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Identification and Use of Theoretical Frameworks for a Qualitative Understanding of Mathematics Transfer

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Abstract

This paper identifies and uses theoretical models and frameworks for understanding transfer of higher-level mathematics amongst science students in a naturalistic university environment. It uses the models and frameworks as a lens for obtaining qualitative understandings of how first year science students transfer their mathematical skills and knowledge to a physical context. Forty-nine student volunteers attempted a transfer test consisting of mathematics and microbiology questions that contained common mathematical concepts. The associated quantitative measure of transfer is reported in Roberts, Sharma, Britton and New(2007). Interviews subsequent to the test provided qualitative data from which both cognitive resources and processes involved in transfer were identified. Other factors that influence the transfer process such as student expectations and literacy skills were also identified from the interviews. The integration of memory theory, situated learning, mathematical resources and framing, and transfer taxonomy is novel and was adequate for our study. Some questions for consideration are raised.

Introduction

An understanding of transfer must begin with the work of cognitive psychologists, who were amongst the first researchers to study transfer. Questions that have stirred the interest of those studying transfer include (Barnett & Ceci, 2002; Wagner, 2006):

- Can we transfer what we learn?
- How similar does the learning context have to be to the transfer context?
- Why is transfer so difficult?

In our modern context, the rapid growth of knowledge and the increasing availability of information make it harder than ever for school syllabi and tertiary courses to keep pace with changes. The result is that a great deal of information that students learn is potentially redundant by the time they finish studying. What, then, is the point of studying? High school and tertiary qualifications are highly valued in the workforce, but the assumption made by educators and employers is that students learn, and can apply, far more than mere information (Broudy, 1977). Generic skills such as problem solving, independent thinking and the ability to perform critical analysis are espoused by institutions as desirable, and expected to be displayed by graduates (Billing, 2007; Bransford & Schwartz, 1999; University of Sydney, 1997).

In addition to the `training' of students in secondary and tertiary education is workplace training that is directed towards increasing skills of workers specifically for use in the workplace, where the training is often off-site (Hesketh, 1997). If transfer of skills learnt in a training context does not occur, then there is a great deal of wasted time and money being spent on training, and education in general (National Research Council, 1994). Of particular concern is the claim of some researchers that there is negligible empirical support for the view that training is generalisable (Schooler, 1989) or that it even exists in the form espoused by its proponents (Detterman, 1993). If these critics are right then there needs to be a re-assessment of educational and training philosophies on a grand scale.

Due to the lack of agreement about transfer, we suggest that researchers need to develop common theoretical frameworks for modelling and measuring transfer. These theoretical approaches must provide opportunity for quantitative measurements and qualitative understandings of transfer in a wide variety of contexts, including mathematics and science at the tertiary level (see for example diSessa (1993) and Wagner (2006).)
To this end we discuss a model of student thinking (Redish, 2003) that is a synthesis of neuroscience, cognitive science and observational science of humans. Secondly, we explore situated learning (Lave & Wenger, 1991), which takes into account factors external to the mind. Thirdly we discuss research from the field of mathematics education which provides descriptions of how students transfer mathematics to physics (Tuminaro, 2004).

The primary research question of this study is *Can we identify an adequate and comprehensive theoretical framework for analysis and interpretation of qualitative information about transfer?* A secondary question is *How do students see their transfer process?* Our study used situated learning, Redish's model of student thinking and Tuminaro's descriptions to interpret the results of interviews to help understand how students transfer mathematics (Figure 1).

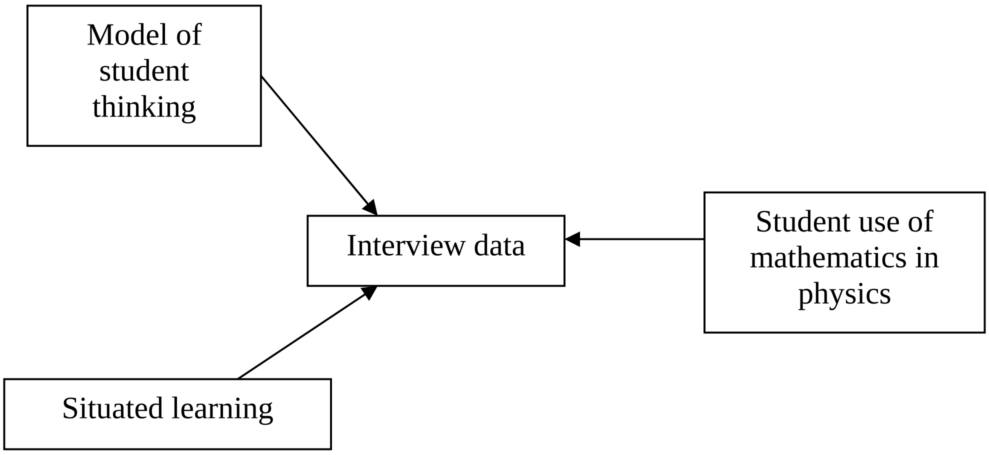

Figure 1. Use of theoretical frameworks in this study

Theoretical approaches

A model of student thinking

The nature of education research tends to be goal-oriented, trying to answer questions such as `What do we have to do to get students to learn more effectively?' But to treat education scientifically, an observationally-based framework is required, in which different models of student thinking can be compared. Redish (2003) has proposed and detailed such a theoretical framework with solid foundations in the fields of neuroscience, cognitive science and observational science of humans. This framework has been chosen for this study for two reasons:

1) As education researchers with a science background we have a greater affinity with researchers with the same background;
2) Redish’s framework covers a broad range of areas and provides easily applicable structures: he has created an “over-arching theoretical framework that allows us to both make sense of what we see in the classroom and to compare a variety of specific theoretical approaches” (Redish, 2003).

The framework is concerned with the cognition of individuals and how it interacts with the environment. The framework consists of a two-level system – a *knowledge-structure* level and a *control-structure* level. On the knowledge-structure level, structures of association are utilised to explain how *resources* are integrated. Resources are compiled knowledge elements, which may be at different structural levels in different individuals. The control-structure level deals with identifying the environment and cuing certain associational patterns. Control incorporates the ideas of frames and epistemic games: activities that use particular knowledge and associated processes to solve problems.

Redish's framework also includes a structure of memory that is helpful for the current project (Redish, 2003, p. 9). The transfer of information from working memory to long-term memory requires repetition and time (up to weeks). Memory is obviously a very complex phenomenon, and there are other models besides the one Redish uses, but even a limited understanding of memory structure can contribute substantially to effective teaching and learning. Principles about memory from cognitive science that are useful in this regard are (from Redish (2003)):

- Memory has two functionally distinct components: working (short-term) memory and long-term memory
- Working memory can only handle a small number of data blocks
- Long-term memory contains vast amounts of information in declarative and implicit memory
- Moving information from long-term memory to working memory may be difficult and time consuming

Situated learning

A recent development from cognitive and motivational psychology that has informed and directed mathematics and science education researchers is that of situated learning. Originally proposed by Lave and Wenger (1991), situated learning takes into account variables external to a student as affecting transfer (e.g. social interactions). As outlined by Rebello and Zollman (2005), the situated learning idea combined with the perceived similarity idea of Hoffding (1892) led to Lobato's `Actor-oriented Transfer Model' where transfer is defined as the 'personal creation of relations of similarity' (Lobato, 2003). This `student-centred' approach bears strong resemblance to the dominant educational philosophy of constructivism, where learning is seen as a distinctly social process in which students' prior learning, beliefs and expectations play a large role in determining their future learning (Driver, 1995). In science education, it is now generally accepted that students' alternative conceptions[1] must be challenged and shown to be lacking before they will be modified to more accepted scientific views (Driver, 1995; Matthews, 2000). Hammer & Elby (2001) have pointed out the importance of taking into account students' epistemological beliefs, as this determines how they think about a situation: their *frame* (Fillmore, 1985; Goffman, 1974; Tannen, 1993). A frame is an interpretation of a situation according to expectations – it helps an individual to answer the question `What kind of activity is this?'

Researchers at Kansas State University have developed an analytical framework to analyse student interviews that takes into account dynamic transfer – the *in situ* transfer and knowledge construction by students in a teaching interview environment (Rebello & Zollman, 2005). The teaching interview framework is particularly useful as it allows for an understanding of transfer in a natural educational context of teaching and learning; hence this framework was used in this project for data analysis.

Mathematics Education Research

Tuminaro (2004) has constructed a cognitive framework for describing and interpreting student use of mathematics in the context of physics. The major components of his framework are:

- Mathematical Resources
- Epistemic Games
- Frames

Mathematical resources is Tuminaro's answer to the question `What are the cognitive tools involved in formal mathematical thinking in physics?'. They include intuitive mathematics knowledge; reasoning primitives (abstract cognitive elements); symbolic forms (these describe students' intuitive understanding of equations (Sherin, 2001)); and interpretive devices (resources that determine student interpretation of equations). These resources can exist in *inactive*, *primed* or *active* states.

Epistemic Games are coherent activities that are ‘played’ during mathematical thinking and problem solving. Tuminaro (2004) extends the definition of Collins and Ferguson (1993) to include observation of what students actually do. Epistemic games can be differentiated by their ontology and structure. The ontology of an epistemic game has two components: the knowledge base (set of mathematical resources activated during the game) and an epistemic form (a target structure that guides inquiry).

Frames help in understanding the choices of a student in a particular context. Tuminaro's definition follows that of Goffman (1974) and Tannen (1993).

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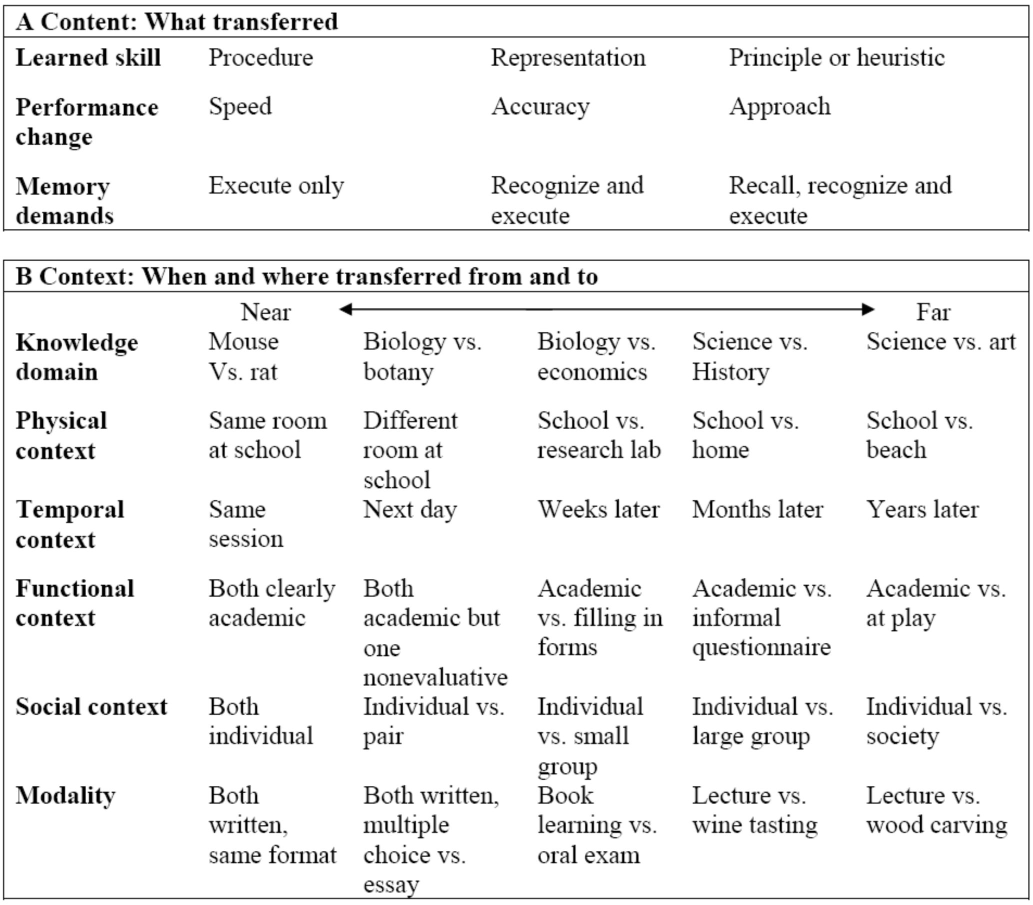
[1] Conceptions which are not the scientifically accepted view.

Taxonomy for Far Transfer

Due to the diversity of transfer research, it is important to situate this study of transfer within a common reference or framework to enable comparisons with different studies and to discuss results. Although acknowledged by its authors as lacking `sharp edges' (in regard to generating quantitative predictions), Barnett and Ceci's taxonomy (Barnett & Ceci, 2002) is useful for positioning this project in regard to other work, and in seeing the way forward for future research by those concerned with transfer.

The taxonomy has the following dimensions of context (see Figure 2): Knowledge domain; Physical context; Temporal context; Functional context; Social context and Modality. According to these dimensions, the project described in this paper only deals with non-near transfer in the Knowledge Domain – all of the other contexts are near transfer (this judgment was verified independently by members of the SUPER[2] group).



A Content: What transferred			
Learned skill	Procedure	Representation	Principle or heuristic
Performance change	Speed	Accuracy	Approach
Memory demands	Execute only	Recognize and execute	Recall, recognize and execute

B Context: When and where transferred from and to					
	Near	←	→		Far
Knowledge domain	Mouse Vs. rat	Biology vs. botany	Biology vs. economics	Science vs. History	Science vs. art
Physical context	Same room at school	Different room at school	School vs. research lab	School vs. home	School vs. beach
Temporal context	Same session	Next day	Weeks later	Months later	Years later
Functional context	Both clearly academic	Both academic but one nonevaluative	Academic vs. filling in forms	Academic vs. informal questionnaire	Academic vs. at play
Social context	Both individual	Individual vs. pair	Individual vs. small group	Individual vs. large group	Individual vs. society
Modality	Both written, same format	Both written, multiple choice vs. essay	Book learning vs. oral exam	Lecture vs. wine tasting	Lecture vs. wood carving

Figure 2. Barnett and Ceci's taxonomy for far transfer

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[2] Sydney University Physics Education Research

Method

A transfer test was administered to 49 student volunteers in their first semester of university studies. All of the students were in the Faculty of Science or Engineering and enrolled in at least one mathematics subject. They had all completed some senior high school mathematics covering the topics in the transfer test. The test had earlier been trialled by Britton, New, Sharma and Yardley (2005) and was slightly modified for this study. Quantitative results of this study are presented in Roberts et al (2007).
The transfer test had two sections: Section A was attempted first and contained pure mathematics questions about logarithms and exponentials, while Section B was a microbiology-based question using the same mathematical concepts (see Roberts et al (2007) for the full test).

From the cohort that attempted the test, seven students volunteered to be interviewed (for 40 minutes each, with informed consent) within two weeks of completing the test. The goal of the interviews was to elicit information about the thought processes of the students while sitting the test – were they aware of transferring the mathematics from Section A to Section B, and if so, what prompted the transfer? Four interviews were conducted over eight days. Each interview had either one or two students, and all were audio and video recorded. The interviews were conducted in a student laboratory, thus providing a familiar environment for the students.

The first author interviewed the students to attempt to determine their understanding and awareness of the transfer process, following Lobato's suggestion of shifting to an actor's (learner's) point of view (Lobato, 2003). This position of trying to view the situation from the learner's perspective reduces the danger of an experimenter-centred analysis. It also leads to understanding how individuals construe similarity between problems, rather than pre-determining how they should see things, and what they should see (a style of study suggested by Wagner (2006)).

Accordingly, the interviews were semi-structured, with minimal interjections from the interviewer. The general procedure for the interviews was to:

- provide students with a copy of their working from the test, and the test itself;
- ask general questions to help `break the ice';
- allow time for the students to review the test and their answers;
- ask the students how they felt about the test, and how well they thought they did;
- ask further questions such as `Did you notice any similarities between the two sections of the test?' and `Which section did you find harder?' ;
- conclude by thanking the students and providing opportunity for questions.

The interviews were analysed using an adaptation of the teaching interview framework mentioned earlier (Rebello & Zollman, 2005). The framework has four major components: *External Inputs*; *Tools*; *Workbench* and *Answer* (Figure 3). *External Inputs* refers to information provided by the interviewer and can promote either positive or negative transfer, as they can cause a student to think in a particular way. *Tools* are cognitive `entities' used in student reasoning. They may be pre-existing, or created by the student during the interview. Tools are an answer to the question `What is it that is transferred?' The *Workbench* describes mental processes and decision-making by the student. These processes may use the external inputs and tools. Lastly, the *Answer* is a stopping point in a student's reasoning process that is not necessarily the final outcome – it may, at times, be a question.

Here, the framework was used to analyse the interview, providing a lens for probing what occurred during the test. Hence, the framework has been modified so that the External Inputs are limited to the test itself, while the Answer is a student's written answers, as the framework is being used to identify what happened during the test, rather than during interviews. The strength of the framework is that it is designed to describe and interpret student thinking, as is the primary purpose of this study. From Tuminaro (2004), Epistemic Games are comparable with Workbench, and Mathematical Resources with Tools.

There were a number of common themes that emerged from the interviews, and the dialogue of the students was used to identify some of the Tools, and some Workbench processes used during the test.

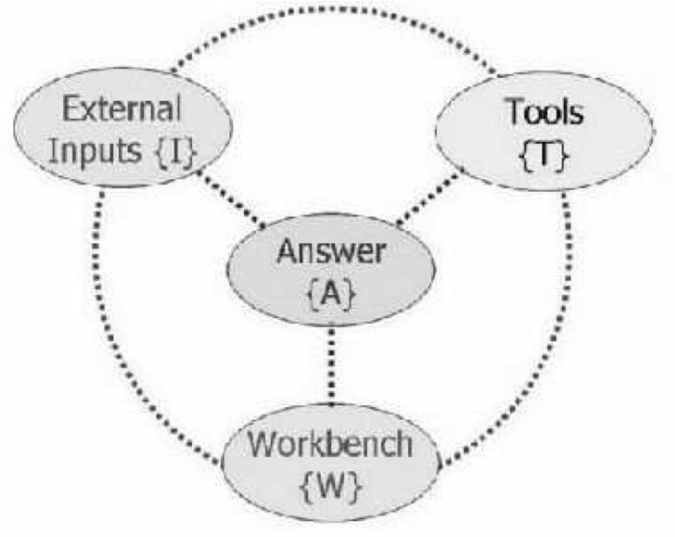

Figure 3. Framework for interview analysis (adapted from (Rebello & Zollman, 2005)

Results

Themes

Relationship between sections The strongest theme that emerged from the interviews was that five out of seven students saw Section A of the test as a `warm-up' for Section B. This included one of the students who had not been aware while taking the test that both sections contained the same mathematics, but in the interview he recognised that he may have been `warmed-up' subconsciously. Of the remaining two students who did not verbalise this theme, one of them did not see the similarity, and the other simply did not make a comment about this, although he recognised similarities between the sections.

Expectations There were a variety of student expectations coming into the test, according to those interviewed. One student, Peter (all names have been changed to protect privacy), said that he treated the test like an exam:

> *`I sort of took it under exam kind of conditions where each question . . . is probably not related. Right so you get the question, like in question 1 – in that, the parts may be related but not necessarily . . . question to question'*

As far as having an exam approach, Peter saw the two sections as separate and was not aware of the mathematical similarities between the sections while taking the test:

> *`I didn't see any offhand, no. There may have been subtle ones but I didn't recognise them'.*

Another student, Christopher, stated that he was not in exam mode, and therefore was not thinking as clearly as he would have under exam conditions. Another student, Elijah, said that he was expecting there to be a mathematics section and then another section that used the same mathematics in a physical context. He considered this to be obvious from the recruiting process for the test – a concern held by some of the researchers prior to the test. However, Elijah was the only one interviewed to comment on this, and in discussions with other students at the time of testing there was no indication that students knew what to expect in the test. However, this does provide the researchers something to consider in regard to promotion and recruiting for any future tests.

When interviewed, all of the students were asked: (1) how they felt about the test; and (2) how well they thought they did. The answers fell into the following categories:

- Great \ Top marks
- Good \ High marks
- Not great \ Average marks
- Not good \ Low marks

When these expectations of achievement were compared with performance, the students were generally quite close to reality. A few students underestimated their performance, while a couple may have slightly over-estimated. Table 1 shows the performance of the students on both sections of the test, and their Transfer Index. The Transfer Index is a measure of the degree to which students transferred mathematical skills and knowledge from Section A to Section B (further details can be found in Roberts et al (2007)).

Blocking factors Another theme that emerged was the existence of additional factors that blocked or impeded the transfer process. The blocking factors are primarily related to graphing and literacy skills. The most frequently noted was the difficulty that students encountered in answering the graph-related questions:

> *‘Section B was probably harder than Section A because you had to read it off the graph, instead of looking for extra information in the question’.*

For two students, the amount of information in Section B and the need to interpret it was a difficulty: literacy as a blocking factor. There were two students that had taken a break of at least six months between Year 12 and university, and they both commented that they had difficulty in applying the mathematics to a new context. One of them, Ivan, said that he was not sure what to do in Section B, although he knew the mathematics. He said that it was *`another step of logic'* to relate the mathematics to a new context, and that *`remembering is different to understanding'*.

Table 1. Student expectations and performance on the transfer test.

Expectation of marks	Section A mark	Section B mark	Transfer Index
Top	100	100	100
Top	89	86	93
High	89	100	100
High	100	86	100
Average	67	57	79
Low	78	71	86
Low	78	43	14

The last blockage that emerged was curious – one student found the mathematics harder in the pure mathematics context than in the physical context. This blockage was reported by the only female student interviewed.

Cognitive Processes

From the interviews, a number of Tools and Workbench processes were identified. There are more that are thought to exist, but those given below emerged directly from verbal testimony of the students.

Tools The *Tools* that students identified as cognitive resources used during the test were:

- Logarithmic (log) laws
- Expectations
- Formulae developed in Section A

The first Tool was identified from statements such as *` [the test] . . . required a bit of thinking and knowing your log laws as well'*.

The last Tool listed here is an example of dynamic transfer – the construction of tools *in situ* that are used later in the test.

Workbench The processes that students identified that they used while doing the test were:

- Use of log laws
- Analysing the test according to expectations
- Interpreting/translating the text in Section B
- Interpreting the graphs
- Familiarity with the mathematical concepts in Section B (exponential growth and decay)

The first two processes listed here are executions of the first two Tools listed above. The last Workbench process was identified from answers to the question if Section B looked familiar: *`Definitely – with the exponential reduction thing . . . in the 3 Unit [Mathematics Extension 1] course last year'.*

Activation of Resources

If applicable, the students were asked what prompted their recognition that the mathematics in Section B was the same as in Section A. The responses were:

- Seeing equations with a 10kt form
- An exponentially decaying graph
- Having to solve Q.1 on Section B (which involved manipulation of an equation)
- Seeing `logs' in the questions

These prompts were identified as the activation[3] of mathematical resources, which according to Tuminaro (2004) can be inactive, primed or active.

Synthesis and Evaluation

Interview results

In his construction of a theoretical framework for analysis of students' mathematical thinking in physics, Tuminaro identifies three different cognitive structures involved in mathematical thinking: resources, epistemic games and frames (Tuminaro, 2004). Resources are here equated with Tools, although the definition of Tools is broader and includes `meta-tools' that control the use of lower-order (cognitive) tools. Of the three Tools identified in this project, the first (log laws) is a lower-order tool, or a mathematical resource. The second, expectations, is a meta-tool that controlled access to cognitive resources during the test, as evidenced by one student's comment that he was not thinking as clearly as he would during an exam: his framing of the situation affected the availability of cognitive resources. The last tool identified (formulae used in Section A) was a dynamic *in situ* construction that was used in Section B.

Thus, the Tools identified represent the three kinds of mental constructs outlined by Tuminaro – **Log laws** as mathematical resources; **Formulae developed in Section A** as epistemic games; and **Expectations** as frames.

In addition to the Tools and Workbench identification made from the interviews, information about the nature of the transfer process was gleaned through the themes and prompts that were identified. In fact, prompts can be seen as one of the themes – the recognising of Section A as

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[3] The hypothesised level of activity of a neuron or set of neurons. A neuron can be in a variety of activation levels

assisting in performance on Section B of the test. The other two themes were expectations and blocking factors. These two themes can be seen to be important in the transfer process as framing and activation of resources. Students' framing of a situation will determine their access to cognitive resources, and hindrances to the transfer process may interfere with the activation of resources.

A Special Case One student, Peter, was unusual in that he did not recognise the relationship between the two sections of the test, yet he performed very well. His interview suggested that during the test, he was not aware of connections between the two sections – there was no conscious priming or activation of resources between sections, yet he was still able to transfer well. This raises questions about the nature of transfer – is it a meta-cognitive process after all, or does it occur on a subconscious level?
More research is required to be able to provide an answer to this question.

Relation to the literature

The taxonomy of Barnett and Ceci (2002) was designed to allow transfer studies to be positioned along dimensions of content and context to enable constructive comparison of results and methodology (see Figure 2). Of the three content dimensions, memory demands is the most important in this project, as performance change is not being measured, and the nature of the learning skill is not of particular importance. For most of the students who took part in this project, the memory demands would have been `recognise and execute' (Barnett & Ceci, 2002). However, for those students who had taken time off (at least six months) between Year 12 and university, the memory demands become `recall, recognise and execute' (Barnett & Ceci, 2002). Aspects of the memory demands involved in transfer are illuminated by Redish (2003), who argues that recalling items from long-term memory is a non-trivial process that can take significant amounts of time. This was evidenced by the difficulty experienced by two students who had taken time off between high school and university in recalling how to use the mathematics that they knew.

In relation to the context dimensions for this project, the setting for transfer is between the two sections of the test, rather than from the original learning context to the test (which would have been much further transfer). Clearly, all of the contexts except for Knowledge Domain are the same – same place, time, function, social context and modality. But how far along the knowledge dimension is microbiology from pure mathematics? As mentioned earlier, members of the SUPER group attempted to position the test along this dimension, with no clear consensus beyond that reported (as non-near transfer). It is apparent that there needs to be more explicit criteria for the taxonomy in order to be able to satisfactorily position studies for comparison.

For the goal of understanding transfer, the situation of having only one non-near transfer dimension is a desirable situation, as varying a single one of the possible six dimensions of transfer context enables a clearer understanding of what is going on in students' minds. Future work needs to focus on extending understanding of transfer by manipulating the other dimensions that affect transfer (along the lines of Wagner's suggestion (2006); see Ellis (2007) for a taxonomy that extends Lobato's (2003) actor-oriented perspective).

Wagner (2006) argues for transfer researchers to investigate learner's perspectives on transfer, and to consider the relationship between their internal knowledge and their "social and contextual circumstances" (Wagner, 2006, p. 3). We see this study as a first step in this direction – analysing learner perspectives on the transfer process, and using recent comprehensive theoretical frameworks to do so.

Conclusion

The aim of this paper was to use theoretical frameworks to examine how first year science students see the transfer process of mathematical skills and knowledge to a different context. We have found the following.

- There is a comprehensive network of theoretical models in which we have embedded our work and have shown how these models can be applied.
- Students' when *transferring* rely on expectations, are susceptible to blocking factors and use discipline specific tools in particular ways.

It was found that the chosen theoretical frameworks (Rebello & Zollman, 2005; Redish, 2003; Tuminaro, 2004) provided useful and sensible results from our data. The use of these frameworks has enabled us to begin to answer the primary research question, but more studies are required. This study is a novel and valuable addition to the body of work on transfer of mathematics in that it has identified and used appropriate theoretical frameworks.

Future Work

Questions that have arisen from this project include:

- Is awareness of transfer related to the ability to transfer?
- What part do activation and memory play in the transfer process?
- How does the context aid or hinder transfer?

Qualitative studies are needed to examine the situation that was encountered in this study where a student transfers well yet is unaware of the transfer occurring. It has aided in identifying cognitive resources and processes, and relating the findings to theoretical frameworks for the purposes of understanding the transfer process in a deeper way by `getting inside' the students' heads. Further extensive qualitative analysis in future studies by transfer researchers (e.g. Wagner (2006)) will provide opportunity to identify more cognitive resources and processes involved in the transfer of mathematics skill and knowledge. Furthermore transfer studies in higher-level mathematics may benefit from engagement by researchers who have experience with the discipline specific ways of knowing and learning.

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