A Somewhat Brief History of Research on Scientific Thinking and Reasoning

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Introduction

The cognitive abilities of the mind have been of great interest and have been subjected to much scrutiny since the emergence of early modern-day science in Europe during the sixteenth and seventeenth centuries. This period in the history of science, popularly described as the 'Scientific Revolution', witnessed a complete overhaul of the existing metaphysical knowledge from the Middle Ages, leading to a collective social and intellectual transformation. Since then, historians have recorded how scientists and non-specialists alike have routinely and vigorously debated the most appropriate scientific methods and attendant thinking. However, systematic studies of how scientists reason as they engage in their activities have only been traced back to the early twentieth century with Gestalt psychologist Wertheimer's methodical investigation of Einstein's thought processes. From then on, there have been multiple scientific thinking and reasoning perspectives. Some of these perspectives have significantly impacted teaching and assessment approaches.

This essay is an account of the research on scientific thinking and reasoning. It presents the argument that despite long-standing interest in science research and education, there is limited understanding about the specific nature of the higher-order cognitive proficiencies valued by the scientific community. A novel conceptualisation of scientific thinking and reasoning, based on emerging philosophical, psychological and cognitive perspectives, is briefly described.

Conceptions of Scientific Reasoning in the Antiquity and Middle Ages

Science is a uniquely human endeavour. A key distinguishing feature of humankind is a scientifically engaged mind (Huff, 2003). Surviving off the land and the sea were the practical reasons that led to the beginnings of science in the early literate cultures of antiquity around 3000 B. C. Understanding and predicting the seasons and weather with mathematical tools and detailed records required the development of new ways of thinking and abstraction (Lindberg, 2007). However, evidence suggests that focus on the cognitive abilities underlying scientific pursuits only started about 2,500 years ago in ancient Greece (Feist, 2006). The teachings of philosophers such as Socrates and Aristotle broke from traditional supernatural assumptions and attributed the origins of material and sensory observations to forces of nature (Cohen, 2010). The Greek form of science or natural philosophy sought more to know and describe than to create and invent (Huff, 2003). Besides accruing and organising knowledge about the natural world, Greek philosophers developed novel mathematical principles, as well as expounded original criteria and techniques for logical analysis of theories (Crombie, 1994). The Greeks initiated the methodical use of various reasoning forms in their scientific arguments, chief of which were deduction, induction and abduction (Folger & Stein, 2017). Greek accomplishments in science also expanded into the area of scientific experimentation and demonstrated an awareness of epistemic notions such as the value of a control variable and the difference between correlational and causal conclusions (Cohen, 2010).

Although Greek culture fell sharply into decline with the rise of the Roman empire, its philosophy continued to dominate and influence the subsequent work and ideas of later philosophers (Cloud, 2007). For instance, from the 900s till around the 1200s, Arab scholars translated Greek writings and actively extended Greek philosophical ideas and reasoning (Huff, 2003). From the twelfth century onward, there was more extensive dissemination of key ideas and philosophy from Greek and Arabic sources by medieval European universities (Grant, 1984). The next four hundred year period in western history – the Middle Ages – witnessed some innovative development and inquiry of both scientific activities and the thinking required. Contemporary commentators argued that some medieval thinkers substantially modified prevailing Greek or Aristotelian views of science, without intellectual and cognitive compromises on syllogistic inferences, logical reasoning, mathematical postulations, and the use of theoretical and experimental investigations (Lindberg, 2007; Perler, 2015).

Conceptions of Scientific Reasoning from the Sixteenth to the Eighteenth Centuries

However, scrutiny of the mental processes required for scientific experimentation and discoveries only came to the forefront with the emergence of early modern science during the sixteenth and seventeenth centuries (Dunbar & Klahr, 2012). Commonly referred to as the 'Scientific Revolution' (Butterfield, 1962), this epochal period witnessed the inauguration of "a great social and intellectual transformation" (Huff, 2003, p. 5). Many of the prevalent Aristotelian and medieval views of science were dismantled and replaced with a brand-new science conception that focused on methodical observations and systematic experimentation for constructing knowledge or confirming theories (Hatfield, 1990). Important and wide-ranging scientific discoveries such as the heliocentric view of the universe, laws of motion and gases, mechanics, and taxonomical rules, were established. Besides the growth of knowledge, there was a proliferation of quantification methods in fields such as astronomy and physics. This 'mathematisation of nature' (Henry, 2008, p. 18) signified the primacy of the language of logic, shape and quantity, not just as a tool for calculation, but also as a means of symbolically representing how nature works. Aiding the increasing adoption of empirical measures in the scientific discovery process was the creation of various innovative instruments and techniques such as telescopes and liquid thermometers (Hall, 1983). Assisted by these technical advances, philosophers and scholars of this scientific era expounded the 'experimental method' – a system of rules and processes for the investigation of phenomena (Henry, 2008). The rules and processes were not just solution-seeking devices; they were also the means to generate further questions and theories. In this significantly different world-view, new ways of scientific thinking were articulated to organise and account for original ontological, epistemological, mathematical and methodological propositions and constructs (Hall, 1983).

In particular, at least five radical forms of reasoning linked to this new science world-view are prominently studied and debated. They are induction, experimental-abstraction, hypothetical modeling, taxonomic and evolutionary reasoning. The earliest reasoning form to be noted is induction – the inferrence of common principles or axiomatic 'truths' applicable to a population from observable instances in a sample. Francis Bacon (1561-1621) was the first to explicate its working mechanism and importance to scientific inquiry in the Novum Organum in 1620 (Bortolotti, 2008). Although Bacon's pioneering insights on inductivism were ground-breaking, it was the synergistic power of his methodology with the well-established deductive arguments that has come to characterise the scientific breakthroughs and knowledge that the scientific revolution is reknown for (Crombie, 1994). The following sections will briefly discuss the four other novel forms of reasoning which precipitated the discoveries and inquiries from the scientific revolution period until the beginning of the twentieth century. As will be obvious from the ensuing discussion, induction and deduction are crucial mental components of more complex forms of reasoning (Reichertz, 2014).

The experimental work of Galileo (1564-1642) and Newton (1642-1727) exemplified the first of the four complex forms of reasoning. A distinctive hallmark of their work is an empirically-focused epistemology which commonly featured a pragmatic use of instruments and incorporated a heavy quantitative emphasis (Hall, 1983). There are two typical stages to this form of reasoning. In the first inductive-inference stage, users discern consistent patterns or non-random features from observational or experiential data. Subsequently, in the next abstraction stage, there is manipulation of theoretical mathematical structures to notionally describe or account for these inferences. The outputs of the manipulations are then deductively used to explain or predict other physical or conceptual phenomena (Crombie, 1994).

Discerned from the inquiry efforts of philosophers such as Descartes (1596-1650) and Hooke (1635-1703) is yet another form of reasoning prominently studied between the sixteenth and the eighteenth centuries. The cognitive historian A. Crombie (1994) described this form of thinking as 'hypothetical modeling'. Distinctive to this reasoning is the ubiquitous construction of scale or analogical models to isolate and represent key features of complex phenomena or multi-faceted scientific processes which would otherwise have been impossible to study. In contrast to a scale model, an analogical model extracts non-physical commonalities from a situation based on some criteria or assumptions. Modelling aims to offer explanatory or predictive insights. For example, Decartes creatively envisaged the human form as a mechanistic hydraulic model, an 'automaton' (Kwa, 2014b). Using the model, he analysed the physiological workings of various biological and sensory processes and provided various perceptive hypotheses which anticipated the actual mechanisms. Although this form of reasoning proved useful for generating possible conjectures, it also involves a high likelihood of excluding other causal conditions as factors are necessarily limited in a theoretical model.

From the 1800s onwards, the next major form of scientific reasoning associated with the scientific revolution arose to prominence in Europe (Kwa, 2014c). Curiosity and interest in natural history – the study of the natural world – were fuelled by expeditions to exotic lands by travellers who sent unusual plant and animal specimens back to Europe (Huxley, 2003b). The great increase in the number of hitherto unknown flora and fauna prompted communities of naturalists to consider more methodical and efficient ways of organisation and classification (Huxley, 2003a). This reasoning about the placement of scientific subjects or objects into categories in accordance with pre-determined criteria is referred to as taxonomic thinking (Crombie, 1994).

One particularly influential classification method was Linnaeus's hierarchical system (Eddy, 2010). This system firstly involved the identification of a rational basis for distinguising between two categories of organisms. Within a single category, the process of sub-division reiterated until no differences between the remaining organisms could be detected. At this juncture, the commonalities that united these organisms are noted and described (Kwa, 2014c). Over time, taxonomic methods, whose criterion of comparison signify 'natural' or true biological differences or similarities, came into favour for their prognostic powers (Crombie, 1994). Meanwhile, the discoveries of fossils and concurrent developments in embryology and comparative structures in the early 1800s unearthed striking patterns in morphology, suggesting a mechanism for the systematic transmission of characteristics from common ancestral sources (Huxley, 2003a). The last of the reasoning types from the late nineteenth century arose from this context (Kwa, 2014a).

Attributed to the pioneering efforts of Charles Darwin and Alfred Wallace, evolutionary reasoning is thinking and theorising about the formation process of a species (Crombie, 1994). The Darwinian theory ascribed the diversity of organisms over time to competitive forces. As species take on different forms, they split from their parental stock in a manner described as a 'branching, tree-like pattern' (Ridley, 2004, p. 5). Identifying the characteristic(s) that definitively delineate a species from another species – the point of branching – is an important facet of evolutionary reasoning. Interestingly, constructing a representation of the biological lineages between species as a corollary of using demarcation criteria is similar to the systematic process of sub-dividing subjects on grounds of morphological differences in taxonomic reasoning discussed above (Crombie, 1994).

In conclusion, various forms of reasoning preceded the inquiry efforts and discoveries of scientists from the scientific revolution era. Although correspondences and written records showed that intense self-reflections and vigorous debates were occuring over the most appropriate scientific methods and reasoning to undertake, there was no systematic examination of the specific mechanisms involved (Bortolotti, 2008; Dunbar & Klahr, 2012; Hall, 1983).

Conceptions of Scientific Reasoning from the 1900s Onwards

Methodical investigations into the mental schemes of scientists began with the Gestalt psychologist Wertheimer's seminal investigation of Einstein's thought processes and Roe's descriptions of personality traits of scientists in the middle of the twentieth century (Roe, 1953; Tweney, Doherty, & Mynatt, 1981; Wertheimer, 1945). After the 1950s, research into scientific reasoning was largely based on cognitive science and had its greatest impact on science education (Klahr et al., 2001; Klahr & Simon, 1999). While there is broad consensus that scientific reasoning is a set of cognitive, meta-cognitive and meta-strategic skills, different specific definitions exist depending on the research literature and the predominant thought milieu about learning in science education (Kind, 2013; Morris, Croker, Masnick, & Zimmerman, 2012; Sodian & Bullock, 2008). What follows is an account of the various significant scientific reasoning conceptions from the educational perspective.

For over thirty years since the 1950s, science educators frequently referred to the psychological model of formal operations proposed by Piaget for insights on the nature and development of scientific reasoning (Lawson, 1983). In the same period, Gagne's 'science as process' (Sanderson & Kratochvil, 1971) proposition, with a set of processes and attendant reasoning, became influential in science education (Finley, 1983). Though the two ideologies have impacted science research, curriculum development, and instruction in different ways, they both emphasised the use of reasoning faculties and posited that cognitive strategies are content-independent and transferable across learning contexts (Kuhn, Amsel, & O'Loughlin, 1988).

Scientific Reasoning as Logical Reasoning

Jean Piaget's proposal of combinatorial logic is part of a broader developmental theory describing intellectual growth from birth to maturity (Inhelder & Piaget, 1958; Kuhn et al., 1988). Of interest in his theory is the culminating stage in the cognitive development process: the period of formal operations (11-15 years). An individual in this stage is postulated to be able to deal effectively not only with reality but also with contemplation of abstractions and hypothetical scenarios. It is this unique quality that characterises formal thought and suggests that the underlying basis for cognitive strategies is of a hypothetico-deductive nature (Flavell, 1963). Significantly, the young adolescent builds on the abilities of the earlier concrete stage to organise information, casting the products as propositions and then proceeding to manipulate these further by drawing different logical relationships amongst them. In effect, formal operations are second-order operations conducted on the results of the previous concrete operations. An implication of the adolescent's ability to differentiate between reality and possibility is that he is now capable of combinatorial analysis – a method of testing various scenarios (or hypotheses) by isolating variables appropriately in problem solving situations (Flavell, ibid). These postulated cognitive strategies (and in particular control of variables) are of particular interest to science educators as efforts are sought to nurture these abilities in students (Kuhn et al., 1988). Overall, Piaget's theory contributed greatly to insights about children's thinking. However, doubts were cast both on the methodology employed by Piaget and on the replicability of results. There is also a substantial amount of literature which strongly suggests that mental developments are not universally attained in the stages as postulated by Piaget (Keating, 1980).

Scientific Reasoning as Inductive Reasoning

In his process approach, Gagné proposed activities for building cognitive abilities in an increasingly complex hierarchical fashion (Gagné, 1968). One well-known application of his theory to science education was the re-design of a large-scale American curriculum project which introduced process skills as 'intellectual tools of science' (Sanderson & Kratochvil, 1971, p. 6) to enable pupils to learn scientific knowledge (Fields, 2000). There are two types of processes: basic and integrated. According to Finley (1983), Gagné's processes or 'generalisable intellectual skills' (p. 48) are hierarchical; simpler processes build up to enable the use of more complex processes. The process approach with its inductive and empiricist roots was heavily criticised by researchers and science educators alike, based on philosophical, psychological and pedagogical grounds. In sum, critics largely disapproved of its underlying theoretical and pedagogical posits that situate the processes as constituting the reasoning and intellectual outcomes of instruction rather than as means to educational goals (Millar & Driver, 1987). From the late 1970s onwards, the collective dissatisfaction with the nature of scientific reasoning expounded by Piaget's cognitive development theory and Gagné's process approach led the science research and education communities to respond in three important and distinctive ways. The remaining section of this essay describes these responses.

Post-Piagetian and Post-Process Scientific Reasoning: Three Research Responses

Scientific Reasoning as Conceptual Change

This first response to address the lack of a satisfactory rationale for scientific reasoning drew focus away from how pupils are reasoning to the subject of their reasoning processes (what they are reasoning). Conceptual change research investigates learning which requires a substantial revision of prior knowledge and the acquisition of new concepts, usually under conditions of systematic instruction (Vosniadou, 2013). This research is of particular interest since the early 1980s because children's conceptions of the natural and physical environment impact their subsequent learning in science classrooms and incorrect conceptions are particularly resistant to change by instruction (Driver & Easley, 1978; Osborne & Wittrock, 1985).

Scientific Reasoning as Procedural Knowledge Interacting with Conceptual Knowledge

The second research response focussed on modifying the rationale for scientific reasoning underlying Gagné's process approach (Kind, 2013). To differentiate from terms such as 'skills', 'processes', and 'process skills', this understanding has been termed 'procedural knowledge' to signal the significant role of knowledge (Millar, Lubben, Gott, & Duggan, 1994). This response posited scientific reasoning as theory-laden with a focus on procedural knowledge.

Scientific Reasoning as Evidence Evaluation and Coordination, with Epistemic Knowledge

More recently, there is general agreement from diverse fields (e.g. philosophy, sociology, linguistics) that science is a social entity constructed from the products of enquiry and normative practices adhered to by the scientific community (Garcia-Mila & Anderson, 2008). These normative practices, also known as epistemic practices, include reasoning and coordinating between evidence and dialogic, as well as dialectic and discursive processes such as evaluating alternatives, weighing evidence and evaluating claims (Garcia-Mila & Anderson, 2008; Sandoval & Reiser, 2004).

Concurring, Duschl & Osborne (2002) added that cognitive and psychological research now view "thinking and reasoning as socially-driven acts which are language dependent, and governed by context or situation" (p. 47). They concluded that science education should seek to engage pupils beyond the declarative realm of knowledge to further encompass procedural and strategic aspects. The aim is to support the development of reasoning and meta-cognitive reflectivity. In essence, the scientific reasoning conceived in this strand moves away from the 'positivist perspective' characterised by a set of irrefutable facts, uncontroversial theories and confirmed outcomes (Driver, Newton, & Osborne, 2000). Instead, scientific reasoning is honed by discourse-based tasks that support the social construction of knowledge – exposing pupils' thinking to critique, debate and argumentation around competing ideas, contending theories, methodologies and claims (Newton, Driver, & Osborne, 1999). Scientific discourse, and in particular argumentation, has been promoted as an ideal language tool for the construction of explanations, models and theories (Jiménez-Aleixandre & Erduran, 2008; Siegel, 1995).

Science as a Practice-based Activity

Notably, taken as a whole, the three aforementioned responses describe key scientific practices in a scientific investigation cycle (Kind, 2013). Specifically, in any cycle, the three scientific practices are theory development, collection of empirical data, and coordination and evaluation of evidence. Kuhn (2011) has further characterised the investigation cycle as consisting of four major phases: enquiry, analysis, inference, and argument. The enquiry phase involves formulation of investigative goals and questions, and adoption of strategies to address the goals and questions. This phase encompasses the two scientific practices of hypothesis (theory) generation and collection of empirical data to test theories. The remaining three phases of data analysis, inference, and argument entail justifying claims, as well as understanding the implications of evidence as supporting or disconfirming one's theories. These remaining three phases thus correspond to the scientific practice of coordinating and critically evaluating evidence.

Scientific Reasoning as Evidence Evaluation and Coordination with Conceptual, Procedural, and Epistemic Knowledge in Science Practices

The discussion in the earlier sections provides a picture of an emerging conception of scientific reasoning; that it is an evaluation of evidence and coordination with theories involving three types of scientific knowledge bases – conceptual, procedural and epistemic while engaged in science practices (Kind, 2013; Osborne, 2013). This perpsective of scientific reasoning aligns with the broader notion of scientific reasoning as a set of cognitive, meta-cognitive and meta-strategic skills.

In conclusion, up until the middle of the last century, research in the specific nature of higher-order cognitive proficiencies for achieving scientific experimentation and discoveries was limited. Developments in science education during the five decades after the 1950s suggested that there existed a weak consensus about the nature of scientific reasoning. This essay presented a novel conceptualisation of scientific thinking and reasoning, consolidated from insights in emerging philosophical, psychological and cognitive science literature.

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