that - to the extent that the instruments in use faithfully assessed participants' NOS views - an explicit approach was generally *more* 'effective' in fostering 'appropriate' conceptions of NOS among prospective and practising science teachers. This conclusion is based on the fact that, on the one hand, all eight studies that employed an explicit approach reported statistically significant gains in participant science teachers' conceptions of NOS as measured by the respective instruments in use (Akindehin 1988, Billeh and Hasan 1975, Carey and Stauss 1968, 1970, Jones 1969, Lavach 1969, Ogunniyi 1983, Olstad 1969). On the other hand, of the eight studies that employed an implicit approach, four reported no statistically significant gains in participants' understandings of NOS as measured by the same instruments (Haukoos and Pennick 1985, Riley 1979, Scharmann and Harris 1992, Spears and Zollman 1977). Moreover, the results in a fifth study (Scharmann 1990) were equivocal.

Nonetheless, a more critical appraisal of the effectiveness of the various attempts undertaken to enhance science teachers' conceptions of NOS is central to the present review. This appraisal should, as noted earlier, be undertaken from the standpoint that the teachers' resultant understandings of NOS would adequately meet the condition deemed necessary to enable those teachers to convey appropriate conceptions of the scientific enterprise to their students.

The success of the reviewed attempts in meeting the necessary condition

Before addressing this issue it is crucial to delineate the knowledge base deemed necessary for teaching NOS to pre-college students. In the following argument, attaining an understanding of NOS is taken to be a *cognitive* learning outcome.

Generally, mastery of two components is deemed necessary for one to be able to 'effectively' teach a certain topic. The first is knowledge of the content of the target topic. In the case of NOS, this component would correspond to, for instance, knowledge of various aspects of NOS emphasized in recent reform documents (e.g. AAAS 1990, 1993, Millar and Osbourne 1998, NRC 1996). The second component is knowledge of pedagogy. This component refers to knowledge of generic pedagogical principles, the characteristics of the learner, and classroom management skills. However, a third component has been gaining increased recognition as pivotal to effective teaching. This component is pedagogical content knowledge (PCK) (Shulman 1986, 1987, Wilson *et al.* 1987). Applied to teaching about NOS, PCK would include, in addition to an adequate understanding of various aspects of NOS, knowledge of a wide range of related examples, activities, illustrations, explanations, demonstrations, and historical episodes. These components would enable the teacher to organize, represent, and present the topic for instruction in a manner that makes target aspects of NOS accessible to pre-college students. Moreover, knowledge of alternative ways of representing aspects of NOS would enable the teacher to adapt those aspects to the diverse interests and abilities of learners.

It is against this knowledge base that one is tempted to appraise the success of the attempts undertaken to enhance science teachers' understandings of NOS. However, such an appraisal may be unrealistic given that PCK usually develops as a result of extensive and extended experiences in teaching a certain topic. Alternatively, what needs to be emphasized is that teaching about NOS requires science teachers to have *more* than a rudimentary or superficial knowledge and understanding of various aspects of NOS. Those teachers should be able to comfortably discourse about NOS (Robinson 1969), lead discussions regarding various aspects of NOS, design science-based activities that would help students to comprehend those aspects, and contextualize their teaching about NOS with some examples or 'stories' from history of science. For instance, it is not enough for teachers to 'know' that scientific knowledge is socially and culturally embedded. They should be able to use examples and/or simplified case histories from scientific practice to substantiate this claim and make it accessible and understandable to students.

Appraised against the above background, it is safe to conclude that, in general, the aforementioned studies were *not* successful in fostering among science teachers understandings of NOS that would enable them to effectively teach this valued aspect of science. This conclusion is based on three common features of the studies. This first relates to the practical significance of the gross numerical gains reported in the various studies. If we grant that teachers' scores on the various instruments that purported to measure their NOS conceptions were faithful representations of those teachers' views of science, we still come to the conclusion that the statistically significant gains reported were mostly too small to be of any practical significance (see the sixth column in table 2 and table 3).

Haukoos and Penick (1985) and Riley (1979) reported no statistically significant gains in participants' scores on the SPI and TOUS respectively. Scharmann and Harris (1992) reported no significant gains in participants' NOSS scores. Significant gains, nevertheless, were reported for participants' scores on another instrument (Johnson and Peeples 1987). However, the reported mean gain scores on this latter instrument amounted to a mere 1.5 percentage points. Participants in the Spears and Zollman (1977) study achieved no significant gains on three of the four components of the SPI. The authors, however, reported a gain that amounted to 2.5 percentage points on the activities component of that instrument. Ogunniyi (1983) reported a statistically significant gain that amounted to about 3 percentage points on the NOSS. Barufaldi *et al.* (1977) obtained an average gain of about 4 percentage points on the VOST. Carey and Stauss (1968) and Olstad (1969) reported mean gain scores of about 4.5 percentage points on the TOUS. The gain achieved in Lavach's (1969) study was on the order of about 6 percentage points. Finally, Haukoos and Penick (1983) obtained a significant gain on the order of 8 percentage points on the SPI. However, this result was severely compromised by the fact that the authors were not able to replicate it in their second study (Haukoos and Penick 1985).

A second feature that characterized many studies was that irrespective of the gains achieved, the participants' post-treatment scores indicated, at best, limited understandings of NOS (see the seventh column in table 2 and table 3). For instance, the post-test mean NOSS scores achieved by teachers in the Ogunniyi (1983) study indicated less than 20 per cent agreement with the model for NOS adopted by the developers of the instrument. Bileh and Hasan (1975) reported

statistically significant mean gain scores on the order of 10 percentage points. However, the post-test mean scores achieved by the teachers in the experimental group indicated a little bit more than 50 per cent agreement with the model for the NOST. Similarly, even though the gains reported by Trembath (1972) amounted to about 20 percentage points, the participants' mean post-test scores indicated a little more than 50 per cent agreement with the model of NOS adopted by the author.

Only in two of the reviewed studies did participants achieve gains that might start to count as practically significant. Carey and Stauss (1970) and Jones (1969) reported statistically significant gains that were on the order of about 11 percentage points. More importantly, the participants' post-test scores indicated about 85 per cent and 73 per cent agreement with the models for NOS that underlie the WISP and the TOUS respectively. Finally, the post-test mean NOSS scores reported by Akindehin (1988) indicated more than 90 per cent agreement with the models for NOS adopted by the author. However, given that Akindehin did not report the mean pre-test and post-test NOSS scores, it was difficult to assess the impact of the ISTE package that he used in the study.

The third feature that characterized the reviewed studies was the relatively short duration of the various treatments. These treatments typically ranged from a few hours to a few days (see the fifth column in table 2 and table 3). For instance, Trembath's (1972) programme spanned a mere $2\frac{1}{2}$ hours. Scharmann (1990) implemented his diversified instructional strategy over the course of $4\frac{1}{2}$ hours. Both Billeh and Hasan (1975) and Akindehin (1988) delivered their instruction about NOS in 12 hours. In most of the remaining studies, attempts to improve science teachers' understandings of NOS were framed within the context of science methods courses. Given the multitude of objectives that such courses often aim to achieve, it is difficult to imagine that the time dedicated to dealing with NOS was significantly longer than the time this topic was allotted in the aforementioned studies. Given the well-documented resistance of learners' misconceptions to change, even in response to formal instructions (Hewson and Hewson 1983, Treagust *et al.* 1996), it is highly unlikely that participants' views of NOS could be substantially 'improved' during such short treatments. Thus, it can be concluded that the conditions necessary for enabling teachers to effectively convey to students adequate views of NOS (i.e. helping teachers to develop elaborate understandings of such views themselves), has *not* been sufficiently met

Implications for teacher education

In the absence of any systematic reform of science teaching, especially at the college level, it is highly likely that candidate teachers will continue to join teacher education programmes with naive views of the scientific enterprise (Lederman and Latz 1995, Stofflet and Stoddart 1994). As such, science teacher education programmes should continue their attempts to promote among prospective teachers more adequate conceptions of NOS. The present review suggests that approaches that utilize elements from history and philosophy of science and/or direct instruction on NOS are more effective in achieving that end than approaches that utilize science process-kills instruction or non-reflective inquiry-based activities. To be effective, the use of science-based activities should be coupled with opportunities to help prospective teachers reflect on their experiences from within an explicit

framework that outlines certain aspects of NOS. Irrespective of the specific approach used, explicitness and reflection should be made focal to any attempt geared toward improving science teachers' conceptions of NOS (see, for example, Dickinson *et al.* 1999).

Moreover, NOS should be made a pervasive theme throughout science teacher education. The aforementioned research on the translation of teachers' views of NOS into their classroom practice indicates that prospective teachers should be given opportunities to discuss and reflect on the various aspects of NOS within the various contexts of teacher education. For instance, prospective teachers could be asked to design lessons that aim to promote understandings of NOS in micro-teaching courses. They could be asked to design an instructional unit on NOS in curriculum courses. They could be assigned the task of designing alternative methods to assess students' understandings of NOS in evaluation and assessment classes, and so on. The idea is to get prospective teachers to reflect on and think about the various dimensions related to teaching about NOS in context specific situations such as planning and assessment (see for example, Lederman *et al.* 1999).

Implications for research

The realities of teacher preparation programmes and courses, however, impose limits on what can be done within the context of those programmes and/or courses to enhance science teachers' views of NOS. As noted above, the relative ineffectiveness of the reviewed attempts to enhance teachers' conceptions of NOS should not be surprising given that the duration of the treatments was very short. It is highly unlikely that prospective and practising teachers' NOS views, views that have developed over the course of at least 14 years of high school and college science, could be effectively changed, updated, or elaborated during a few hours, days or weeks for that matter.

The relatively limited time that can be dedicated to improving science teachers' views of NOS within teacher education programmes is understandable given that agendas of those programmes are already extensive and overly long. During their years in teaching education, prospective teachers enrol in courses designed to familiarize them with areas related to educational psychology, foundations of education, pedagogy, classroom management, instructional design, teaching methods, evaluation, school policies and laws, and current reforms in, and the recent research literature relevant to teaching and learning. Over and above that, prospective teachers spent roughly one-third of their final year in teacher preparation student teaching in schools.

As such, and rightly so, some educators argue that the efforts to enhance prospective teachers' NOS conceptions undertaken within science teacher education programmes need to be argued with relevant coursework in other disciplinary departments (Bork 1967, Brush 1969, Matthews 1994). *Intuitively*, coursework in philosophy and history of science, disciplines which respectively deal with the epistemology of scientific knowledge and its development, serve as primary candidates. Indeed, during the past 70 years, many science educators have argued that coursework in history and/or philosophy of science could serve to improve science teachers' conceptions of NOS (Abimbola 1983, Brush 1969, Conant 1947, Haywood 1927, Klopfer and Watson 1957, Matthews 1994, O'Brien

and Korth 1991, Robinson 1969, Rutherford 1964). A multitude of wide-ranging courses in history and philosophy of science are already instituted in the respective academic departments. Moreover, many science educators have advanced elaborate outlines for courses in history (e.g. O'Brien and Korth 1991) and philosophy of science (e.g. Loving 1991).

However, despite the longevity of these arguments, and to the best of our knowledge, there is *not* one single empirical study in the science education literature that examined the influence of college level history of science or philosophy of science disciplinary courses on learners' conceptions of NOS. Science educators have mainly studied the influence of science teaching that incorporates history of science on learners' conceptions of NOS (Russell 1981). Based on those studies, they inferred a potentially useful role for history of science courses in improving science teachers' NOS conceptions. Nonetheless, an examination of the efforts that aimed to assess the influence of incorporating history of science in science teaching on students' conceptions of NOS (Klopfer and Cooley 1963, Solomon *et al.* 1992, Welch and Walberg 1972, Yager and Wick 1966) indicates that evidence concerning the effectiveness of the historical approach is, at best, inconclusive.

As such, suggestions to include courses in history and philosophy of science in the preparation of science teachers do not seem to be grounded in any firm empirical literature. Indeed, it is rather perplexing that this line of research has not been pursued. While there might be compelling theoretical arguments that support such an intuitive claim, empirical research that critically examines the influence of history and philosophy of science courses on prospective and practising science teachers' views of NOS needs to be pursued.

Additionally, research efforts on the effectiveness of various instructional sequences undertaken within the context of science teacher education and inservice training programmes to respectively improve prospective and practising science teachers' conceptions of NOS should be continued. In this regard, research into the effectiveness of NOS instruction undertaken from within a conceptual change philosophy is certainly worthwhile pursuing.

Moreover, it should be emphasized that possessing adequate understandings of NOS is not sufficient to enable teachers to enhance students' conceptions of the scientific enterprise. Research efforts that aim to identify and isolate the factors that constrain or facilitate the translation of teachers' conceptions of NOS into classroom practice need to be pursued as well. Attempts to mitigate constraining factors or augment facilitating ones need to be investigated. These latter research efforts, however, should always keep in mind that having 'adequate' conceptions of NOS is necessary for 'effective' NOS instruction. Research into factors that might impede or facilitate the translation of teachers' views of NOS into their instructional practices should always clearly delineate participant science teachers' views of NOS. Finally, research efforts that aim to investigate the relationship between teachers' conceptions of NOS and students' conceptions need to be pursued.

References

- (AAAS) American Association for the Advancement of Science (1990) *Science for all Americans* (New York: Oxford University Press).
- (AAAS) American Association for the Advancement of Science (1993) *Benchmarks for Science Literacy: A Project 2061 Report*. (New York: Oxford University Press).

- ABD-EL-KHALICK, F., BELL, R. L. and LEDERMAN, N. G. (1998) The nature of science and instructional practice: making the unnatural natural. *Science Education*, 82, 417-437.
- ABD-EL-KHALICK, F. and BOUJAOUDE, S. (1997) An exploratory study of the knowledge base for science teaching. *Journal of Research in Science Teaching*, 34, 673-699.
- ABIMBOLA, I. O. (1983) The relevance of the 'new' philosophy of science for the science curriculum. *School Science and Mathematics*, 83, 181-193.
- AIKENHEAD, G. (1973) The measurement of high school students' knowledge about science and scientists. *Science Education*, 57, 539-549.
- AIKENHEAD, G., RYAN, A. and DESAUTELS, J. (1989) Monitoring student views on science-technology-society issues: the development of multiple choice items. Paper presented at the annual meeting of the National Association for Research in Science Teaching, San Francisco, CA, April.
- AKINDEHIN, F. (1988) Effect of an instructional package on preservice science teachers' understanding of the nature of science and acquisition of science-related attitudes. *Science Education*, 72, 73-82.
- BALL, D. L. and McDIARMID, G. W. (1990) The subject-matter preparation of teachers. In W. R. Houston (ed.) *Handbook of Research on Teacher Education* (New York: Macmillan), pp, 437-465.
- BARNES, B. (1974) *Scientific Knowledge and Sociological Theory* (London: Routledge and Kegan Paul).
- BARUFALDI, J. P., BETHEL, L. J. and LAMB, W. G. (1977) The effect of a science methods course on the philosophical view of science among elementary education majors. *Journal of Research in Science Teaching*, 14, 289-294.
- BEHNKE, F. L. (1950) Reactions of scientists and science teachers to statements bearing on certain aspects of science and science teaching. *School Science and Mathematics*, 61, 193-207.
- BILLEH, V. Y. and HASAN, O. E. (1975) Factors influencing teachers' gain in understanding the nature of science. *Journal of Research in Science Teaching*, 12, 209-219.
- BLOOR, D. (1976) *Knowledge and Social Imagery* (London: Routledge and Kegan Paul).
- BORK, A. M. (1967) *The Reed College M.A.T. Program in Science: A Study* (Portland, OR: Reed College).
- BRICKHOUSE, N. W. and BODNER, G. M. (1992) The beginning science teacher: classroom narratives of convictions and constraints. *Journal of Research in Science Teaching*, 29, 471-485.
- BROADHURST, N. A. (1970) A study of selected learning outcomes of graduating high school students in South Australian schools. *Science Education*, 54, 17-21.
- BROWN, S. and CLARKE, N. (1960) *International Education in Physics* (Michigan: Michigan Institute of Technology).
- BRUSH, S. G. (1969) The role of history in the teaching of physics. *The Physics Teacher*, 7, 271.
- California Department of Education (1990) *Science Framework for California Public Schools* (Sacramento, CA: California Department of Education).
- CAREY, R. L. and STAUSS, N. G. (1968) An analysis of the understanding of the nature of science by prospective secondary science teachers. *Science Education*, 52, 358-363.
- CAREY, R. L. and STAUSS, N. G. (1969) An analysis of the relationship between prospective science teachers' understanding of the nature of science and certain academic variables. *Bulletin of the Georgia Academy of Science*, 27, 148-158.
- CAREY, R. L. and STAUSS, N. G. (1970) An analysis of experienced science teachers' understanding of the nature of science. *School Science and Mathematics*, 70, 366-376.
- CARNAP, R. (1937) *The Logical Syntax of Language* (London: Routledge and Kegan Paul).
- Centre of Unified Science Education (1974) *The Dimensions of Scientific Literacy* (Columbus, OH: Ohio State University).
- Central Association for Science and Mathematics Teachers (1907) A consideration of the principles that should determine the courses in biology in secondary schools. *School Science and Mathematics*, 7, 241-247.
- COLLINS, H. M. (1985) *Changing Order: Replication and Induction in Scientific Knowledge* (2nd edn) (London: Sage).

- CONANT, J. B. (1947) *On Understanding Science: An Historical Approach* (New Haven: Yale University Press).
- COOLEY, W. W. and KLOPPER, L. E. (1961) *Test on Understanding Science* (Princeton, NJ: Educational Testing Service).
- DICKINSON, V., ABD-EL-KHALICK, F. and LEDERMAN, N. G. (1999) The influence of a reflective activity-based approach on elementary teachers' conceptions of the nature of science. Paper presented at the annual meeting of the National Association for Research in Science Teaching, Boston, MA, March.
- DUSCHL, R. A. and WRIGHT, E. (1989) A case study of high school teachers' decision making models for planning and teaching science. *Journal of Research in Science Teaching*, 26, 467-501.
- FEYERABEND, P. (1988) *Against Method* (New York: Verso).
- GABEL, D. L., RUBBA, P. A. and FRANZ, J. R., (1977) The effect of early teaching and training experiences on physics achievement, attitude toward science and science teaching, and process skill proficiency. *Science Education*, 61, 503-511.
- GIERE, R. N. (1988) *Exploring Science: A Cognitive Approach* (Chicago: The University of Chicago Press).
- GRUBER, H. E. (1960) Science teachers and the scientific attitude: an appraisal of an academic year institute. *Science*, 132, 467-468.
- GRUBER, H. E. (1963) Science as doctrine or thought? A critical study of nine academic year institutes. *Journal of Research in Science Teaching*, 1, 124-128.
- HABERMAS, J. (1972) *Knowledge and Human Interest* (trans J. Shapiro) (Boston: Beacon Press).
- HAUKOOS, G. D. and PENICK, J. E. (1983) The influence of classroom climate on science process and content achievement of community college students. *Journal of Research in Science Teaching*, 20, 629-637.
- HAUKOOS, G. D. and PENICK, J. E. (1985) The effects of classroom climate on college science students: a replication study. *Journal of Research in Science Teaching*, 22, 163-168.
- HAYWOOD, H. (1927) Fundamental laws of chemistry. *School Science Review*, 9, 92.
- HEWSON, M. G. and HEWSON, P. W. (1983) Effect of instruction using students' prior knowledge and conceptual change strategies on science learning. *Journal of Research in Science Teaching*, 20, 731-743.
- HODSON, D. (1985) Philosophy of science, science and science education. *Studies in Science Education*, 12, 25-57.
- HODSON, D. (1993) Philosophic stance of secondary school science teachers, curriculum experiences, and children's understanding of science: some preliminary findings. *Interchange*, 24, 41-52.
- JOHNSON, R. L. and PEEPLES, E. E. (1987) The role of scientific understanding in college: student acceptance of evolution. *American Biology Teacher*, 49, 96-98.
- JONES, K. M. (1969) The attainment of understandings about the scientific enterprise, scientists, and the aims and methods of science by students in a college physical science course. *Journal of Research in Science Teaching*, 6, 47-49.
- KIMBALL, M. E. (1967-68) Understanding the nature of science: a comparison of scientists and science teachers. *Journal of Research in Science Teaching*, 5, 110-120.
- KLOPPER, L. E. (1964) The use of case histories in science teaching. *School Science and Mathematics*, 64, 660-666.
- KLOPPER, L. E. (1969) The teaching of science and the history of science. *Journal of Research for Science Teaching*, 6, 87-95.
- KLOPPER, L. E. and COOLEY, W. W. (1963) The history of science cases for high schools in the development of student understanding of science and scientists. *Journal of Research for Science Teaching*, 1, 33-47.
- KLOPPER, L. E. and WATSON, F. G. (1957) Historical materials and high school science teaching. *The Science Teacher*, 24, 264-293.
- KUHN, T. S. (1962) *The Structure of Scientific Revolutions* (Chicago: The University of Chicago Press).
- KUHN, T. S. (1970) *The Structure of Scientific Revolutions* (2nd edn) (Chicago: The University of Chicago Press).
- KUHN, T. S. (1977) *The Essential Tension* (Chicago: The University of Chicago Press).

- LAKATOS, I. (1980) Falsification and the methodology of scientific research programmes. In J. Worrall and G. Currie (eds) *Imre Lakatos Philosophical Papers: Vol. 1. The Methodology of Scientific Research Programs* (Cambridge: Cambridge University Press) (pp. 8-101).
- LANTZ, O. and KASS, H. (1987) Chemistry teachers' functional paradigms. *Science Education*, 71, 117-134.
- LATOUR, B. (1986) *Science in Action: How to Follow Scientists and Engineers through Society* (Milton Keynes: Open University Press).
- LATOUR, B. and WOOLGAR, S. (1986) *Laboratory Life: The Construction of Scientific Facts* (Princeton, NJ: Princeton University Press).
- LAUDAN, L. (1977) *Progress and its Problems* (Berkeley, CA: University of California Press).
- LAVACH, J. F. (1969) Organization and evaluation of an inservice program in the history of science. *Journal of Research in Science Teaching*, 6, 166-170.
- LAWSON, A. E. (1982) The nature of advanced reasoning and science instruction. *Journal of Research in Science Teaching*, 19, 743-760.
- LEDERMAN, N. G. (1992) Students' and teachers' conceptions of the nature of science: a review of the research. *Journal of Research in Science Teaching*, 29, 331-359.
- LEDERMAN, N. G. (1999) Teachers' understanding of the nature of science and classroom practice: factors that facilitate or impede the relationship. *Journal of Research in Science Teaching*, 36, 916-929.
- LEDERMAN, N. G. and LATZ, M. S. (1995) Knowledge structures in the preservice science teacher: sources, development, interactions, and relationships to teaching. *Journal of Science Teacher Education*, 6, 1-19.
- LEDERMAN, N. G. and O'MALLEY, M. (1990) Students' perceptions of tentativeness in science: development, use, and sources of change. *Science Education*, 74, 225-239.
- LEDERMAN, N. G., SCHWARTZ, R. ABD-EL-KHALICK, F. and BELL, R. L. (1999) Preservice teachers and their nature of science instruction: factors that facilitate success. Paper presented at the annual meeting of the National Association for the Research in Science Teaching, Boston, MA, March.
- LEDERMAN, N. G., WADE, P. D. and BELL, R. L. (1998) Assessing understanding of the nature of science: a historical perspective. In W. McComas (ed.) *The Nature of Science and Science Education: Rationales and Strategies* (Dordrecht, The Netherlands: Kluwer Academic Publishers, pp. 331-350).
- LONGINO, H. E. (1990) *Science as Social Knowledge: Values and Objectivity in Scientific Inquiry* (Princeton, NJ: Princeton University Press)
- LOVING, C. C. (1991) The scientific theory profile: a philosophy of science model for science teachers. *Journal of Research in Science Teaching*, 28, 823-838.
- MACKAY, L. D. (1971) Development of understanding about the nature of science. *Journal of Research in Science Teaching*, 8, 57-66.
- MATTHEWS, M. R. (1994) *Science Teaching: The Role of History and Philosophy of Science* (New York: Routledge).
- MERILL, R. and BUTTS, D. (1969). Vitalizing the role of the teacher. In D. Butts (ed.) *Designs for Progress in Science Education* (Washington, DC: National Science Teachers Association) pp. 35-42.
- MERTON, R. K. (1949) *Social Theory and Social Structure* (New York: Free Press).
- MILLAR, R. and OSBORNE, J. (eds) (1998). *Beyond 2000: Science Education for the Future* (London: King's College).
- MULKAY, M. J. (1979) *Science and the Sociology of Knowledge* (London: Allen & Unwin).
- MULKAY, M. J. (1981) Action and belief or scientific discourse? A possible way of ending intellectual vassalage in social studies of science. *Philosophy of the Social Sciences*, 11, 163-171.
- (NRC) National Research Council (1996) *National Science Education Standards* (Washington, DC: National Academic Press).
- (NSTA) National Science Teachers Association (1982) *Science-Technology-Society: Science Education for the 1980s* (An NSTA position statement) (Washington, DC: NSTA).
- O'BRIEN, G. E. and KORTH, W. W. (1991) Teachers' self-examination of their understanding of the nature of science: a history and philosophy of science course responsive to science teachers' needs. *Journal of Research in Science Teacher Education*, 2, 94-100.

- OGUNNIYI, M. B. (1982) An analysis of prospective science teachers' understanding of the nature of science. *Journal of Research in Science Teaching*, 19, 25-32.
- OGUNNIYI, M. B. (1983) Relative effects of a history/philosophy of science course on student teachers' performance on two models of science. *Research in Science & Technological Education*, 1, 193-199.
- OLSTAD, R. G. (1969) The effect of science teaching methods on the understanding of science. *Science Education*, 53, 9-11.
- PINCH, T. J. (1986) *Confronting Nature: The Sociology of Solar-Neutrino Detection* (Dordrecht: Reidel).
- POMEROY, D. (1993) Implications of teachers' beliefs about the nature of science: comparison of the beliefs of scientists, secondary science teachers, and elementary teachers. *Science Education*, 77, 261-278.
- POPPER, K. R. (1959) *The Logic of Scientific Discovery* (London: Hutchinson Education).
- POPPER, K. R. (1970) Normal science and its dangers. In I. Lakatos and A. Musgrave (eds) *Criticism and the Growth of Knowledge* (Cambridge: Cambridge University Press), 51-59.
- POPPER, K. R. (1994) *The Myth of the Framework: In Defense of Science and Rationality* (London: Routledge).
- RAMSEY, G. and HOWE, R. (1969) An analysis of research on instructional procedures in secondary school science. *The Science Teacher*, 36, 62-68.
- REICHENBACH, H. (1938) *Experience and Prediction* (Chicago: University of Chicago Press).
- RILEY, J. P. II (1979) The influence of hands-on science process training on preservice teachers' acquisition of process skills and attitude toward science and science teaching. *Journal of Research in Science Teaching*, 16, 373-384.
- ROBINSON, J. T. (1965) Science teaching and the nature of science. *Journal of Research in Science Teaching*, 3, 37-50.
- ROBINSON, J. T. (1969) Philosophy of science: implications for teacher education. *Journal of research in Science Teaching*, 6, 99-104.
- RORTY, R. (1991) *Objectivity, Relativism, and Truth: Philosophical Papers* (Vol. 1) (Cambridge: Cambridge University Press).
- ROWE, M. B. (1974) A humanistic intent: the program of preservice elementary education at the University of Florida. *Science Education*, 58, 369-376.
- RUBBA, P. A. (1977) The development, field testing and validation of an instrument to assess secondary school students' understandings of the nature of scientific knowledge. *Dissertations Abstracts International*, 38, 5378A (University Microfilms No. 78-00, 998).
- RUBBA, P., HORNER, J. and SMITH, J. M. (1981) A study of two misconceptions about the nature of science among junior high school students. *School Science and Mathematics*, 81, 221-226.
- RUSSELL, B. (1914) *Our Knowledge of the External World* (London: Allen & Unwin).
- RUSSELL, T. L. (1981) What history of science, how much, and why? *Science Education*, 65, 51-64.
- RUTHERFORD, J. F. (1964) The role of inquiry in science teaching. *Journal of Research in Science Teaching*, 2, 80-84.
- SCHARMANN, L. C. (1988a) Locus of control: a discriminator of the ability to foster an understanding of the nature of science among preservice elementary teachers. *Science Education*, 72, 453-465.
- SCHARMANN, L. C. (1988b) The influence of sequenced instructional strategy and locus of control on preservice elementary teachers' understandings of the nature of science. *Journal of Research in Science Teaching*, 25, 589-604.
- SCHARMANN, L. C. (1990) Enhancing the understanding of the premises of evolutionary theory: the influence of diversified instructional strategy. *School Science and Mathematics*, 90, 91-100.
- SCHARMANN, L. C. and HARRIS, W. M., JR. (1992) Teaching evolution: understanding and applying the nature of science. *Journal of Research in Science Teaching*, 29, 375-388.
- Scientific Literacy Research Center (1967) *Wisconsin Inventory of Science Processes* (Madison, WI: The University of Wisconsin).
- SHAPIN, S. (1996) *The Scientific Revolution* (Chicago: The University of Chicago Press).

- SHAPIRO, B. L. (1996) A case study of change in elementary student teacher thinking during an independent investigation in science: learning about the 'face of science that does not yet know.' *Science Education*, 80, 535-560.
- SHULMAN, L. S. (1986) Those who understand: knowledge growth in teaching. *Educational Researcher*, 15, 4-14.
- SHULMAN, L. S. (1987) Knowledge and teaching: foundations of the new reform. *Harvard Educational Review*, 57, 1-22.
- SHYMANSKY, J. A. and PENICK, J. E. (1977) The use of systematic observations to improve college science laboratory. *Science Education*, 63, 195-203.
- SOLOMON, J., DUVEEN, J., SCOT, L. and MCCARTHY, S. (1992) Teaching about the nature of science through history: action research in the classroom. *Journal of Research in Science Teaching*, 29, 409-421.
- SPEARS, J. and ZOLLMAN, D. (1977) The influence of structured versus unstructured laboratory on students' understanding the process of science. *Journal of Research in Science Teaching*, 14, 33-38.
- STOFFLET, R. and STODDART, T. (1994) The ability to understand and use conceptual change pedagogy as a function of prior content learning experience. *Journal of Research in Science Teaching*, 31, 31-51.
- TAMIR, P. and ZOHAR, A. (1991) Anthropomorphism and teleology in reasoning about biological phenomena. *Science Education*, 75, 57-68.
- TREGUST, D. F., DUIT, R. and FRASER, B. J. (1996) Overview: research on students' pre-instructional conceptions - the driving force for improving teaching and learning in science and mathematics. In D. F. Treagust, R. Duit and B. J. Fraser (eds) *Improving Teaching and Learning in Science and Mathematics* (New York: Teachers College Press), pp. 1-14.
- TREMBATH, R. J. (1972) The structure of science. *The Australian Science Teachers Journal*, 18, 59-63.
- VAN FRAASSEN, B. C. (1985) Empiricism in the philosophy of science. In P. M. Churchland and C. A. Hooker (eds) *Images of Science* (Chicago: University of Chicago Press), pp. 245-308.
- WELCH, W. W. and PELLA, M. O. (1967-68) The development of an instrument for inventorying knowledge of the processes of science. *Journal of Research in Science Teaching*, 5, 64.
- WELCH, W. W. and WALBERG, H. J. (1967-68) An evaluation of summer institute programs for physics teachers. *Journal of Research in Science Teaching*, 5, 105-109.
- WELCH, W. W. and WALBERG, H. J. (1972) A national experiment in curriculum evaluation. *American Educational Research Journal*, 38, 373, 383.
- WILSON, L. (1954) A study of opinions related to the nature of science and its purpose in society. *Science Education*, 38, 159-164.
- WILSON, S. M., SHULMAN, L. S. and RICHERT, E. R. (1987) '150 different ways' of knowing: Representation of knowledge in teaching. In J. Calderhead (ed.) *Exploring Teachers' Thinking* (New York: Taylor and Francis).
- WOOD, R. L. (1972) University education student's understanding of the nature and process of science. *School Science and Mathematics*, 72, 73-79.
- YAGER, R. E. and WICK, J. W. (1966) Three emphases in teaching biology: a statistical comparison of results. *Journal of Research in Science Teaching*, 4, 16-20.