Connecting Mathematics with Science to Enhance Student Achievement- A Position Paper

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Students in secondary school often find mathematics abstract and irrelevant, frequently questioning its usefulness and purpose. The discourse around STEM education has encouraged secondary teachers to attempt connecting mathematics with other STEM disciplines, most commonly with science. By making connections between content and skills through applications, it is anticipated that secondary school students will engage more in class that may result in improved mathematics achievement. This paper explores the rationale for making connections with science, examines the impact on student achievement in mathematics from previous research and discusses challenges for schools and teachers.

When students enter secondary school, mathematics becomes an isolated discipline that is often seen as abstract, non-purposeful and with little connections to students' lives (Boaler, 2000). In the transition from primary school, it is common for students to disengage (Collie, Martin, Bobis, Way & Anderson, 2018), as they begin to question the usefulness of and their ability in mathematics. Students' views about mathematics get progressively worse as they continue through secondary school (McPhan, Morony, Pegg, Cooksey & Lynch, 2008), a potential cause for the low number of students currently studying higher levels of mathematics (Office of the Chief Scientist, 2017).

In response, Australian Government policy reports (Australian Curriculum, Assessment and Reporting Authority [ACARA], 2016) and research studies (Honey, Pearson & Schweingruber, 2014) are encouraging mathematics teachers to make connections with other STEM (Science, Technology, Engineering and Mathematics) disciplines, often through real-world projects. For the purpose of this position paper, curriculum connections involves making links between concepts, skills or practices from two or three disciplines to create meaningful knowledge (Naylor, 2014), whilst the disciplines remain separate entities in themselves.

Some argue that making connections between mathematics and science is possible as they have closely related systems of knowledge that relate to the physical world, they share common fields of application and practice, and have a mutual approach to solving complex problems (Honey et al., 2014; Kiray, 2012). These arguments portray a sense of simplicity in connecting outcomes and skills, however, making authentic and meaningful connections is difficult in practice and has implications for the way mathematics could be taught in secondary school. Therefore, the research question guiding this position paper is 'What has been the impact of connecting mathematics with science on secondary school students' achievement in mathematics and what can we learn from previous attempts?'

Theoretical Framework

To improve achievement in mathematics the expectancy-value theory of achievement motivation (Eccles & Wigfield, 2002) is a useful theoretical framework in understanding the rationale for making connections between mathematics and science. The framework emphasises the importance of enhancing students' values towards and expectations to

succeed in mathematics for improvements to student achievement. Theorists argue that an individual's persistence and performance can be explained by their views on how well they achieve in a subject and the extent to which they value a subject. This has previously been applied to mathematics learning, demonstrating that when students value or perceive competence in mathematics, they are more likely to persist and engage in deeper learning practices (Eccles & Wigfield, 2002), potentially resulting in increases to student achievement. Common practices such as an over-reliance on textbook work, traditional assessments focused on memorisation and little application to the outside world (McPhan et al., 2008) can potentially make it challenging for students to appreciate the value of mathematics. By drawing explicit connections to the application and usefulness of mathematics with science, there may be further possibilities to make the content more meaningful and to enhance students' views about the value of mathematics.

Rationale for Making Connections

The separation of mathematics from science in curriculum documents and the rare communication between subject teachers in secondary school has led to the fragmentation of content in students' minds (Bybee, 2013). Whilst mathematics knowledge and skills are crucial for the understanding of concepts in other disciplines (Fitzallen, 2015), mathematics teaching and learning can also benefit in making these connections. For example, science can provide opportunities to apply mathematical concepts, can assist in the transfer of knowledge and can present real-world contexts to learn abstract concepts (Honey et al., 2014).

Whilst mathematics and science have a different body of knowledge, curriculum authorities suggest that they share common practices such as inquiry learning and problem solving (ACARA, 2016). However, there are differences in the style of problem-solving approaches between mathematics and science. In mathematics, problem solving involves students using mathematics to represent unfamiliar situations or applying their existing strategies to seek solutions (Anderson, 2016). Whilst in science it involves evaluating claims, investigating ideas, drawing valid conclusions and developing evidence-based arguments (Berlin & White, 1994). These differences need to be acknowledged as they have implications for planning authentic and rigorous connected learning experiences.

Recent evidence has indicated that connecting mathematics with science can enhance students' values towards mathematics and provide a rich context for learning (Diedorp, Bakker, Maanen & Eijkelhof, 2014), which may result in improved achievement and later course enrolments (Eccles & Wigfield, 2002). In Diedorp et al.'s (2014) study, a connected unit of work was implemented that incorporated content from mathematics (correlation and regression) and science (sports physiology) and was delivered to a large cohort ($N = 415$) of students aged 16-17 years. The use of statistics as a bridge between mathematics and science is common as it provides the mathematical foundations for analysing data in the real world (Watson, 2017). Students found the work more meaningful and the application of knowledge assisted them to make connections between the content areas. Interestingly, student responses indicated that whilst the task assisted them to see the link between science and its' use in practice outside of school, they struggled to appreciate the relationship between mathematics and real-life application. This highlights the need for teachers to make explicit the usefulness of mathematics and the connections between mathematics and science, and to ensure that students develop a deep understanding of the mathematical concepts in order to apply them and make relevant connections (Honey et al., 2014). Previous curriculum models have demonstrated the possibilities of making connections between mathematics and science in secondary school, which have attempted to assist teachers in planning and implementing connected learning experiences.

Models for Connecting Mathematics and Science

The dominant term in the literature for a broad range of connected curriculum practices is 'integrated curriculum' and commonly refers to making connections between disciplines. In practice it is more than making relevant connections and can be seen as a step towards creating another entity, such that the separate disciplines are not distinguishable (Berlin & White, 1994). Whilst most curriculum models for mathematics and science have been labelled as 'integrated' their design and resources are useful for teachers who are planning to make connections whilst keeping the disciplines recognisable.

In 1994, Berlin and White developed one of the first models to demonstrate the diversity in opinion of what it meant to connect mathematics with science. It included six aspects (Figure 1) to help teachers develop connected learning tasks. They emphasised the importance of students recognising content overlap; the impact of the teachers' level of content expertise; the use of real-life projects and problems for authenticity; the need for cross-curricula assessments and the importance of a common language between the two subjects. The strengths of this model include the attention to detail of the teaching methods and the assistance it provides in enabling teachers to identify connections. Whilst the model identifies commonalities between the six aspects for both mathematics and science, there are different epistemic practices between mathematics and science, different ways of reasoning and different types of knowledge used and produced (Clarke, 2014). These key differences provide insight into the difficulty teachers have experienced in using this model to develop totally integrated curriculum experiences (Kiray, 2012).

Figure 1. Summary of the Berlin-White Integrated Science and Mathematics Model (BWISM). (Berlin & White, 1994).

In response to concerns and challenges by teachers attempting to connect the disciplines, Kiray (2012) published the Balance Model (Figure 2), which advocates for partial integration without removing the core differences between science and mathematics. This model demonstrates the varied approaches to connecting content areas on a balance scale and was developed alongside teachers after the implementation of a connected learning experience. It begins with 'math-centred science-assisted integration' where few mathematics outcomes are covered in detail, whilst science is the interval discipline whose outcomes are briefly used to make relevant connections. This slides into 'math-intensive science-connected integration' where the mathematics outcomes dominate the program and the science

outcomes are intentionally covered to make connections. The middle of the scale incorporates a more balanced approach through 'total integration' where there is an equal share of mathematics and science. The focus on science outcomes is observed on the other side of the balance scale.
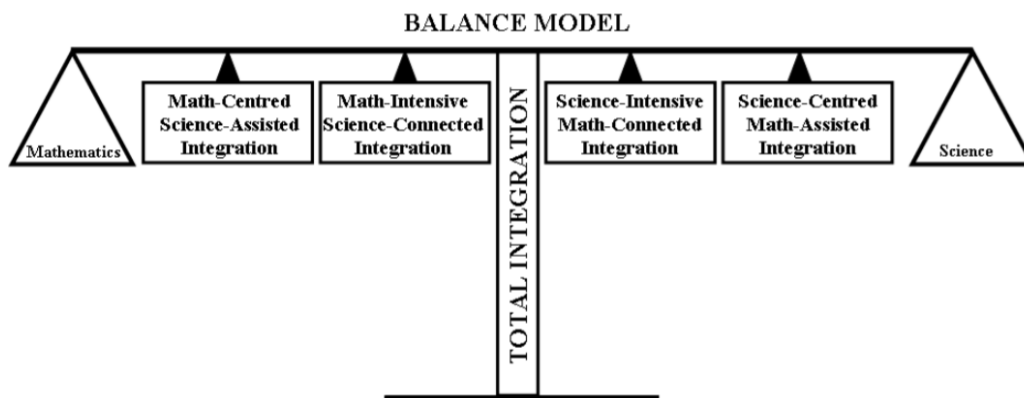
BALANCE MODEL

Figure 2. The Balance Model. (Reproduced from Kiray, 2012, p. 1185).

Unfortunately, both of these models have not been tested to determine whether they help students learn or analysed to see if they have been helpful for teachers in classroom practice. Future research is needed in this area as secondary school teachers begin to plan and implement connected learning experiences. Whilst questions still exist about the cognitive coherence of connected learning experiences, previous findings provide insight into what could be possible for challenging the traditional approach to teaching secondary mathematics as an isolated discipline. However, changes in student achievement have not been as positive for mathematics learning and the impact has depended on how the connections were made.

Impact on Students' Achievement in Mathematics

In a meta-analysis of 28 empirical studies, Becker and Park (2011) investigated the effects on student learning of connected approaches among the STEM disciplines. Whilst the knowledge gained from their research is important, the authors do caution that the number of studies was quite low and that many did not document changes in mathematics achievement.

Despite this, the largest effect size for mathematics came from Judson and Sawada's (2000) study, where a connected learning intervention was implemented with one group of eighth-grade students. In the intervention class, students were taught by the same teacher for both mathematics and science and used their science class as a context for learning statistics. The other class (control) continued their science and mathematics learning in separate non-connected experiences with different teachers. The results indicated that the students' statistics achievement in mathematics was significantly higher in the intervention class, χ^2 (4, $N = 53$) $=16.92$, $p < 0.005$, whilst science achievement remained consistent in both groups. The science teacher of the intervention class had strong content knowledge in mathematics and statistics and connected concepts, skills and language between the disciplines on their own. This is different to other interventions discussed in Becker and Park's (2011) analysis where content was connected across the disciplines through team-teaching and taught by multiple teachers who each had expertise in one discipline. These studies highlighted the importance of consistency in the terminology used and the need for

explicit connections to be made between disciplines (Honey et al., 2014); a difficult task in the dis-jointed structure of most secondary schools.

Despite these positive results, it has been more common for connected learning interventions to impact on mathematics achievement the least (Honey et al., 2014). As English (2016) suggests, the current sequence and structured approach to mathematics instruction may actually hinder learning when connecting with science. There is a concern that in changing the structure to mathematics instruction by adopting connected learning experiences, it may have the potential to disrupt the coherence present in mathematics programs. It is also uncommon for mathematics teachers to be leading connected learning experiences in STEM throughout secondary schools (Timms, Moyle, Weldon & Mitchell, 2018). This results in a disconnected approach where the mathematics is often included as procedural and simple practices such as calculations and measurements, failing to develop students' deep understanding required to observe and appreciate connections.

One study compared several interventions and examined how the connections were made (Hurley, 2001). The effect size for mathematics achievement was positive and large (d = 0.85) when connections used a 'sequenced model', where the mathematics and science content was planned and taught sequentially, usually by the same teacher. Interestingly, for 'total integration' where science and mathematics were taught together in intended equality, science achievement was significantly higher (d = 0.96). Both of these effect sizes exceeded Cohen's (1988) convention for a large effect (d = 0.80), however, mathematics achievement in the 'total integration' approach was negatively impacted (d = -0.11). Most often in this approach, students were taught by a non-mathematics trained teacher (i.e., usually a science teacher). This reflects English's (2016) concerns in connected learning experiences about the impact that non-qualified mathematics teachers may have when teaching mathematics.

For secondary mathematics teachers working on connecting mathematics to other STEM disciplines, they are now expected to become curriculum re-designers, working with multiple curriculum documents and aligning relevant discipline outcomes. Given that most secondary school teachers have strong content knowledge in only one discipline this presents a number of challenges for secondary schools and teachers.

Challenges in Connecting Mathematics with Science

Whilst there has been strong policy support for making connections between mathematics and science in Australia (ACARA, 2016), previous research has highlighted several challenges for secondary schools and teachers that have hindered efforts to connect discipline areas (Figure 3). Ultimately, the discipline-specific approach to learning has always prevailed in secondary schools (Tytler, Hobbs & Prain, 2016), so an awareness of these challenges may assist teachers when planning for connected learning experiences and provide opportunities for them to overcome these challenges.

Firstly, recent research has highlighted the difficulty for secondary mathematics teachers to develop conceptual links with science, whilst maintaining the integrity of the discipline (Tytler, Williams, Hobbs & Anderson, 2019). This may be because teachers have not acknowledged the marked differences in discursive practices, reasoning and artefacts between mathematics and science (Clarke, 2014). Without a coherent plan for curriculum connections, teachers' attempts at connecting the content areas may dismiss deeper learning practices, possibly resulting in an "epistemic stew" (Tytler et al., 2019, p. 53). Too often in connected learning experiences with science, mathematics plays a servant role where students use pre-existing knowledge and simple procedural applications. This is problematic for the development of students' knowledge and skills in mathematics (Honey et al., 2014) and provides insight into why some interventions have failed to improve achievement in mathematics.

School executive	Secondary teachers
•Timetabling •Staffing •Time for staff •Sustainability •Assessment •Parental expectations	•Beliefs •Subject-specific differences •Content knowledge •Pedagogical content knowledge •Time (teacher workload) •Curriculum documents •Executive support

Figure 3. Challenges faced by secondary teachers and the school executive.

For secondary mathematics teachers embarking on making connections with science, they are encouraged to ensure outcomes relevant to the stage of learning are covered in depth and with rigour (Tytler et al., 2019). Assessing learning development in both disciplines is crucial to maintain academic integrity and to gain support from other teachers and school executive (Honey et al., 2014). For sustainable innovation it is encouraged that work should be shared and critiqued with other staff members through professional development days (Timms et al., 2018).

Secondly, a prominent challenge is secondary teachers' level of content and pedagogical content knowledge. These have been linked to the engagement of both the teacher and the student during learning experiences (Brown & Bogiages, 2019), which is particularly challenging in connected learning environments when most secondary teachers have expertise in one discipline. In practice, it is common for schools to adopt models of team-teaching or sequenced integration (Judson & Sawada, 2000) where teachers work with students in their own subject classrooms, making links with other disciplines within each class. Whilst this is far from total integration (Kiray, 2012), this approach is possibly more sustainable and maintains the integrity of both disciplines.

In Brown and Bogiage's (2019) professional development study, they examined fifty secondary STEM teachers' implementations of two connected STEM tasks. When the task matched the teachers' content expertise, they observed behaviours described as an 'engager disposition' where both the student and the teacher asked questions, felt challenged and reflected on ideas. However, when the task was different to the teachers' content expertise, they observed patterns of discomfort with the task and a lack of confidence was expressed by the teacher. Calls for teachers to up-skill their content knowledge before embarking on connected learning experiences (Brown and Bogiage's, 2019) is further mirrored in Dare, Ellis & Roehrig's (2018) recommendations. Their study showed that when teachers lack the content knowledge for the tasks, concepts drawn between disciplines may lose their authenticity and the connections risk damaging the academic rigour. This most commonly impacts on mathematics more often than other STEM disciplines (English, 2016).

Thirdly, given the strong and complex relationship between teachers' beliefs and their classroom practice (Beswick, 2005), their beliefs about teaching and learning can be a significant challenge for schools attempting to connect the disciplines. Teachers' beliefs can influence the implementation of the experience, the planning and involvement in decision-making. School executive need to select appropriate mathematics teachers that are interested and have an understanding of the science curriculum (Brown & Bogiages, 2019). Priority should be given to those teachers who are qualified to teach both mathematics and science, and then to those who would work well in a collaborative environment (Dare et al., 2018). The incorporation of connected learning experiences in mathematics at pre-service teacher education and in-service professional development may provide teachers with opportunities

to learn and question connected curriculum approaches in mathematics and science, many of which are different to the way they were taught at school or university. With support and positive learning experiences, teachers may reflect on their beliefs about what could be possible in mathematics classrooms.

Finally, in preparing for changes to curriculum design, teachers have extensively discussed the significant time investment required and increases to teacher workload (Tytler et al., 2019), a contributing factor to the failure of previous attempts to connect the disciplines. Teachers will need to invest extra time to plan, reflect and negotiate on teaching programs. This will require strong support from the school executive for release time and support for teachers in changing the way students view mathematics as an isolated discipline.

Conclusion

Historically, attempts to develop and implement connected learning experiences have failed because of school traditions, discipline-specific syllabus and the realities of school practice. Whilst these still persist, it is easy to dismiss the next wave of momentum in STEM education and to have little hope for connected learning experiences in mathematics. However, Tytler et al. (2016) argues that there is more promise to this curriculum change. They suggest that factors including changes to the way knowledge is generated and used, urgency for more authentic practice, productive and positive findings from other countries connecting disciplines, and enthusiasm from schools and teachers are all signs that now is a good time for change in mathematics education.

It is important for future research to provide more empirical evidence and information about how teachers and schools are making connections between mathematics and science. This should consider the conditions that are best to connect mathematics with science to improve achievement in mathematics and to examine if making connections negatively impacts on student achievement by removing the rigour, abstractness and sequential approach to mathematics teaching and learning.

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