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The Key Role of Working Memory: The Contribution of the Late Professor Alex H. Johnstone

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Abstract

Starting with the known areas where students find difficulty learning in the sciences, Johnstone directed research students in a series of studies that led eventually to the key understanding that the limited capacity of working memory controlled thinking, extent of understanding and success in problem solving. It has long been known that subjects like mathematics, chemistry and physics are regarded as difficult. Science students have to deal with different concepts, symbols, equipments, equations etc. Johnstone addresses key issues related to learning such as specific areas of difficult learning and reasons of such learning difficulties. Johnstone research pointed to simple ways by which difficulties could be reduced. In learning, the role of working memory is very much significant. The capacity of working memory is found to be fixed genetically and cannot be expanded. However, it can be used more efficiently but this seems to depend on growing knowledge and experience and not on formal instruction. When the number of pieces of information gets to be near the capacity of 's*hort-term memory*', performance suddenly collapses. This review outlines the way he approached the research, his key findings, their implications for learning and then concludes by suggesting key areas for future research.

Keywords: Working memory, information load, chunking, over load

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Introduction

In the previous review (Reid, 2019), it was noted that Alex H Johnstone started his long research career by looking at difficulties learners in his native Scotland were facing in highly conceptual subjects. It has long been known that subjects like mathematics, chemistry and physics are regarded as difficult. With the introduction of new curricula in chemistry and physics in Scotland in 1962 (Curriculum Papers 490 and 512, 1962) (followed quickly with new curricula in mathematics and biology), the emphasis in Scottish schools moved from recall to understanding. It rapidly became clear that learners found this difficult (Johnstone, 1974). The problem lay in the understanding of concepts. Two questions arose:

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

Johnstone addressed both questions. With his research students, he first of all identified areas of difficulty (Johnstone, Morrison and Sharp, 1971; Johnstone and Mahmoud, 1980; Bahar, Johnstone and Hansell, 1999; and, later: Zapiti, 1999; Ali and Reid, 2012). He then proceeded to supervise students who took these specific topics and themes and tried to explore what caused the difficulties and what might be done to help learners (for example: Duncan and Johnstone, 1973; Johnstone and Kellett, 1974; Garforth, Johnstone and Lazonby, 1976; Johnstone and Mughol, 1976, 1978; Johnstone, MacDonald and Webb, 1977a, b). Was it intrinsic to the nature of the subject matter, or was it related to the way humans learn in highly conceptual areas? It turned out to be both (Johnstone, 1997, 1999, 2000).

His findings eventually led to an understanding of the fundamental reason why the difficulties exist and pointed to simple ways by which difficulties could be reduced. Despite the possibility of improvement, it is an interesting but sad observation that the areas of difficulty have persisted today in most countries. Although a very large number of research studies has explored specific areas and these studies have found, on occasion, ways to teach specific topics which lead to improved examination performance, few of these approaches have found their way into textbooks or teaching materials. It is a sad reflection that the textbooks and materials of today still perpetrate the same '*pedagogicalerrors*' of those of past decades. Modern materials may be more colourful, be better presented and can be highly attractive.

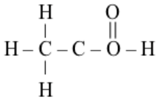
However, it is very rare to find a textbook that is designed and planned in the light of research evidence about how a subject can be more accessible to learners. Johnstone pioneered by publishing a school textbook where the way the material was presented was in line with the way conceptual understanding could be enhanced, based on the evidence at that time (Johnstone, Morrison and Reid, 1980).

The Early Discoveries

The breakthrough in the programme of research directed by Johnstone arose when one of his students, near the end of her PhD research, observed patterns in her data. She realised that the difficulties related in some way to what she called '*information load*'. A paper was published which summarised her observations and proposed a simple hypothesis (Johnstone and Kellett, 1980). This suggested the fundamental reason why understanding was difficult related to the way the brain was being overloaded with information.

At that stage, it was not completely clear what was mean by '*information load'*. Today, it can be described as the number of pieces of information which the learner has to hold *at the same time* in order to perform the task successfully. It is important to stress that the holding is *at the same time*. It is also critical to note that we are talking about holding things *in the mind*. Once ideas are written down, then these ideas need not be held in the brain.

There are endless examples in mathematics and science areas of learning. For example, we can look at the formula for ethanoic acid:



$$\begin{array}{ccccccccc} & & H & & & & O & & \\ & & | & & & & \| & & \\ H & - & C & - & C & - & O & - & H \\ & & | & & & & & & \\ & & H & & & & & & \end{array}$$

For the novice learner, research showed that this might be '*read'* as H, hyphen, C (with an H above and below), hyphen, C, (with equals O above), with a hyphen, O, hyphen H below (Johnstone and Kellett, 1980). This is far too much information and the brain simply cannot cope. The learner may memorise, give up, or perhaps decide that they hate chemistry. For the novice, it is a meaningless pattern of strange symbols. For the experienced person, the representation carries meaning. Indeed, the experienced person '*sees*' the structure in three dimensional terms for this entity does not lay flat on the page. With more experience, the relative length of the bonds is important and, perhaps, the idea that delocalisation of electrons occurs.

Another major area of difficulty relates to the mole. Young students find it hard to grasp the mole as a counting device and see it related to mass or volume. When we start to talk of concentration expressed in terms of moles per unit volume, and then the students are typically completely bewildered. They memorise ways to carry out calculations but simply do not understand what they are doing (Danili and Reid, 2004).

If we take an apparently simple idea like density, this makes high information demands on young learners. The concept of mass is involved (and how this is not the same as weight but we measure it by weighing), the concept of volume is involved (easy to grasp in regular shapes but intrinsically difficult with irregular shapes), division is involved (generating units that are unfamiliar like gcm^{-3}) while the idea that density relates to mass and volume but is unrelated to the amount of matter present.

Energy is also a complex concept, carrying numerous ideas implicit within it. One aspect is the fact that energy cannot be seen but the outcomes of energy are observable. In the physics class, the learners may be told that energy is the '*capacity to do work*', this having little meaning because the physics concept of work is not fully established and is confused with the normal use of the word '*work*'. We are then instructed that energy cannot be created or destroyed. How then can there be an energy crisis, with energy running out…..?

This is a classic example of a concept. The concept is not understood properly. Indeed, it is not easy to understand the concept properly, simply because there are so many underpinning ideas that we need and our working memories have difficulty coping. In most countries, the theme of energy is introduced far too early before the underpinning ideas are well established. The brain cannot cope. The learners then memorise phrases and statements in order to pass examinations, often deluding us to *think* that they understand. The end result is that several apparently contradictory outcomes are left unresolved and these often persist into adulthood.

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. However, one major area relates to genetics. The overload problem here relates to what is known as levels: genetics involves entities right down to genes at one end and traits at the other, with the added complexity of probability ideas being important (Chandi, Gray, Gray and Reid, 2009).

Insights from the Literature

Johnstone then returned to the psychology literature. Arising from medical research, it had been noticed that there were at least two distinctive parts to the brain: what become called '*short-term memory'* and *'long-term memory*'. Some brilliant work by Miller, a psychologist, had developed methods to measure the capacity of what he called '*short-term memory'*. He found that the short-term memory had a fixed and limited capacity. Individuals varied but almost everyone in the adult population could hold between 5 and 9 '*chunks*' of information at the same time. Miller described '*chunks'* of information as what the person perceives as a unit of information. His paper was the key breakthrough and is considered to be the most cited paper in the entire academic literature (Miller, 1956).

The Key Experiments

The brilliance of Johnstone (with essential contributions from his students) was to appreciate that it might be the limited capacity of '*short term memory*' that controlled conceptual understanding. His next PhD student started to test this idea (El-Banna, 1987). Examination data from over 20000 school students, aged about 16, were considered. For each question, the sum of pieces of information provided in the questions plus the additional pieces to be recalled plus the processing steps required was estimated. This was carried out by a jury of experienced teachers and then checked by asking some students to solve the questions out loud. This was seen as the information demand (or information load) of the question.

Student success was then related to the information load (figure 1):

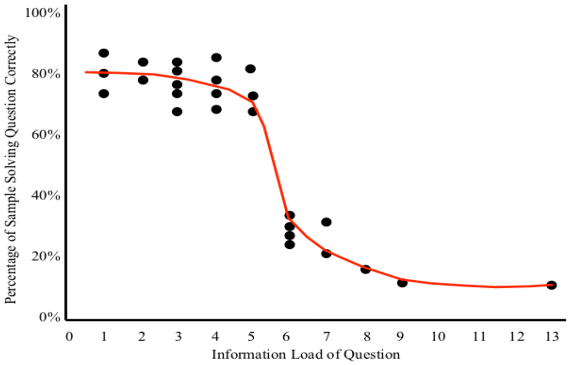


Figure 1: Performance related to Information Load (school data)

Johnstone expected to find a steady drop in performance as information load increased. However, what was found was a very sharp drop in performance when the information load exceeded 6. If he had employed statistics like correlation, he would have missed the true nature of the relationship. What it showed was that we cope fine and then, when the number of pieces of information gets to be near the capacity of ‘s*hort-term memory*’, performance suddenly collapses.

It was then appreciated in much psychology work that the ‘*short-term memory’* was better to be seen as a ‘*working memory*’. It was this part of the brain where we not only held information temporarily but it was where we processed and understood that information to gain *‘answers*’. It was re-named as the ‘*working memory*’ and numerous studies were published (see Reid, 2009a for lists). Its location in the brain is now known from medical research.

The PhD study went on to measure the capacity of the working memories of over 300 first year university students, using two methods. Then, the students all sat a test. The information load for each item in the test was agreed, again using experienced teachers. Information load is the number of pieces of information or processes that the student has to hold in his/her mind *at the same time*. The researchers then plotted the marks (as percentages) against the information load (re-labelled here as ‘*question working memory demand*’) for each question. Again, they obtained a curve (figure 2).

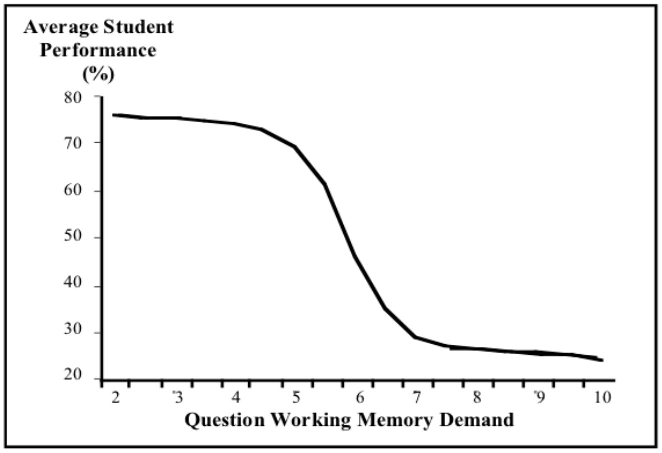


Figure 2: Performance related to Information Load (university data)

This suggests that, when the information load of a question exceeds the normal capacity for working memory, performance suddenly collapses. In other words, when a question requires the candidate to hold too many ideas at the same time, the working memory simply cannot cope.

However, the study went further. The working memory capacity of the students had been measured. Most of the students were found to have working memory capacities of 6, 7 or 8, exactly as found by Miller (1956). In other words, most of the students could hold 6, 7 or 8 '*chunks*' of information in their minds *at the same time*. They divided their student group into three groups:

- Those with above average working memory capacity (>7);
- Those with average working memory capacity (7);
- Those with below average working memory capacity (<7).

Their graph is shown in simplified form:

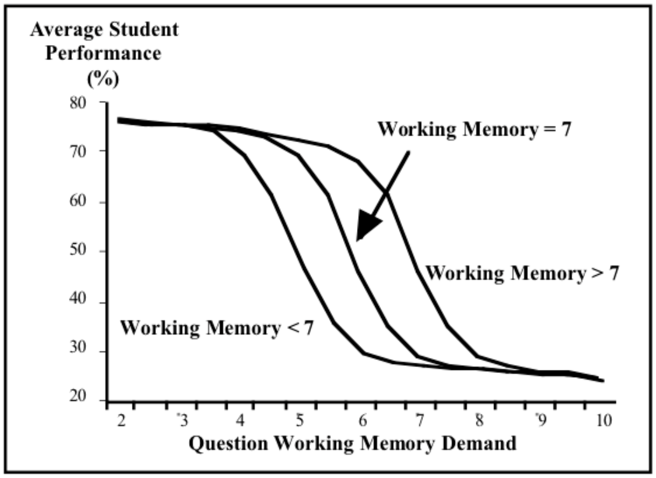


Figure 3: Performance, Information Load, Working Memory Capacity

It was the brilliant way that Johnstone directed this student to analyse the data that led to the key finding (Johnstone and El-Banna, 1986, 1989). The graph shows that it is the working memory capacity which is *controlling* success. Those with *below* average working memory capacities tended to fail with questions where 5 or more chunks of information were needed while those with *above* average working memory capacities did not fail until the demand of the questions exceeded 6 chunks. The papers were breakthroughs and the work was repeated and expanded in many studies, confirming the essential principle: Johnstone, Hogg and Ziane, 1993; Stamovlasis and Tsaparlis, 2000; Danili and Reid, 2004; Chen and Whitehead, 2009. Johnstone (1991) summarised the central findings in a clear way: the key reason for difficulties in conceptual learning is the limitation brought about by working memory capacity.

It has now been shown that working memory capacity *controls* performance in all subject areas (Hindal, Reid and Badgaish, 2009) but the effect is more marked in the sciences and mathematics The is simply because, by the nature of these subjects, 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. The limited capacity of this part of the brain, and the fact that the capacity CANNOT be expanded, make conceptual learning demanding.

In all this, the central goal for teaching is seen as developing understanding. The working memory is the location where this takes place. This explains the central importance of working memory capacity. This *controls* whether understanding can take place. If the working memory is overloaded, then understanding is impossible. To pass examinations, the students have to memorise. Research shows that this is a major cause of attitude deterioration, sometimes with learners opting out of the sciences when they can (Jung and Reid, 2009).

Working memory capacity is nothing to do with what is often called '*intelligence'*. It simply reflects the way our brains are '*wired up'*. It is how we use our working memories that will determine our academic success or otherwise. In simple terms, working memory is where we think, understand and solve problems. It controls all three. Teaching methods do NOT hold the key as many have shown (e.g. Kirschner, Sweller and Clark 2006). Papers have been published summarising the key issues (Reid, 2009a, b) while two papers explored some of the implications (St Clair-Thompsonand Botton, 2009; St Clair-Thompson, Botton, and Overton, 2010).

Key Issues Identified by Research

Working Memory and Age

Building on the findings of Pascual-Leone (1970), working memory is found to grow with age to about age 16 (table 1).

Table 1:
Average working memory capacity and age

Approximate Age	Approximate Average Working Memory Capacity
16	7
14	6
12	5
10	4

Topics which make a high demand on limited working memory resources cannot be introduced at too young an age, a finding that experienced teachers have known for centuries. The capacity of working memory is found to be fixed genetically and cannot be expanded. However, it can be used more efficiently but this seems to depend on growing knowledge and experience and not on formal instruction.

Working Memory Functions

Baddeley has developed detailed insights into the structure of the working memory (Baddeley, 1986, 1994, 1996, 1997, 1999, 2000, 2002; Baddeley and Hitch, 1974; Baddeley, Eysenck and Anderson, 2015). He has found specialist functions which he describes as '*loops'*: a visual-spatial loop and an auditory loop. Thus, the working memory seems to handle visual information and symbolic information in distinct ways. He also has found clear evidence for what he calls '*the central executive*' - the *controlling function* in the brain (Miyake and Shah, 1999).

Measuring Working Memory Capacity

There are two standard tests. In the Digits Span Backwards Test, students have to record a series of numbers in reverse order, the length of the series increasing. In the Figural Intersection Test, students have to show the common overlap in increasing numbers of geometrical shapes. The two tests have been used with the same students and, despite the difference in their approaches; the outcomes are almost identical (El-Banna, 1987).

The Idea of Chunking

Miller (1956) first used the word '*chunking'* to refer to the skill of bringing ideas together so that the working memory saw them as one, thus reducing pressure on limited working memory capacity. Considerable work has explored the whole area of chunking (Gobet and

Simon, 1996, 1998; Gobet, Lane, Croker, Cheng, Jones, Oliver, and Pin, 2001; Gobet and Jackson, 2002). Chunking seems a quite straightforward process. By means of experience, a person learns to group ideas together so that they are seen as one and can be handled in the working memory as one item, one chunk. However, we all seem to do this in a variety of ways and it appears very difficult to train learners so that they can learn to chunk more efficiently.

The human being is a natural pattern-seeker. Pattern seeking is part of the process where the working memory is looking for ways to chunk information. The chunked information can be stored as chunks in long term memory and when brought back into working memory, the information is seen as one chunk.

Reducing Working Memory Overload

Numerous studies have developed ways to minimise working memory overload. This is one of the central issues for all educational research for today. It is, of course, critically important that topics are not introduced at too young an age, given that working memory capacity grows with age. It is possible to adapt teaching materials and several research studies have shown this is possible, with quite remarkable increases in performance. The development of c*hunking skills* is also important while the key role of working memory in assessment has also been explored. Some of the key studies are shown in table 2:

Table 2.
Teaching approaches to minimise overload

Reducing Working Memory Overload	**Solution**	**Key Papers**
In traditional lecturing	The use of pre-learning	Sirhan, Gray, Johnstone, and Reid, 1999 Sirhan and Reid, 2001
In laboratory learning	The use of pre-laboratory exercises	Johnstone, Sleet and Vianna,1994 Johnstone, Watt and Zaman, 1998 Carnduff and Reid, 2003 Reidand Shah, 2010

In written materials	Multiple ways can be employed	Hassan, Hill and Reid, 2004 Danili and Reid, 2004 Hussein and Reid, 2009 Chu and Reid, 2012
In assessment	Multiple ways can be employed	Danili and Reid, 2005, 2006 Ud Din, Reid and Malik, 2016
In specific themes and topics	A method in mole calculations	Reid, 2010, 2013

A book is now available which discusses ways forward in the context of primary education (Gathercole and Alloway, 2008).

Conclusion

Working memory is that part of the brain where we do our temporary holding of information while we process it for possible storage in long-term memory. It is where we understand and where we solve problems. The average capacity of the average adult working memory, when used simply to hold information, is 7. When the working memory is used for processing that information, then much less information can be held. The capacity of working memory is genetic and there is no way of increasing it. However, it can be used more efficiently.

One way to use the limited space more efficiently is by means of '*chunking'* information. In this process, several items of information are grouped together (chunked) and then handled as one item in the working memory. Knowledge already held in long-term memory can be used to chunk incoming information. This means that the expert can chunk much more efficiently and effectively than the novice learner. There is no easy way to teach chunking skills. The working memory grows with age (to about age 16) and this strongly influences what can be taught at any age. There is no evidence that working memory deteriorates in old age, other than with brain damage caused by accident or disease.

Future Lines of Research

Four broad areas require much research:

- More needs to be known about the kinds of ways teachers can assist learners in chunking.
- More studies are needed to look at ways to minimise working memory overload, building on the studies shown in table 2.

- The entire area of *speed* of processing in working memory needs detailed exploration. There are very few studies in this area and none related specifically to the sciences
- The key roles of the '*loops*' in working memory, especially the visual-spatial loop need study, other research suggesting that learning visually-spatially is both common and very powerful.

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.

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