Journal of Science Education
Volume: II, Issue I, 2020, 47-61

The Triangle Model: The Contribution of the Late Professor Alex H. Johnstone

Norman Reid*

Abstract

Having established the key role of the working memory in understanding and that the limited capacity of the working memory *controlled* success in understanding, Johnstone considered the nature of chemistry and why a subject like chemistry (along with other sciences and mathematics) caused young learners so many difficulties. This led him to develop his '*triangle model*' and this has proved to be a very useful way to guide curriculum planners and teachers to help to make a subject like chemistry more accessible to learners. In developing the triangle model, he established that it is the way the sciences are presented in typical curricula and textbooks that made the problem a major one for learners. This review outlines the key findings and their implications for learning and then concludes by suggesting key areas for future research. The overall goal in all future work is to develop new understandings that can lead to practices that enable future learners to move towards greater success in understanding in the sciences.

Keywords: Chemistry Learning, Sub-micro interpretation, Symbolism, Science Education

---

* Emeritus Professor of Science Education, University of Glasgow, Scotland.
Email: dr_n@btinternet.com

Introduction

In the previous review (Reid, 2019), it was noted that Alex H Johnstone had explored the reasons why learners found understanding in highly conceptual subjects so demanding. Two questions arose in his mind (Johnstone, 1997):

a) In what precise areas were the difficulties that learners experienced?
b) Was there any underlying fundamental reason to explain the difficulties?

His many studies related to working memory revealed the way the capacity of working memory *controlled* all learning (other than rote memorisation). Thus, he established the central role of the working memory. At this stage, he turned his attention to the nature of the sciences and mathematics, focussing on chemistry, the discipline he taught. Was there something about the nature of chemistry itself that made it intrinsically demanding?

Implications from Working Memory Research

Johnstone applied the findings about the central importance of working memory capacity to learning in various situations. Others have also followed up by looking at other aspects.

He studied lecturing and developed the idea of the pre-lecture. One lecture teaching slot was removed and employed to allow students to apply the ideas they had learned from former courses. The findings were quite dramatic and are described in two papers (Sirhan, Gray, Johnstone, and Reid, 1999; Sirhan and Reid, 2001). The research programme lasted for six years, looking at a first year university chemistry course with about 200 students involved in each year. The work was carried out by two PhD students. For the first two years, pre-lectures were employed. For the next three years, the pre-lectures were removed and the time given back to extra lectures. In the sixth year, a written form of pre-lectures was offered to students on a voluntary basis (most enthusiastically took up the offer). The findings showed that:

a) Pre-lectures (as lectures or as written materials) allowed the *least-well qualified* students (from past qualifications) to perform as well as the best qualified students.
b) When pre-lectures were absent, the least-well qualified students performed at a significantly poorer level when compared to the best qualified students.

This brilliant work established, in a practical teaching and learning situation, what Ausubel (1968) had found many decades before although he had described it in general terms: what the student understands from past learning is a very powerful factor in controlling future understanding. By '*freshening up*' past understandings before a lecture course, the students could make much more sense of the new material.

Johnstone applied the same logic to university laboratory work. He created the idea of pre-laboratory exercises. These were developed and tested in action by another two PhD students. Again, there was strong evidence of very significantly improved understanding when '*pre-labs'* were in use. In addition, time was saved in the laboratory and student attitudes were enhanced (Johnstone, Sleet and Vianna, 1994; Johnstone, Watt and Zaman, 1998). Later, the work was summarised and guidance offered constructing such exercises (Carnduff and Reid, 2003) while a practical extension of the idea was developed in a school teacher training context for Pakistan (Reid and Shah, 2010).

Another area where the limitations of working memory capacity are very important relates to language and this has major importance for a country like Pakistan. When learning in a second language, it was found that, even when that language is excellent, about one seventh of working memory capacity is employed in handling the less familiar language, leaving less for the central tasks of understanding the sciences being taught (Johnstone and Selepeng, 2001). This has major implications not only for learning but also for assessment when conducted in a second language.

The limitations of working memory capacity explain why learners very often have difficulties in applying ideas from physics in a chemistry situation, why teachers of chemistry and physics frequently complain that learners find it very hard to apply the mathematics they have been taught in their mathematics courses to situations in chemistry or physics. The working memory simply does not have the capacity to handle ideas from two subject disciplines at the same time. However, using mathematics in the sciences becomes possible when the mathematical procedures are '*automated*': the procedures then require little working memory space (Alenezi, 2008).

The Early Analyses

In a key paper (Johnstone, 1991), he considered the nature of the concepts in chemistry. He noted that many concepts in general life can be exemplified and thus made real to learners. Thus, concepts like hot and cold can be illustrated by examples of hot and cold situations while a concept like '*kindness*' can be made real to children as they experience acts of kindness. The problem in chemistry is to find any '*real-life*' examples of key concepts: concepts like element and compound, along with concepts like electron, bonding and bond energy, photon, polarity ……. In some ways, the problems are not so demanding in physics while much biology is very much related to real-life experiences.

Chemistry is simply full of conceptual ideas for which there are few tangible exemplifications. For example, consider an element. A yellow power may be an element like sulphur, a complex compound like an azo dye or a spice to be used in cooking. There is no way to know which it is simply by looking at it. Indeed, a whole series of chemistry experiments may be carried out but none will demonstrate easily whether we have an element or a compound. Johnstone observed '*These ideas are all beyond our senses and pupils have little or no experience in constructing such concepts*'. He went on to note that '*….definitions purported to act as anchors for these concepts but whether they were ever understood was open to debate'* (Johnstone, 1991, page 78). The fact that our students are able to state definitions does NOT imply that they have real understanding of the concept.

In earlier papers (Johnstone, 1982, 1999), Johnstone had considered chemistry in terms of the macro and the micro. This laid the foundation for his triangle analysis which can be presented as in figure 1 (Johnstone, 1999).

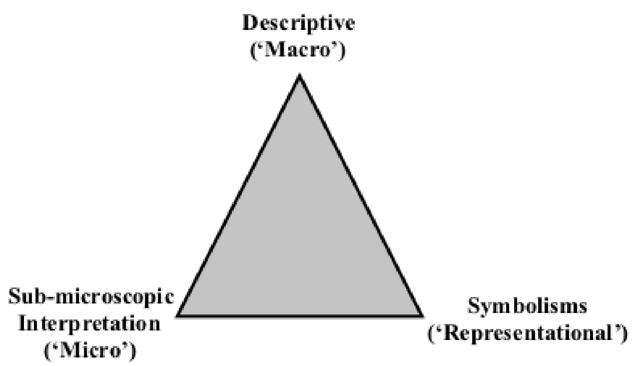

Figure 1: Johnstone's triangle model

In the new curricula that developed in many countries in the 1960s, chemistry was seen as built upon the key three ideas: structure, bonding and energy. However, what Johnstone was observing that chemistry was built on three *levels of thought*. This proved to be *much more important* in gaining understanding when studying chemistry.

This can be illustrated very simply by considering salt crystals dissolving in water.

Table 1:
Illustrating the three levels of thought

Macro	Descriptive	The student sees white crystals '*disappear*' into water to give a clear solution	The *'expert'* can move comfortably between these levels of thought ***BUT*** The working memory of the *'novice learner'* is totally overwhelmed
Micro	Sub-micro interpretation	The student is given an '*explanation*' in terms of polar water models surrounding the ions and the lattice breaking down	
Representational	Symbolisms	The students is given an equation to represent what is happening: $Na^+Cl^-(s) + H_2O \rightarrow Na^+(aq) + Cl^-(aq)$	

The limitations of working memory hold the key. The sheer number of ideas that the young learner has to hold *at the same time* far exceeds the capacity of working memory:

They observe what is happening and are left confused by the ideas of '*melting*' and '*dissolving*'. The concept of the polar molecule is not understood while the mental picture of polar water molecules interacting with ions (the idea of charged entities is itself demanding to understand - just what is electrical charge?). On top of that, they are now given an ionic equation when the ideas associated with the various symbolisms are not yet well established in their minds. By contrast, the '*expert*' understands polarity and an ionic equation is completely comprehensible. Thus, there is enough working memory capacity left to picture the interactions between the salt lattice and the water molecules.

One of the remarkable insights found by Ausubel (1968) in his research was that what we understand already has a powerful effect on understanding new ideas. We now know that, when faced with some unfamiliar idea, the working memory of the learner starts to search the long-term memory for any understandings which can assist (Yang, 2000). The problem with a subject like chemistry is two-fold. There is often nothing in long-term memory, from either life experience or specific learning, that can help us make make sense of new observations and ideas. In fact, there may be ideas held in long-term memory that can create confusions. Thus, for example, a young learner has observed melting (ice melting in the sun or fat melting in a frying pan) and then mistakenly uses ideas associated with melting to interpret dissolving.

The word '*energy*' itself causes major problems. Students at school and university are familiar with ideas of energy production (like a power station) or a society facing energy shortage (causing electricity supply rotas). Ideas like the conservation of energy and, indeed, some of the basic principles of thermodynamics then conflict with these familiar ideas: how can conservation of energy relate to energy shortages?

The entire area of misconceptions and alternative conceptions is an *inevitable outcome* of the limitations of working memory capacity. In passing, there is another misconception that salt dissolving in water illustrates: is dissolving a physical or chemical change? The process can be reversed easily but dissolving involves the breaking and forming of new bonds. This shows the foolishness of trying to distinguish between physical and chemical changes, a topic that should be removed from all curricula in that it is artificial and causes later confusions.

All of this illustrates some simple principles:

a) Many of the problems learners have in the sciences are created by the way these ideas are presented.
b) Many of the problems of presentation are generated by curricula in the sciences that are badly constructed (usually by those outside the classroom) and by confusions created in typical textbooks.

Later, Johnstone showed how we can minimise the problems.

Taking Ideas Further

Johnstone went on to note that there would be parallel models for physics and biology. In physics, he suggested the macro (open to our senses), the invisible (eg. energy, forces, fundamental particles), the symbolic (diagrammatic and mathematical representations) (Johnstone, 1991). However, the model was not taken up much in physics. His triangle model[1] is widely to be seen in studies in chemistry (eg. Towns, Raker, Becker, Harle and Sutcliffe, 2012; Taber, 2013; Bradley, 2014; Chittleborough, 2014). However, the simple insight of Johnstone has often been lost as it has been extended. What he emphasised was that chemistry, by its very nature, involved three *levels of thought.* This places heavy demands on working memory capacity for the learners

[1] A web search on '*Johnstone's triangle model*' will generate many hits

meeting ideas for the first time. Therefore, it is essential not to involve all three levels at the same time but to introduce them the levels step by step.

One later study looked at biology and this generated a tetrahedral model:

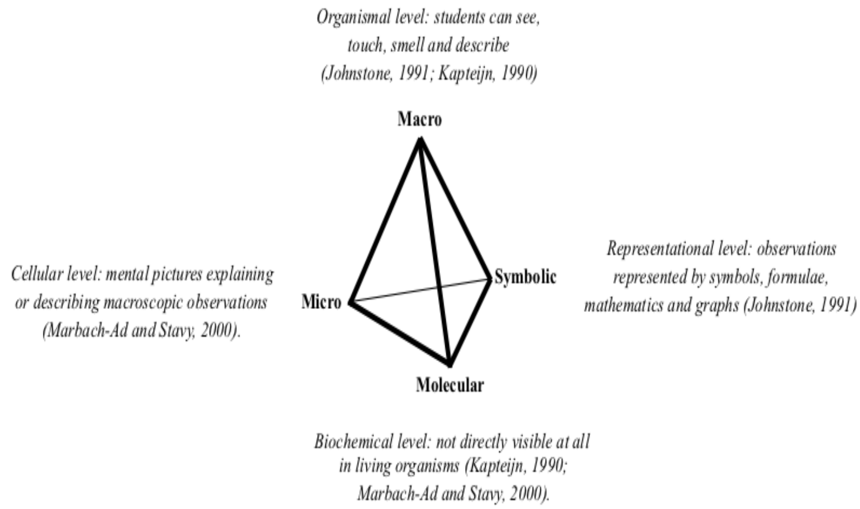

Figure 2: The Biology Triangle (Chu and Reid, 2012)

A tetrahedral model for mathematics was also developed and can be found in two theses (Alenezi, 2008; Ali, 2008) as well as one paper (Ali and Reid, 2012).

In all of this, there are some key fundamental issues which Johnstone stressed throughout:

a) The fact that understanding in the sciences and mathematics places great demands on limited working memory capacity is NOT an argument for making the sciences trivial by avoiding difficult ideas. That would undermine the very nature of these subject disciplines and their contribution to humanity in enabling us to understand, and to benefit from, the world around.
b) The limitations posed by working memory capacity DOES demand that we re-consider the way curricula in the sciences are constructed and the way complex ideas are introduced at both school and university levels.

Johnstone addressed both the issues in some detail in relation to chemistry.

Concepts are central to the very nature of the sciences. We cannot avoid teaching about density, energy, the mole, while, at university stages, ideas like the quantisation of energy, entropy and its probabilistic nature, the central importance of free energy, the basis and nature of spectroscopy are of fundamental importance in understanding interactions in matter while concepts related to relativity underpin any understanding of many modern technological developments.

The number of fundamental ideas in both chemistry and physics that, by their very nature, make heavy demands on working memory capacity is very large and this explains why these subjects are often found to be '*difficult'*. By contrast, biology has fewer areas of difficulty at early stages of learning although conceptual demands can be very extensive in later studies, especially in relation to genetics.

Towards a Summary

Johnstone had established that the limited capacity of working memory *controls* understanding and performance (Johnstone and Elbanna, 1986, 1989) the sciences are known to be difficult for young learners This is simply because, by the nature of the sciences, conceptual ideas are introduced very early. Thus, understanding concepts requires a learner to hold many ideas in the mind *at the same time*. The working memory is the ONLY part of the brain where this can happen. In developing the triangle model, he was now establishing that it is the way the sciences are presented in typical curricula and textbooks that made the problem a major one for learners.

Towards Ways Forward

In a brilliant paper based on a conference presentation, Johnstone (2000) noted that the difficulties in understanding a subject like chemistry arose because of the way humans learn as well as the '*intrinsic nature of the subject*'. His earlier work had established the central importance of working memory. He now drew together much research on the nature chemistry (and other sciences). He offered clear criticisms of much research that generated little value for teachers but was able to demonstrate that we now possessed enough understanding of the difficulties to be able to re-think the way a subject chemistry was presented so that to might become accessible for all learners.

He argued that we were now able to show how two '*models - information processing and the chemistry triangle, can be used to help* *our teaching by making 'logical' and 'psychological' coincide*' (Johnstone, 2000, page 11). He then developed a practical guide into how curricula can be re-structured and the way mental models can be usefully developed, applying this approach to some of the topics in chemistry where research has shown there are the greatest difficulties for learners.

In another paper presented at the same conference, findings were then extended by looking at evidence from research that related to actual way the chemistry was to be presented in the classroom (Reid, 2000). This gave exemplars of the way the descriptive aspects of chemistry can be taught allowing the interpretations and symbolisms to be added step-by-step. This presentation was built upon a previous study that had applied the ideas into all three sciences (Reid, 1999).

Preliminary Summary

It is well established that the sciences are regarded as difficult subjects. Very often, the difficulties in gaining understanding, coupled to the demands in passing examinations, have '*forced'* learners to focus on memorisation. This has generated deteriorating attitudes towards studies in the sciences, especially physics and chemistry (Jung and Reid, 2009).

Johnstone directed many projects with his PhD students which established the sources of the understanding problems:

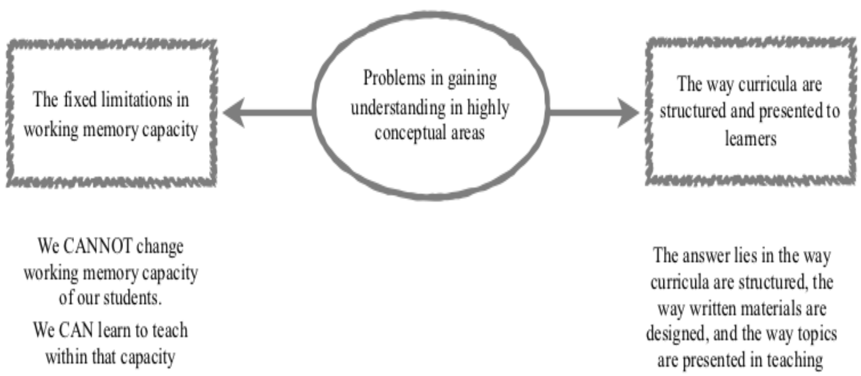

Figure 3: Problems in understanding chemistry

Others started to test out the way science materials were presented to see if the increased levels of understanding were observed. Three later studies, all stemming from the Centre for Science Education in Glasgow, gave strong evidence to support Johnstone's brilliant insights.

In a small study, the approach to teaching the mole concept was changed in line with the need to take the limitations of working memory into account. Specifically, the way the descriptive, the sub-microscopic interpretations and the the use of symbolisms was considered, avoiding the need for learners to work at all three levels at the same time. The outcomes were a marked improvement in understanding (Danili and Reid, 2004).

A second study built on this. With very large samples, written materials for major areas of the senior school chemistry curriculum were re-cast. The outcomes were quite dramatic, with not only very marked improvements in understanding but very big changes in the development of positive attitudes (Hussein and Reid, 2009).

Alongside this study, the difficult area of genetics was examined. The research study had several goals but one was to avoid the problem of working memory overload when working at four levels of thought (the biology tetrahedron) at the same time. Again, there were very marked improvements in understanding (Chu and Reid, 2012).

These three studies only looked at written materials. There is a need to expand this in future research. In addition, the idea of focussing at the start on the descriptive, especially that which was familiar to the ordinary daily life of the learners can be seen in the applications-led curriculum (Reid, 1999, 2000). One national physics curriculum (sadly discontinued) did employ this approach [2], with some remarkable outcomes in terms of the performance and attitudes of the learners. The approach was so successful that it made physics one of the most popular subjects in the entire senior school curriculum. Some of the work is described in Reid and Skryabina (2002).

An interesting development arose with the work of Hindal (2007, 2014). Her focus was on very able learners and, among other things, she considered the visual-spatial, developing a test to measure this skill level in learners. There is considerable research that shows the central importance of the visual-spatial for large numbers of learners. What Hindal found was that those with high skills in the visual-spatial tended to perform much better in assessments (Hindal, Reid and Whitehead, 2013).

---

[2] The Scottish Standard Grade Course in Physics (for ages 13-15) ran for about 30 years before being phased out recently.

When a learner can chunk ideas successfully (Miller, 1956), then working memory capacity is available for thought and understanding. The use of the visual-spatial can be a powerful tool to bring ideas together (while this is true, the inappropriate use of the visual can be a hindrance: Alenezi, 2008)

The visual-spatial is more about the ability to link ideas (it can be seen in flow charts, simple diagrams and, indeed, life experiences), The evidence suggests very strongly that here we have a powerful tool for understanding. Too much teaching depends on the symbolics of language and number, with excessive use of logical progressions of thoughts and the use of bullet points. The use of sub-microscopic interpretations and the use of representations can be harnessed as ways to bring ideas together, provided that we do not work at too many levels *at the same time* with novice learners. There is now an extensive literature on the visual spatial and a good starting point is Hindal (2007, 2014). Johnstone was perhaps becoming increasingly aware of this in his descriptions of the use of '*mental models*' (Johnstone 1991).

Future Lines of Research

Four broad areas require much research:

- Much more research is needed to explore other ways to avoid teaching at too many levels at the same time, looking to see the extent of improvement in understanding that can occur.
- Science curricula need re-thought, especially for ages from about 11-14. The applications-led paper (Reid, 1999) gave exemplars - this needs extension and development.
- The way the visual-spatial can be used as a '*chunking*' device needs detailed exploration. Does this level of thought bring universal benefits?
- The Johnstone triangle model (and the derivative tetrahedral models) are rarely taught in teacher education: why is this so and what can be done?

The overall goal in all future work is to develop new understandings that can lead to practices that enable future learners to move towards greater success in understanding in the sciences.

References

Alenezi, D. (2008). *A study of learning mathematics related to some cognitive factors and to attitudes*, [PhD Thesis[, University of Glasgow, Glasgow. [http://theses.gla.ac.uk/333/)

Ali, A. A. (2008) *Perceptions, difficulties and working memory capacity related to mathematics performance*, [MSc(R) thesis[, University of Glasgow,. Glasgow. [http://theses.gla.ac.uk/441/]

Ali, A.A. & Reid, N. (2012). Understanding Mathematics - Some Key Factors, *European Journal of Educational Research*, 1(3), 283-299.

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

Bradley, J. D. (2014). The chemist's triangle and a general systemic approach to teaching, learning and research in chemistry education. *African Journal of Chemical Education, 4*(2), 64-79.

Carnduff, J. & Reid, N. (2003). *Enhancing Undergraduate Chemistry Laboratories,* London: The Royal Society of Chemistry.

Chittleborough, G. (2014) The development of theoretical frameworks for understanding the learning of chemistry, in: I Devetak and S.A. Glazar, *Learning with Understanding in the Chemistry Classroom,* 25-40, Springer.

Chu, Y-C & Reid, N. (2012). Genetics at school level: addressing the difficulties, *Research in Science and Technological Education, 31*(1), 1-25.

Danili, E. & Reid, N. (2004). Some Strategies to improve performance in school chemistry, based on two cognitive factors, *Research in Science and Technological Education, 22*(2), 203-226.

Success in an Introductory Course in Organic Chemistry, University Chemistry Education, 8, 40-51.

Hindal (2007). *Cognitive characteristics of students in middle schools in State of Kuwait, with emphasis on high achievement*, [PhD Thesis[, University of Glasgow, Glasgow. [http://theses.gla.ac.uk/5717/]

Hindal, H. (2014). *Cognitive characteristics of high achievers*, Germany: Lambert Academic Publishing.

Hindal, H. & Reid, N. (2009). Working memory, performance and learning characteristics, *Research in Science and Technology Education*, 27(2), 187-204.

Hindal, H., Reid, N. and Whitehead, R. (2013). A fresh look at high ability, *International Journal of Instruction, 6*(1), 59-76.

Hussein, F. & Reid, N. (2009). Working memory and difficulties in school Chemistry, *Research in Science and Technological Education*, *27*(2), 161-186.

Johnstone, A.H. (1982). Macro and microchemistry, *School Science Review, 64* (227), 377-9.

Johnstone, A.H. (1991). Why is science difficult to learn? Things are Seldom What They Seem, *Journal of Computer Assisted Learning*, *7*, 75-83.

Johnstone, A.H. (1997). Chemistry teaching, science or Alchemy?, *Journal of Chemical Education, 74*(3) 262-268.

Johnstone, A.H. (1999). The nature of chemistry, *Education in Chemistry*, *36*(2), 45-48.

Johnstone, A.H. (2000). Teaching of Chemistry – logical or psychological?, *Chemistry Education: Research and Practice, 1*(1), 9-15.

Johnstone, A.H. & El-Banna, H. (1986). Capacities, demands and processes: a predictive model for science education, *Education in Chemistry*, *23*(3), 80-84.

Johnstone, A.H. & El-Banna, H. (1989). Understanding learning difficulties - a predictive research model, *Studies in Higher Education*, *14*(2), 159-68.

Johnstone, A.H.& Selepeng, D. (2001). A language problem revisited, *Chemistry Education: Research and Practice*, *2*(1), 19-29.

Johnstone, A.H., Sleet, R.J. & Vianna, J.F. (1994). An information processing model of learning: its application to an undergraduate laboratory course in chemistry, *Studies in Higher Education, 19*(1), 77-88.

Johnstone, A.H., Watt. A. & Zaman, T.U. (1998). The students' attitude and cognition change to a physics laboratory, *Physics Education, 3*3(1), 22-29.

Jung, E-S., & Reid, N. (2009). Working Memory and Attitudes, *Research in Science and Technological Education, 27*(2), 205-224.

Kapteijn, M. (1990). The functions of organizational levels in biology for describing and planning biology education, *Relating macroscopic phenomena to microscopic particles,* 139-150, CD - Press, Utrecht, The Netherlands.

Miller, G. (1956). The magical number seven, Plus or minus two: Some limits on our capacity for processing information, *Psychological Review, 63*, 81-87.

Reid, N. (1999). Towards an Application-Led Curriculum, *Staff and Educational Development International*, *3*(1), 71-84.

Reid, N. (2000). The Presentation of Chemistry: Logically Driven or Applications Led?, *Chemistry Education: Research and Practice, 1*(3), 381-392.

Reid, N. (2019). The Key Role of Working Memory, *Journal of Science Education*, *1*(2), 39-50.

Reid, N & Shah, I. (2010). The Idea of the Paper Laboratory, *Journal of Science Education*, *11*(10), 8-12.

Reid, N. & Skryabina, E (2002). Attitudes Towards Physics, *Research in Science and Technological Education, 20*(1), 67-81.

Sirhan. G. & Reid, N. (2001). Preparing the Mind of the Learner - Part 2, *University Chemistry Education, 5*(1), 52-58.

Sirhan. G., Gray, C. Johnstone, A.H. & Reid, N. (1999). Preparing the Mind of the Learner, *University Chemistry Education*, *3(*2), 43-46.

Taber, K. S. (2013). Revisiting the chemistry triplet: drawing upon the nature of chemical knowledge and the psychology of learning to inform chemistry education. *Chemistry Education Research and Practice*, *14*(2), 156-168.

Towns, M. H., Raker, J. R., Becker, N., Harle, M., & Sutcliffe, J. (2012). The biochemistry tetrahedron and the development of the taxonomy of biochemistry external representations (TOBER). *Chemistry Education Research and Practice*, *13*(3), 296-306.

Yang, M-J. (2000). *Problem solving in chemistry at secondary school*, [PhD thesis], University of Glasgow, Glasgow. [http://theses.gla.ac.uk/2161/]

Citation of this Article:
Reid., N. (2020). The Triangle Model: The contribution of the late Professor Alex H. Johnstone, *Journal of Science Education*, *2*(1), 47-61.