The science of science teaching and learning

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In this paper I will outline why we need a scholarly and empirical investigation into current and new methods of teaching and learning in science, highlight the relevance of research in allied areas such as cognition, learning, and self-regulatory theories, and compare the short and long-term effectiveness of approaches.

The need for a scholarly and empirical approach

Over the past decade there has been an increasing emphasis on student evaluation of teaching and learning, and a plethora of methods have been developed to assess student reactions. Involving students in the feedback process and taking into account their views is essential, and the trend toward doing this is to be welcomed. However, there is very little experimental research comparing different methods of teaching, using hard performance data as the criterion to accompany the information obtained from student evaluations. Research on IT and Teaching tends to be based on show-and-tell case studies, which provide useful ideas for ways in which to introduce IT, but little hard data about the effectiveness in terms of improved learning on the part of the students. We need hard evidence of the value underlying whatever teaching and learning methods are popular. In this paper, I draw primarily on research that has been undertaken in cognitive psychology and that has been related to training. Although I suspect that the issues apply equally to teaching and learning in the higher education sector, we do still need to assess this.

The dilemma

I have written previously about a dilemma in the area of training and transfer (Hesketh, 1997). Drawing on the research of Bjork (1994), we know that the methods of training that foster long-term retention and transfer, are often not the methods that students find most enjoyable. Conversely, the methods that students enjoy and rate positively, such as, for example, clear goals, do not necessarily develop independent structuring and learning skills that foster transfer and retention.

In the 1990s the USA Academy of Science was concerned about the limited uptake in industrial training of knowledge arising from experimental psychology research on cognition and learning. The Academy funded a review chaired by Professor Bjork to investigate why industry was not using the latest research findings in the fields of cognition and learning in the design of their training programs (Druckman and Bjork, 1994). Although an oversimplification of the findings from this review, it did appear that both trainers and trainees were ‘addicted’ to courses that are enjoyable. The use of the word ‘addicted’ helps to highlight the time dilemma in training.

Enjoyable courses make trainees feel good during and immediately after the course, and because trainees feel good and provide positive reactions in feedback at the end of a course, trainers also feel good. Very few companies collect hard data so there is little evidence that enjoyment correlates with performance. Furthermore in much of the applied training research there is very little long-term follow-up to explore whether skill and knowledge learned during training transfers back into the work place or is retained after a delay. This means that there is little evidence that the methods of training preferred by trainees lead to long-term skills that foster transfer. Without follow-up research, employers will never know that their training is not working, nor that it might even be bad for them and their employees. On outlining this dilemma to a group of industrial trainers, one described the courses that were run as ‘cigarette’ courses. Employers and employees knew that they may not have positive outcomes in the long run, but behaviour was maintained because of the current enjoyment – hence the addiction analogy.

Transfer of training paradigm (Bjork, 1994)

A standard methodology used in experimental studies on cognition and learning in training and transfer is to compare different methods of training (say method A and method B) in terms of performance immediately after training and then again after a delay, or to compare performance on a task that is similar to the one used in training with performance on a transfer task involving different deep (far transfer) or surface (near transfer) features (Hesketh and Ivancic, 2002; Hesketh, 1997).

A stylised summary of the outcomes of many studies of this sort point to the fact that methods which show superior performance immediately and on the task similar to the training task, tend to be comparatively less effective after a delay and on a transfer task. Conversely, the methods that at first appear to be less effective on the training task, often show superior performance when tested after a delay or on a transfer task.

The methods which appear less effective on a training task, but which demonstrate superior outcomes on transfer (Bjork, 1994) include:

1. ***Varying the conditions of practice*** This might include exposing learners to a range of different examples that challenge them, with changing and slightly unpredictable features, compared with exposure to a limited range of examples all of which use similar features and provide consistent information. Challenging and varied examples may attenuate performance shortly after training, but show enhanced performance on transfer tasks.
2. ***Providing contextual interference*** Kintsch (1994) has shown that providing an 'advance organiser' that is consistent with the subsequent information results in superior immediate knowledge of the information it foreshadows. In comparison, an advance organiser that is inconsistent leads to poor knowledge of the information it foreshadows. However, where an advance organiser is inconsistent, this leads to superior performance on novel information, in part because the participants exposed to the inconsistent advance organiser had to develop their own structure for the material. What transferred was their superior meta-cognitive skill of being able to develop their own structure. Note, however, that this finding only applied to higher ability participants. Lower ability participants were not able to develop their own structures for this particular task.
3. ***Distributing practice on a given task*** There is a long history of research showing that massed practice results in superior immediate performance, but when re-engaging with a task, initial performance is lower than participants exposed to chunked or spaced practice. By spacing the practice learners have the opportunity to practice recall and relearning every time a new block of information appears. What appears to foster transfer is their superior skill in practising memorising or relearning during the breaks between spaced practice. The phenomenon has been described as the transfer appropriate principle (Morris, Bransford and Franks, 1977). If one wants learners to be able to memorise, reason or solve problems in the long term or on a transfer task, then they need to practise memorising, reasoning and solving problems during training. The cognitive processes required for transfer need to be used during training.
4. ***Reducing feedback to the learner*** The learning and behavioural literature has shown the value of feedback to help shape a particular behaviour to the desired goal. Frequent and regular feedback results in attainment of the performance goal more rapidly than intermittent or irregular feedback. However, on transfer, those exposed to the intermittent and irregular feedback tend to perform better. One mechanism for this may lie in the development during training of superior self-assessment skills. If feedback is intermittent, or if feedback is faded, the learner is required to develop his or her own standard, and to assess performance against that standard without external feedback. These meta-cognitive self-assessment skills can be applied subsequently to the delayed or transfer task providing them with an advantage over learners who were shaped exclusively by external feedback. It is interesting to note that one of the features differentiating novices from experts is the accuracy of their self-assessments. Experts know what they do and don't know; novices tend to think they know

everything. Hence the process of fading feedback during training may be one mechanism for fostering the development of expertise.

5. ***Making errors during learning*** The literature on the role of errors in learning is controversial (Ivancic and Hesketh, 1995/6), in part arising from a body of opinion that learners should be protected from making errors because of the anxiety associated with the errors. However, where the motivational aspect of errors can be managed, making errors provides an ideal basis for checking the accuracy of the mental model or schema being used. Negative feedback associated with inappropriately applying prior knowledge to an inconsistent problem generates 'surprise', motivating trainees to examine why an attempt failed. This enhances sensitivity to structural features of the problem. Errors are also significant events, and help remind trainees of mistakes so that they can avoid them in future. Active error training can reduce confidence (Ivancic and Hesketh, 2000). We examined this on a driving simulator, and were able to demonstrate that participants who made errors during training trials were both better able to deal with a transfer task, and had reduced 'over-confidence'. In the context of driving, reducing 'over-confidence' particularly among young male drivers has positive safety outcomes. However, passive error training (or worked examples of errors) is preferable if high anxiety and lower self-confidence are to be avoided.

In summary, the research suggests that to reduce cognitive load one needs to provide:

- highly structured and error free learning environments;
- instructional support;
- clear advance organizers; and
- regular positive feedback,

... but these features may inhibit transfer.

On the other hand, to enhance transfer, one needs to:

- vary the conditions of practice;
- provide contextual interference;
- distribute training on a given task;
- reduce feedback to the learner; and
- encourage errors during learning,

… but these may affect motivation and self-confidence.

Trainers need to make sound judgements about when to shift the nature of the training environment from being supportive to being challenging. In doing so the issues that need to be considered include:

1. ***Stages of skill acquisition*** During early stages of skill acquisition, before basic components have been automated, attentional capacity is taken up on the task, with little spare capacity for meta-cognitive processes. In later stages, once the basic skills have been automated, more challenging methods that foster appropriate meta-cognitive skills can be used.

2. ***Ability levels*** Trainees with higher ability tend to have more spare capacity to engage in relevant meta-cognitive tasks. Lower ability learners may need much longer to automate basic tasks, and may need more help in the structuring processes.

3. ***Task difficulty*** Easy tasks require less attentional resources, and hence one can move to challenging training conditions earlier.

4. ***Self-efficacy*** Self-efficacy is an expectancy that one can do a particular task. It is not identical to self-confidence. Self-efficacy is increased through successful performance, observation of others performing successfully, verbal persuasion and the avoidance of anxiety. The stage of skill acquisition, ability levels and task difficulty need to be taken into account (in an interactive way), to provide just the right level of challenge in order to enhance self-efficacy.

5. ***Anxiety level of learners*** High levels of anxiety are incompatible with self-efficacy and also occupy attentional resources inhibiting learning. The staging of challenging material needs to be managed very carefully to avoid inappropriate anxiety levels.

In the above discussion, an understanding is assumed of the concepts of skill acquisition and expertise. Within the cognitive literature, traditionally skill acquisition has been divided into three stages: 1. Declarative or factual stage during which learning is resource intensive; 2. proceduralisation, when facts become compiled; and 3. automatic, at which point only minimal resources are required. The stages are important in understanding the novice-expert shift. Among other differences, compared with novices, experts show the following features: 1. they are quicker to identify a problem and read off the appropriate solution; 2. they have hierarchical and integrated knowledge structures; 3. they have more automated categorisation and decision skills; and 4. they are more accurate at self-assessing and using meta-cognitive skills.

Solutions to the dilemma

Training needs to be tailored to the needs of the learner. I am not referring here to the concept of learning styles that has received comparatively little serious empirical research. Rather, it is the notion of the levels of skill acquisition and ability, and the ways in which these interact with task difficulty that should be examined in determining when to shift learning into a challenging mode. For each individual the challenge should be sufficient to require active processing and effortful learning, but not so challenging that anxiety is generated. It is important to ensure that basic skills have been automated, and that task difficulty is appropriate to ability and level of skill acquisition.

Another approach is to place the emphasis on learning goals rather than on outcome goals. For example, trainees can be told the value of errors, and how to learn from them. This places a focus on the process of learning as distinct from outcome or performance. Obviously one needs to also introduce outcome or performance goals, but timing and sequencing may be important.

Most importantly, more long-term follow-up evaluation is needed to avoid the 'cigarette training' trap. Carefully designed follow-up can provide a booster session for learners, and also signals the importance of the knowledge and skill covered during training. A blurring of training and evaluation may offer opportunities for this, and there are interesting new possibilities to introduce technology into evaluation and follow-up.

In my laboratory we have been studying some of these issues using a driving simulator, and in research on training fire-fighters to develop adaptive expertise. Future work will highlight the best ways of combining rules and examples to foster transfer and adaptability. The extent to which these ideas relate to higher education needs to be assessed and researched. However, I anticipate that our current research on rules and examples may help inform discussion about the best ways of combining problem-based learning with more traditional discipline approaches.

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