DOCTORAL THESIS IN TECHNOLOGY AND LEARNING
STOCKHOLM, SWEDEN 2018

Investigating the role of spatial ability as a factor of human intelligence in technology education

Towards a causal theory of the relationship between spatial ability and STEM education

JEFFREY BUCKLEY

KTH ROYAL INSTITUTE OF TECHNOLOGY
SCHOOL OF INDUSTRIAL ENGINEERING AND MANAGEMENT

JEFFREY BUCKLEY Investigating the role of spatial ability as a factor of human intelligence in technology education

KTH 2018

TRITA-ITM-AVL 2018:9
ISBN 978-91-7729-744-4

www.kth.se

Investigating the role of spatial ability as a factor of human intelligence in technology education

Towards a causal theory of the relationship between spatial ability and STEM education

Jeffrey Buckley

Doctoral Thesis
Department of Learning in Engineering Sciences
School of Industrial Engineering and Management
KTH Royal Institute of Technology
Stockholm, Sweden

Completed under the supervision of:
Dr Niall Seery, KTH Royal Institute of Technology, Stockholm, Sweden
Dr Donal Canty, University of Limerick, Limerick, Ireland
Dr Lena Gumaelius, KTH Royal Institute of Technology, Stockholm, Sweden

TRITA-ITM-AVL 2018:9
ISBN 978-91-7729-744-4

Doctoral thesis which, with due permission of KTH Royal Institute of Technology, is submitted for public defence for the degree of Doctor of Philosophy on Wednesday the 29th August 2018, at 14:00, in Salongen, KTHB, Osquars backe 31, Stockholm, Sweden.

Printed by Universitetsservice US AB

Abstract

Education is a particularly complex discipline due to the numerous variables which impact on teaching and learning. Due to the large effect of human intelligence on the variance in student educational achievement, there is a substantial need to further contemporary understandings of its role in education. Multiple paradigms exist regarding the study of human intelligence. One in particular, the psychometric tradition, has offered many critical findings which have had a substantial impact on STEM education. One of the most significant offerings of this approach is the wealth of empirical evidence which demonstrates the importance of spatial ability in STEM education. However, while categorically identified as important, a causal relationship between spatial ability and STEM is yet to be confirmed

As there is insufficient evidence to support a causal investigation, this thesis aims to develop an empirically based causal theory to make this possible. Five studies were conducted to achieve this aim and are described in the appended papers. As the research explores spatial ability in technology education, Paper I examines the epistemological position of technology education within STEM education. Based on the evidence showing spatial ability is important in Science, Engineering and Mathematics, Paper II explores its relevance to Technology. Paper III offers an empirically based definition for spatial ability through a synthesis of contemporary research and illustrates empirically where it has been observed as important to STEM learning. Paper IV examines the perceived importance of spatial ability relative to intelligence in STEM education from the perspective of technology education. Finally, Paper V examines the psychometric relationship between spatial ability and fluid intelligence (Gf) based on a hypothesis generated throughout the preceding papers.

The main results of this thesis illustrate the predictive capacity of visualization (Vz), memory span (MS), and inductive reasoning (I) on fluid intelligence (Gf) which is posited to offer a causal explanation based on the creative, innovative, and applied nature of STEM. Additional findings include the observation that learners use problem solving strategies which align with their cognitive strengths, that external representations of problems can scaffold the use of spatial ability or alleviate the need for it, that the variability of knowledge types across STEM sub-disciplines may affect the nature of reasoning within disciplines, and that for technology education specifically, acquiring an explicit knowledge base is not perceived to denote intelligence while the capacity to reason abstractly to solve novel problems is. This epistemological fluidity and focus on reasoning highlights the unique way in which technology education can provide insight into intelligence in STEM education. The implications of these results are discussed with specific focus on their theoretical validity and potential application in applied educational contexts.

Key Words: Spatial ability, Technology education, STEM education, Learning, Human intelligence.

Sammanfattning

Utbildning är ett mycket komplext forskningsområde, där många olika parametrar påverkar undervisningen och inverkar på lärandet. En viktig parameter är den mänskliga intelligensen som anses ha en relativt stor effekt på hur studenter presterar i skolan. Därför finns det ett behov av att ytterligare utveckla förståelsen kring relationen mellan intelligens och utbildningsresultat. Det finns flera forskningsparadigm att förhålla sig till vid studier av mänsklig intelligens. I synnerhet ett paradigm, den psykometriska traditionen, eller som vi idag kallar området, psykometriska mätningar, har gett oss många viktiga insikter med betydelse för STEM-utbildning. Ett viktigt bidrag är den stora mängd empiri som samlats och visat att spatial förmåga inverkar på möjligheten att prestera inom STEM. Men, samtidigt som att vi nu vet att detta samband finns är det ännu inte bekräftat vad som orsakar detta samband.

Syftet med denna avhandling är att utveckla en empiriskt baserad teori som kan bekräfta detta orsakssamband. Fem studier har genomförts, vilka alla är beskrivna i avhandlingens artiklar. Forskningen har genomförts i en teknikdidaktisk kontext och första artikeln beskriver därför den epistemologiska positionen av teknikundervisning inom STEM. Med utgångspunkt i de bevis som visar att spatial förmåga är viktigt för lärande inom matematik, naturvetenskap och ingenjörsutbildning undersöktes i artikel två om detta också är relevant för teknikämnet. I artikel tre ges en detaljerad definition för spatial förmåga som tagits fram genom en syntes av nutida forskning. Studien visar empiriskt på vilket sätt spatial förmåga påverkar lärande inom STEM. I artikel fyra undersöks den upplevda betydelsen av spatial förmåga i relation till faktisk intelligens i en teknikutbildningskontext. Slutligen, i artikel fem, så undersöks det psykometriska förhållandet mellan spatial förmåga och flytande intelligens (Gf) baserat på en hypotes som tagits fram utifrån framtagna resultat i de tidigare artiklarna.

Resultaten från denna avhandling illustrerar att man till en viss del kan förutspå flytande intelligens (Gf) genom att mäta visualiseringsförmåga (Vz), minnesomfång (MS) och förmågan att föra ett induktivt resonemang (I). Detta resonemang visar på flera parametrar som påverkar studieresultat inom STEM. Detta samband ger en kausal förklaring till vilken del av den mänskliga intelligensen som är viktigt för utbildning inom STEM om man antar att STEM är ett område som är både kreativt, innovativt och tillämpbart. Resultaten visar också att den som är i stånd att lära sig använder problemlösningsstrategier som ligger i linje med sina kognitiva styrkor, det vill säga att de som inte har en välutvecklad spatial förmåga till stor del kan utveckla andra strategier för att lösa problem. Variationen av vilken sorts kunskap som används har också betydelse för hur man använder sin spatiala förmåga, där t.ex. det inom teknikämnet inte bara är ämneskunskaper som är viktiga för att vara duktig inom teknik, utan där det också värderas hur bra man är på att lösa nyfunna problem. Denna typ av resonemang ger oss en insikt i hur teknikämnet kan ge oss en vidare syn på vad intelligens inom STEM är. Konsekvenserna kring resultaten diskuteras i avhandlingen där jag särskilt inriktar mig på resultatens teoretiska validitet och på hur dessa resultat kan tillämpas i pedagogiska sammanhang.

LIST OF APPENDED PAPERS*

I. Buckley, J., Seery, N., Power, J. & Phelan, J. (2018). The importance of supporting technological knowledge in post-primary education: A cohort study. *Research in Science and Technological Education*. https://doi.org/10.1080/02635143.2018.1463981

II. Buckley, J., Seery, N., & Canty, D. (2018). Investigating the use of spatial reasoning strategies in geometric problem solving. *International Journal of Technology and Design Education*. http://doi.org/10.1007/s10798-018-9446-3

III. Buckley, J., Seery, N., & Canty, D. (2018). A heuristic framework of spatial ability: A review and synthesis of spatial factor literature to support its translation into STEM education. *Educational Psychology Review*. http://doi.org/10.1007/s10648-018-9432-z

IV. Buckley, J., O'Connor, A., Seery, N., Hyland, T., & Canty, D. (2018). Implicit theories of intelligence in STEM education: Perspectives through the lens of technology education students. *International Journal of Technology and Design Education*. http://doi.org/10.1007/s10798-017-9438-8

V. Buckley, J., Seery, N., Canty, D. (2018). Visualization, inductive reasoning and memory span as components of fluid intelligence: Implications for technology education. *International Journal of Educational Research*. http://doi.org/10.1016/j.ijer.2018.05.007

*The papers are not included in the electronic version of the thesis.

ACKNOWLEDGMENTS

There are many people who have helped and supported me in completing this thesis. Firstly I would like to express my sincere gratitude to my supervisors, Dr Niall Seery, Dr Donal Canty and Dr Lena Gumaelius. Niall, as my principal supervisor, you have dedicated so much of your time to me, you continue to mentor me and have provided me with so many opportunities over the last few years. Donal, as my co-supervisor, you added alternative perspectives to my work, have always been available and offered much needed advice. Lena, as my newest co-supervisor, you have really helped me in adjusting to life in Sweden and have provoked me to think about how I communicate my work to others.

I would also like to thank my co-authors in the included papers, and great friends, Dr Adrian O'Connor, Joe Phelan, Tomás Hyland and Dr Jason Power. Adrian, you were a great support in my first few years as a PhD candidate in helping me to understand what getting a PhD really involves, and you still continue to give me advice. Joe, you have made me think about technology education very differently over the last year and have been very constructive when you reviewed my work. Tomás, you have always been available to chat when the stress of this work was getting too much, and helped so much by collecting and inputting data. Jason, you helped me when I was beginning to learn statistics and you have been a great support at conferences. Also, while we didn't work together with regards to this thesis, I would also like to thank Andrew Doyle. It has been great to maintain some familiarity since moving to Sweden and you have been a great support this past year.

I would like to thank all those who volunteered to participate in my studies. Without your involvement this work would never have been completed.

I would like to thank Professor Emeritus Richard Kimbell, for acting as my opponent in my 90% seminar. You challenged me on so many aspects of my work, and have really helped me to clarify my interpretation of technology education.

I would like to everyone at KTH who I have worked with since arriving here for making me feel so welcome. Professor Arnold Pears, you initially helped me settle in and continue to help now in these last stages of my PhD. Dr Maria Weurlander, you have helped so much in terms of the practicalities of getting a PhD at KTH. Dr Eva Hartell, you continue to introduce me to new opportunities for research in Sweden. Ebba Berggren, by talking with me about your work, you have influenced how I think about my own. Elizabeth Keller, every time I have had a question since moving to Sweden and I didn't know who to ask, you have been able to help. I would also like to everyone else here for welcoming me, especially Stefan Stenbom, Matts Amundsen, Dr Per Norström, Dr Eva Björkholm, Helena Isaksson Persson, Birgit Fahrman and all of the PhD candidates here.

I would like to thank everyone who worked with me while I was at the University of Limerick for helping me with my research and for making it such an enjoyable place to work, in particular Dr Seamus Gordon, Seamus Harrold, Joe Murray, Dr Diarmaid Lane, Brian Devitt, and Anthony Rynne.

I would like to thank all of the other researchers who have helped me over the last few years, notably Professor Sheryl Sorby and Professor Brian Bowe.

I would like to thank my girlfriend, Jenny, for all of the encouragement and support you have given me during the last three and a half years, and for moving to Sweden with me while I finished this work.

Finally, I would like to thank my brother, Greg, and my parents, Jo and Aubrey, for helping in any way you could throughout all of my life and for continuously supporting me in any decision I make. I wouldn't be in a position to write this thesis today if it wasn't for everything you have done for me.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1. Thesis outline

This thesis consists of an introductory chapter, or “kappa”, which offers a summary and synthesis of the included research which is more thoroughly described across five appended papers. The kappa consists of six sections. The introduction section provides a general context to the thesis and presents the research questions, aim and objectives. The background section presents the pertinent research which underpins this thesis. The methodology section provides a summary of the research which governed the methodological framework for this thesis and an overview of the general approach taken in attending to the research objectives. The summary of papers section provides a brief but explicit overview of the aim, method, results, and contributions of each of the appended papers as they relate to this thesis. The discussion section offers a synthesis of the results from all appended papers and describes their implications for technology education and more generally for STEM education. Finally, the conclusion section provides details on the achievement of the research objectives, offers a description of the limitations of this research, and provides recommendations for the continuation of this research agenda.

1.2. Context

“If there is anything that the last 100 years of social science research has taught us, it is that every person is a one-of-a-kind combination of genes and experience. Each person is unique and not equal to any other in the mathematical sense” (Detterman, 2016, p.2). When considering this relative to education, it becomes clear that teachers are regularly required to negotiate a vast array of interconnected variables, from which they must ultimately design pedagogical approaches that cater for the unique needs of individual learners. This is challenging and complex and in order to positively affect educational practices, the variables that all stakeholders in the learning process have to contend with need to be understood in terms of their situational impact and potential malleability. Broadly, these variables can be categorised into student variables and school variables (Detterman, 2016). Student variables include characteristics inherent to individual students such as intelligence, grit, self-efficacy, motivation, socioeconomic status, and parent or guardian education. School variables include the characteristics of schools that effect groups of students within them such as teacher quality, length of the school day, class size, money spent per student, and the type of pedagogical instruction used. Detterman (2016) reviewed evidence accumulated over the past 50 years and illustrated that approximately 10% of the variance in academic achievement at every level of education in developed countries can be attributed to school variables, while approximately 90% of the variance can be attributed to student variables. More precisely, Detterman (2016) noted that teachers account for between 1% and 7% of the total variance in academic achievement while general cognitive ability or intelligence accounts for somewhere between 50% and 80% of the total variance. O’Connell (2018) provided corroborating evidence illustrating that general cognitive ability could explain nearly all of the variance in mathematical and reading ability in a representative sample of children in Ireland at 13 years of age (n = 7525). Furthermore, Smith-woolley et al. (2018) found that the effect of school type on exam performance in a representative sample of pupils in the UK (n = 4814) disappeared after adjusting for the student variables of socioeconomic status, prior achievement (measured at age 11), and general cognitive ability. Schools contribute greatly to the general academic and holistic development of students, but when specifically considering the academic variance between students, intelligence is a much more powerful predictor. Therefore, research and educational efforts associated with student variables, notably intelligence, have the potential to significantly address the variances in academic achievement between students. While it is acknowledged that school variables can have a significant impact on student learning, this thesis specifically investigates intelligence in technology education with the agenda of ultimately contributing to STEM educational practices.

When subscribing to the definition of learning as being “a change in long-term memory” (Kirschner, Sweller, & Clark, 2006, p.75) which “involves the acquisition of knowledge” (Mayer, 2002, p.226), the contribution of intelligence can be clearly seen. There is a relationship between general intelligence and knowledge in that both can be used together to solve problems but they are dissociable constructs (Hambrick et al., 2012). The agenda of education is student learning, and hence knowledge acquisition, and general intelligence has been identified as a causal factor in learning as it supports the acquisition of knowledge (Kvist & Gustafsson, 2008; Primi, Ferrão, & Almeida, 2010). Essentially, intelligence is posited to enable learning and greater intelligence is therefore posited to enable more efficient information processing, and hence “greater” learning. Therefore, furthering current understandings of the role of intelligence in learning could lead to the development of empirically supported pedagogies which can increase students’ general capacity to acquire knowledge, and hence to learn.

Student variables are often described as individual differences and can take the forms of cognitive, conative, physical or physiological differences (Manichander, 2016). Individual cognitive differences, such as intelligence, have long been acknowledged as critical within education (Cronbach, 1957; Paterson, 1957). As a field of study, research pertaining to individual cognitive differences has accumulated a substantial amount of evidence to support educational practices. In the context of Science, Technology, Engineering and Mathematics (STEM) education, spatial ability, a factor of human intelligence, has been categorically identified as one of the most important cognitive faculties for educational success (Lubinski, 2010; Wai, Lubinski, & Benbow, 2009). Recognising the importance of spatial ability in STEM education, and that low levels of spatial ability can negatively affect STEM learners by preventing their engagement with educational material, Sorby has developed an educational intervention to facilitate learners’ spatial cognitive development (Sorby, 1999, 2009; Sorby & Baartmans, 1996). The results of this intervention have shown both that spatial ability can be developed though targeted interventions, and that increasing learners’ levels of spatial ability results in statistically significant STEM performance gains and improved retention (Sorby, 2009; Sorby, Casey, Veurink, & Dulaney, 2013).

Although the existence of the correlation between spatial ability and STEM education is firmly established, a causal relationship has yet to be determined. Instead, the prevailing discourse is dominated with hypotheses, theories and speculation. Tversky (2005) offered one such theory postulating that the possession of more advanced spatial ability equips people with the capacity to generate more robust mental representations of a problem. While this is likely to be a contributing factor, spatial ability as a cognitive faculty consists of multiple factors which extend beyond mental representation to include imagery generation and mental manipulation (Buckley, Seery, & Canty, 2017c; Carroll, 1993; Schneider & McGrew, 2012). While the identification of the relationship between spatial ability and STEM education has contributed greatly to the agenda of making educational practices more empirically driven, understanding the causal relationship would allow for pertinent interventions to be scientifically refined and developed. As noted by Wai, Lubinski and Benbow (2009, p.829) “such efforts, if successful, will contribute to the urgent social need of effectively identifying and developing scientific and technical talent for the information age”.

While most evidence which illustrates the association between spatial ability and STEM comes from Science, Engineering and Mathematics, this thesis focuses on the relationship between spatial ability and technology education. The main reason for this is that as a factor of intelligence, spatial ability is independent of semantic knowledge (Schneider & McGrew, 2012). A unique aspect of technology education is its epistemological fluidity (Norman, 2013). Technological activity is multidimensional, drawing on subjects such as Science, Engineering and Mathematics, with explicit technological knowledge being relative to specific tasks and circumstances (McCormick, 1997). It is this fluid nature of knowledge in technology education that presents the discipline as an auspicious context in which to examine spatial ability. It is posited that the epistemological fluidity of technology education may support research efforts in gaining further insight into the role of spatial ability in

STEM learning in general. It is clear that spatial ability is important for STEM learners, understanding why and when it is important would have significant implications for practice.

1.3. Research questions

The determination of a causal relationship between spatial ability and STEM education would have a number of profound educational implications. Notably, the identification of a causal explanation may advance contemporary understandings of how students learn in STEM. This thesis initially aspired to empirically determine a causal relationship between spatial ability and STEM educational performance, however at its inception there was insufficient foundational evidence to support a causal investigation. There was therefore a need to determine an empirically supported causal theory which describes the relationship between spatial ability and STEM which could be subsequently examined relative to educational practice. This thesis aims to address this issue by exploring spatial ability in the context of technology education. To guide this exploration, the following research questions were addressed:

RQ1. How does the epistemological position of technology education impact research investigating the relationship between intelligence, in particular spatial ability, and STEM?
RQ2. How do levels of spatial ability affect problem solving performance in technology education?
RQ3. What is the nature of the current evidence which illustrates the correlation between spatial ability and STEM education?
RQ4. How is spatial ability perceived to align with technology teacher education students' perceptions of intelligence in STEM?
RQ5. How is spatial ability psychometrically related to other perceived factors of intelligence in STEM education?

1.4. Research aim

Substantial evidence identifies that spatial ability is paramount within STEM education, it can be developed, and supports performance and retention. However "research should not simply try to find out 'what works' (cf. Chatterji, 2005; Olson, 2004) but should be aimed at explaining why particular methods help and why others do not help to reach particular goals in particular types of education under particular conditions" (Kirschner & van Merriënboer, 2013, p.179). There is now a need to identify why and when spatial ability supports STEM learners so that pertinent pedagogies can be refined and developed. However, as discussed, there are a number of foundational research questions which need to be answered to support a causal investigation. In light of this, the aim of this thesis is to develop an empirically supported causal theory which can be observed and tested in practice. Acknowledging that spatial ability is important, the theory should provide evidence identifying what spatial ability is, what elements are important within STEM education and in which scenarios they are important, why these elements are important, and how they can support education. Importantly, it should be cognisant of the roles that additional cognitive, conative, physical and physiological factors can have in education.

1.5. Research objectives

In an effort to provide answers to the above research questions and to fully attend to the aforementioned aim, the research compiled in this thesis proposed to:

1. Empirically determine the epistemological differences between technology education and other STEM disciplines
2. Investigate whether and to what extent the correlation between spatial ability and STEM educational performance is observable in technology education

3. Establish an empirically derived working definition for spatial ability through a review of contemporary spatial factor literature
4. Empirically ascertain the sociocultural validity of spatial ability for technology education students
5. Develop an empirically based model which can theoretically describe the causal relationship between spatial ability and STEM education

2. BACKGROUND

As this thesis concerns the study of human intelligence, it is important to give a brief overview of how the conception of human intelligence has evolved over time from the perspective of the paradigm adopted within this thesis. The main reason for this is due to the particular language which is associated with the field but it is also necessary to provide context for the methodological design across the appended studies. The primary construct being examined in this thesis is spatial ability which is a cognitive factor. Therefore, there is a need to broadly understand what cognitive factors are and how they are positioned within pertinent theories and frameworks. Similarly, spatial ability itself consists of multiple factors and understanding these is critical to determining how spatial ability relates to STEM. As previously discussed, technology education is the context that is being used in which to study spatial ability. Due to the relationship between intelligence and knowledge in learning, how knowledge is conceived within technology education must be framed. Therefore, within this background section, early theories of intelligence will be described to introduce some of the specific terminology prevalent in this thesis. This will be followed by a description of contemporary theories of intelligence to present the current state of knowledge and illustrate how spatial ability relates to other factors of intelligence. Subsequent to this, spatial ability and what is currently known about its role in STEM will be summarised. Finally, a brief description of technological knowledge will be given to demonstrate why technology education was chosen as a context within which to study intelligence.

2.1. Early theories of human intelligence: Spearman and Thurstone

2.1.1. Defining intelligence as a singular or manifold construct

The concept of human intelligence is contentious and difficult to define. On a macro level, there is a debate as to whether intelligence is one holistic construct or whether it comprises of multiple elements. McKusick (1969) offers the characterisations of lumpers and splitters which could be associated respectively with such theorists. From the lumper perspective, the construct of intelligence is a singular cognitive ability or a general intelligence often referred to as *g* (Spearman, 1904). The expression of this intelligence may differ depending on its context, but an individual is seen to have one singular intelligence which is observable in a variety of intelligence tests (Willis, Dumont, & Kaufman, 2011). In contrast to this, splitter theorists view intelligence as a multidimensional construct consisting of multiple higher order cognitive abilities which are largely independent of each other. Despite agreeing that intelligence is a manifold construct, there are varying conceptions as to the nature of the different elements. For example, some theorists conceive intelligence as a structure of cognitive factors (e.g. Carroll, 1993; Guilford, 1967; Horn & Cattell, 1966; Schneider & McGrew, 2012; Thorndike, 1927; Thurstone, 1938). Other splitter theorists focus more on mental processes such as planning, attention, and negotiating information in sequential or holistic approaches, rather than on discrete cognitive abilities (e.g. Das, Naglieri, & Kirby, 1994; Kaufman & Kaufman, 1983; Luria, 1980). A third group of splitter theorists argue that the concept of intelligence as measured by most intelligence tests offers too narrow a view of intelligence as they omit capacities such as practical intelligence, creativity and rational thinking (e.g. Gardner, 1983; Sternberg, 1985a).

In this thesis intelligence is viewed as consisting of cognitive factors, and from the perspective of a splitter theorist, i.e. that intelligence describes a structure of multiple unique but related cognitive factors. The construct of a cognitive factor will be described in more detail in the following sub-sections. It is important to note that the idea of a single general intelligence is not being contested in this thesis. Substantial evidence accumulated over the last 100 years supports its existence. The reasons for adopting this position are to support the derivation of a causal theory explaining the relationship between spatial ability and STEM education, and to better enable a pragmatic description of spatial ability to facilitate its utility for educational practice.

2.1.2. Spearman's two-factor model

One of the first theories associated with human intelligence was Spearman's (1904) theory of a general intelligence, *g*. Spearman's (1904) early work involved measuring responses to sensory stimuli and correlating these with perceived measures of intelligence which included school test scores and perceptions of intelligence from relevant teachers and peers. However, the theory was initially disputed for not including potentially important activities requiring mental effort, specifically higher order activities classed as reasoning (Burt, 1909, 1911).

Spearman (1927) responded with empirical evidence to support his theory and this resulted in his postulates of *g* and *s*, the general and specific factors of his two-factor theory (Figure 1). He defined *g* as "not any concrete thing but only a value or magnitude" (p.75), identifying it as representative of a general ability which is "common to all abilities that are interconnected by the tetrad equation" (p.76). Specific factors, denoted as *s*, referred to factors of intelligence which emerged from specific tests or subtests but were not common to all tests in a battery. He posited that the interaction between a person's general intelligence and a specific factor of intelligence was responsible for test performance.

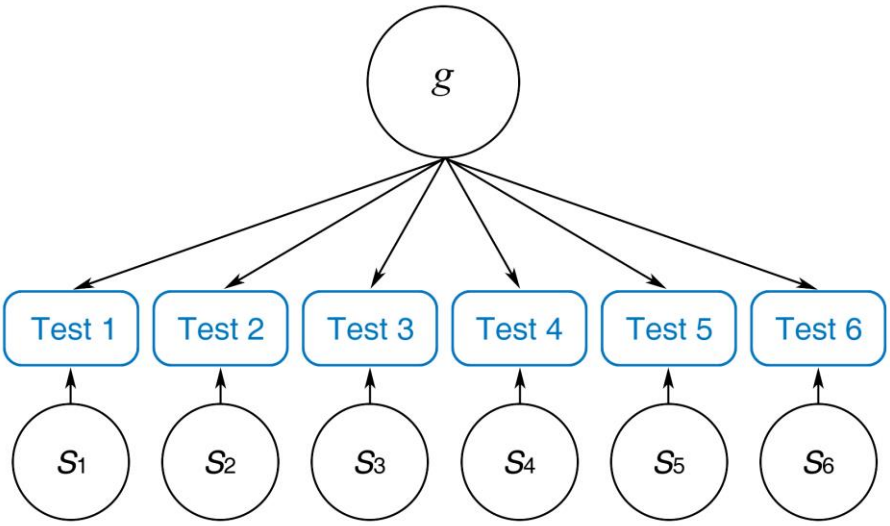

Figure 1. Spearman's (1927) two-factor theory of intelligence.

Evolving from Spearman's two-factor theory, the bi-factor theory was later conceptualised by Holzinger and his colleagues (Holzinger & Harman, 1938; Holzinger & Swineford, 1939). Using Spearman's theory as a framework, the bi-factor theory began to identify a series of specific factors or second-order factors. These were identified as spatial relations, verbal, perceptual speed, recognition and associative memory.

2.1.3. Thurstone's primary mental abilities

At a similar time that the bi-factor theory was being proposed, Thurstone (1938) conceptualised his model of primary mental abilities. Thurstone's model shares many factors with the bi-factor model such as the factors associated with spatial relations and perceptual speed. However, there are some notable differences, potentially resulting from a combination of differences in tests administered, methods of factor analysis and researcher inference. Thurstone (1938) developed new methods of factor analysis which differed to Spearman's and conducted an analysis which identified 13 group factors and no general factor. He argued that the existence of a *g* factor resulted from a statistical artefact based upon the mathematical procedures used by Spearman. Thurstone identified seven of these group factors as primary mental abilities, more commonly known as second-order factors, and labelled them as space (S), perceptual speed (P), number facility (N), verbal relations (V), word fluency (W), memory (M) and induction (I) (Figure 2). His results identified a further six factors which he did not perceive to be primary factors. These included a factor denoted as R which was associated with success in tasks that involved a form of restriction in the solution, a factor denoted as D which appears to represent deduction, three factors which remain uncharacterised and a final factor posited to be a general residuum (Spearman, 1939).

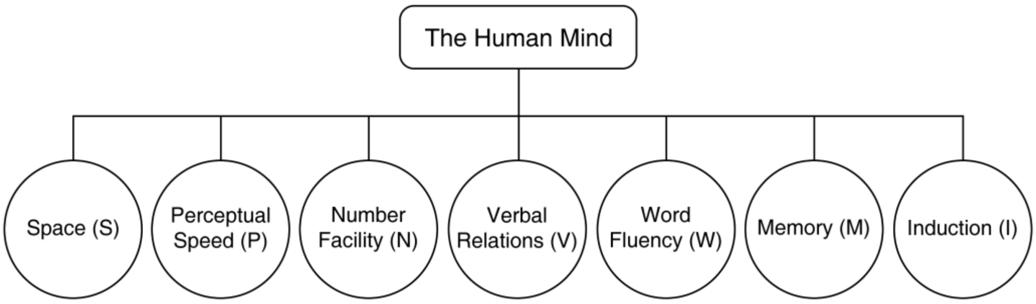

Figure 2. Thurstone's (1938) model of primary mental abilities.

2.1.4. The evolving factor model of intelligence

Following Spearman and Thurstone, many researchers developed their own theoretical models of human intelligence. Presenting these here serves to illustrate how the theories of Spearman and Thurstone evolved over time as they began to more clearly position cognitive factors relative to each other. For example, Burt (1949) hypothesised an idealised hierarchical model with successive dichotomies at different levels of mental generality. Burt's model (Figure 3) is divided into various levels of bifurcation which he identified as relations, associations, perception and sensation. At the relations level, Burt identifies the first major dichotomy as being between the intellectual characteristics (*g*) and the practical or behavioural characteristics. He recognised psychomotor abilities, abilities that deal with space and mechanical affairs, as being contained within the practical domain of intelligence (Guilford, 1967). Burt later had to depart from his strict dichotomisation upon the recognition that certain aptitudes such as memory can be divided into more than two group factors (Guilford, 1967).

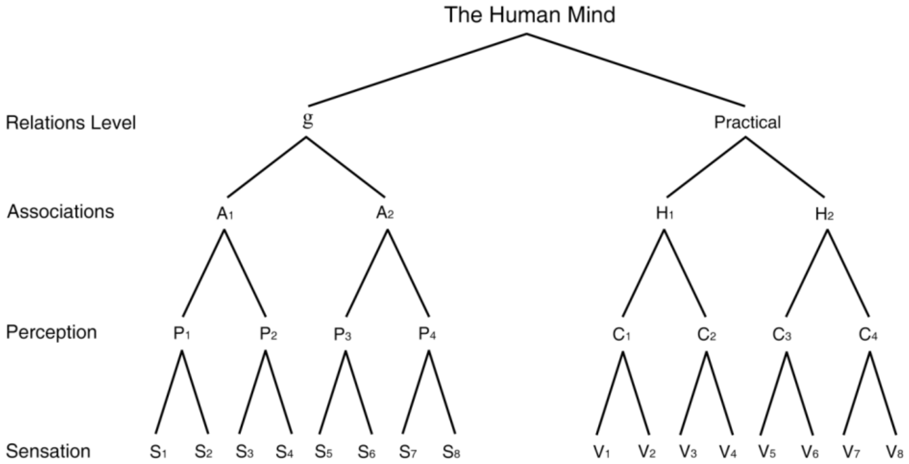

Figure 3. Burt's (1949) hierarchical model of aptitude factors (Guilford, 1967).

At the same time, Vernon (1950) theorised a different hierarchical model (Figure 4) citing *g* as the primary factor with all others deriving from it. Like Burt he conceived that there were two major factors, v:ed for verbal-educational and k:m which is similar to Burt's practical factor. The factor v:ed subdivides into verbal and numerical factors while k:m subdivides into space ability, manual ability and mechanical information (Guilford, 1967; Vernon, 1950). Vernon did not posit a definitive list of minor group factors or specific factors but his model created a more auspicious framework than Burt's as it did not adhere to a strict dichotomous hierarchy. The important aspects of both of these frameworks are that the hierarchical structure was beginning to emerge, and that there was uncertainty in terms of the nature of the factors at each level. In the more contemporary theories described in the next sub-section, this hierarchical structure is maintained, and significant research efforts were invested in determining the factors and relationships between the factors at each level.

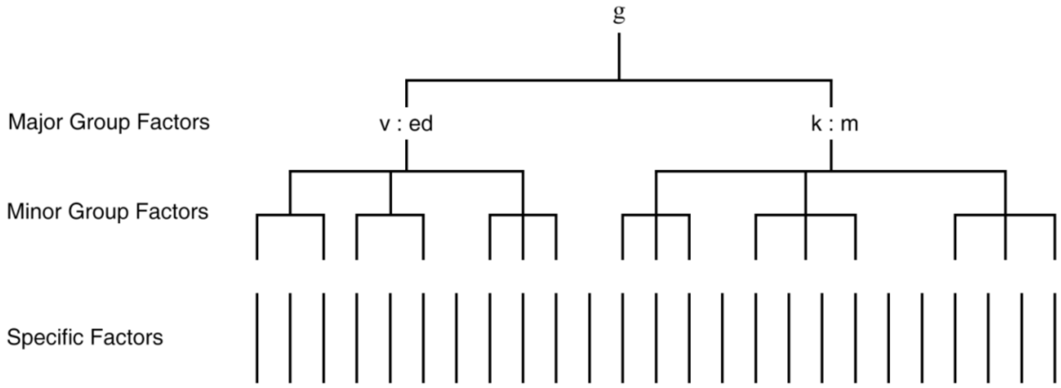

Figure 4. Vernon's (1950) hierarchical model of aptitude factors (Guilford, 1967).

2.2. Contemporary theories of human intelligence: Cattell, Horn and Carroll

2.2.1. Cattell and Horn's Gf-Gc theory

The theory of fluid and crystallised intelligence (Gf-Gc theory) has been described as being "probably the best known and most widely accepted theories of intellectual factors" (Willis et al., 2011, p.44), perhaps due to the high levels of construct validity of each of the second-order factors within it. Initially the Gf-Gc theory was conceptualised as the division of Spearman's *g* into two separate general factors known as fluid and crystallised intelligence (Cattell, 1943, 1963). Fluid intelligence (Gf) is defined as "the use of deliberate mental operations to solve novel problems (i.e., tasks that cannot be performed as a function of simple memorization or routine)" (Primi, Ferrão, & Almeida, 2010, p.446). These include drawing inferences, concept formation, classification, generating and testing hypothesis, identifying relations, comprehending implications, problem solving, extrapolating, and transforming information (Kane, 2005; McGrew, 2009; Primi et al., 2010). It is also the closest second-order factor to *g* (Ebisch et al., 2012). While fluid intelligence (Gf) is associated with novel problem solving, crystallised intelligence is defined as "accessible stores of knowledge and the ability to acquire further knowledge via familiar learning strategies" (Wasserman & Tulsky, 2005, p.18). Fluid intelligence (Gf) "increases until adolescence and then slowly declines" while crystallised intelligence "consists of discriminatory habits long established in a particular field, originally through the operation of fluid ability, but not longer requiring insightful perception for their successful operation" (Cattell, 1943, p.178).

Subsequent to Cattell's bifurcation of *g* into Gf and Gc, his graduate student John Horn concluded that there was more to intelligence than the dichotomous Gf and Gc (Davidson & Kemp, 2011). Over time, this theory was developed (Cattell & Horn, 1978; Horn, 1985; Horn & Cattell, 1966; Horn & Noll, 1997) by drawing on evidence from "neurological damage and aging" and "genetic, environmental, biological, and developmental variables" (Horn & Blankson, 2005, p.45). These developments have resulted in the model now often being referred to as extended Gf-Gc theory.

Horn & Blankson (2005, p.43) offer the following list of the second-order factors contained within this theory:

- Acculturation knowledge (Gc)
- Fluid reasoning (Gf)
- Short-term apprehension and retrieval (SAR)
- Fluency of retrieval from long-term storage (TSR)
- Processing speed (Gs)
- Visual processing (Gv)
- Auditory processing (Ga)
- Quantitative knowledge (Gq)

2.2.2. Carroll's three-stratum theory

Carroll's (1993) three-stratum theory is the second major contemporary theory of human cognitive abilities. Where the Gf-Gc theory emerged from Spearman's theory of *g*, the three-stratum theory was predominantly underpinned by Thurstone's work. Similar to the Gf-Gc theory it has many strong proponents. Horn (1998, p.58), for example, described it as a tour de force summary and integration that is the "definitive foundation for current theory". The three-stratum theory is the result of a meta-analysis of 461 psychometric datasets and was the first empirically based taxonomy that presented all established cognitive factors into a single organised framework (McGrew, 2009). Unlike the Gf-Gc theory which contains two hierarchical layers of factors, the three-stratum theory contains three hierarchical layers of factors. The only third-order factor is a representation of Spearman's (1904) *g*. While Carroll (1993) does not agree with Spearman's (1927) interpretation of *g* as representing mental energy, he does agree that it underlies all intellectual activity (Davidson & Kemp, 2011). The second stratum contains eight factors which are similar to the second-order factors within the Gf-Gc theory. Finally, the theory then contains 69 unique first-order factors with each one aligning strongly with at least one of the second-order factors in the theory. The following is a list showing the third- and second-order factors within the three-stratum theory Carroll's (1993, pp.583-584):

- General intelligence (3G)
- Fluid intelligence (2F)
- Crystallized intelligence (2C)
- General intelligence[1] (2H)
- Broad visual perception (2V)
- Broad auditory perception (2U)
- Broad cognitive speediness (2S)
- Broad retrieval ability (2R)
- Broad memory ability (2Y)

2.2.3. The Cattell-Horn-Carroll theory

The Cattell-Horn-Carroll (CHC) theory of intelligence was conceived as a synthesis of the Gf-Gc theory and three-stratum theory due to the substantial similarities between them (McGrew, 1997). By creating a common framework for use in the development, interpretation, and revision of mental ability tests, the goal of the CHC theory was to provide a bridge between theory and practice (McGrew, 2005, 2009). The CHC theory is now the most current and comprehensive theory of intelligence (Schneider & McGrew, 2012). Initially, the CHC theory was depicted as a two stratum model where *g* was omitted as it was considered irrelevant to the construction and evaluation of mental ability tests (McGrew, 1997, 2005). In the most recent version (McGrew, 2009; Schneider & McGrew, 2012), it is depicted as a three stratum model (Figure 5) where *g* has been introduced as it

---

[1] This factor was not actually named by Carroll (1993), it is named in the above text for coherency.

may have an indirect effect on performance (Davidson & Kemp, 2011). The second stratum is still regarded at the most important layer (Davidson & Kemp, 2011). The CHC theory currently contains 84 first-order factors (Schneider & McGrew, 2012). Figure 5 illustrates the three distinct strata of the CHC theory, identifies the third-order factor of *g* and denotes each of the second-order factors. While currently the CHC theory contains a substantial number of factors, it is not recognised as an ultimate model and it is acknowledged that further research may lead to the continued development of the framework (McGrew, 2009; Schneider & McGrew, 2012). Importantly, while the CHC theory is arguably the most comprehensive theory, it is not universally accepted. Johnson and Bouchard Jr. (2005) and subsequently Major, Johnson and Deary (2012) presented empirical evidence that a model based on Vernon’s (1950) hierarchical model which includes verbal ability, perceptual ability and rotations ability as second-order factors is a statistically better descriptive model for the structure of human intelligence than the three-stratum, Gf-Gc, and CHC theories. However their model is argued against at a conceptual level due to the positioning of mental rotations ability as a second-order factor when it is more widely acknowledged as a first-order factor (Schneider & Newman, 2015). Therefore, the CHC theory has been selected as the predominant theoretical framework for cognitive factors in this thesis.

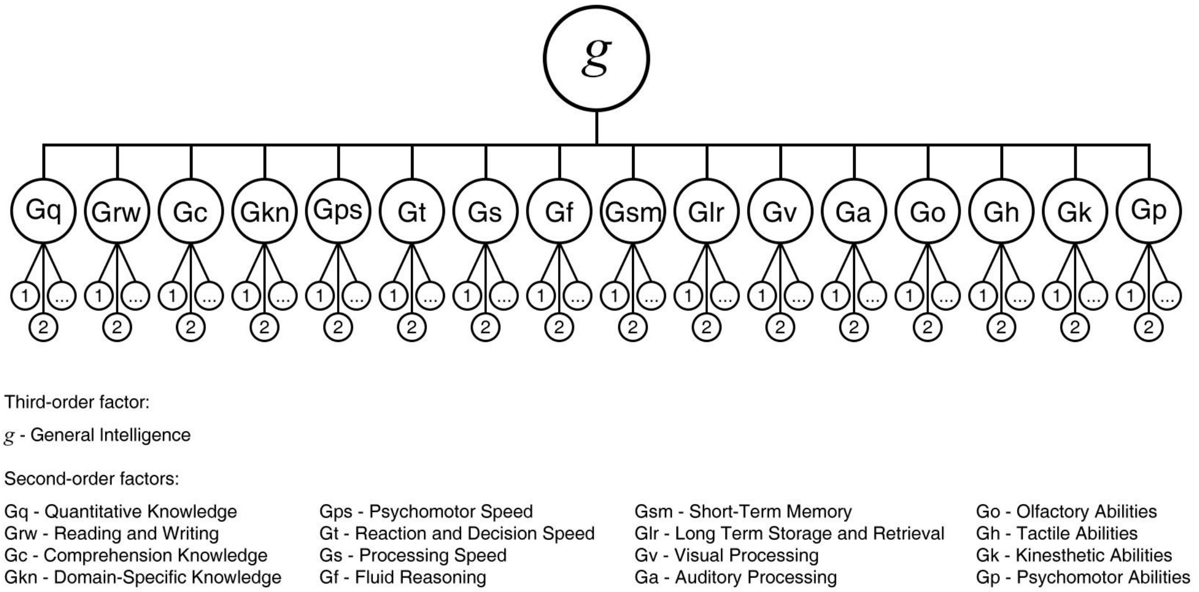

Figure 5. The Cattell-Horn-Carroll theory of intelligence.

2.3. Consolidation of pertinent human intelligence research

It is clear that much of human intelligence research has focused on establishing the factor structure of human cognitive abilities. Through this process a number of critical findings and ideas pertaining to this thesis have emerged including:

- Individual cognitive abilities in this paradigm are denoted as cognitive factors and their structure can be generally considered as hierarchical. There are proponents of a bifactor model, however as this structure is not related to the work in this thesis, no discussion is presented on them
- The CHC theory is currently the most comprehensive and contemporary framework of cognitive factors
- The structure of this theory contains three levels or strata. The top stratum contains a single third-order factor denoted as *g*, the middle stratum contains 16 second-order factors, and the bottom stratum contains 84 specific first-order factors.

- These factors describe cognitive abilities which impact the outcome of a valid performance measure. This explains why knowledge is contained within the above theories of intelligence while not describing general intelligence.
- Historically, there has been a variety in the terminology used to depict the same factor and therefore there is now a need to define cognitive factors empirically through their factor structures rather than through verbal definitions.

2.4. Spatial ability and STEM education

2.4.1. Defining spatial ability

One of the second-order factors within the CHC theory is visual processing (Gv). It is more commonly known as spatial ability and has been firmly established as important within STEM education (Stieff & Uttal, 2015; Wai et al., 2009). Despite its clear importance, conforming on a single definition for spatial ability has proven to be a contentious issue. It was initially termed as the visualising faculty when first theorised and defined by Galton (1879). Over time, this definition has evolved with Lohman (1979, p.126) defining it as “the ability to generate, retain, and manipulate abstract visual images” and Sorby (1999, p.21) defining it as the “innate ability to visualise that a person has before any formal training has occurred”, differentiating it from spatial skills which she defines as “learned or are acquired through training”.

However, “verbal definitions of the intelligence concept have never been adequate or commanded consensus. Carroll’s (1993) *Human Cognitive Abilities* and Jensen’s (1998) *The g Factor* (books which will be the definitive treatises on the subject for many years to come) essentially solve the problem” (Meehl, 2006, p.435). The problem, in essence, is that the variety of verbal definitions impedes research progress. For example, important empirical results described in an atypical context verbally may not be considered important or relevant due to misinterpretation. These books solve this problem as they offer definitions for intelligence factors based on explications of empirical evidence. To this end, it is perhaps more appropriate to define spatial ability based on the first-order factors which load on it. Therefore, its representation within the CHC theory as a second-order factor with 11 first-order factors is the most current definition. To make this clearer, Figure 6 illustrates the factor structure of spatial ability from the CHC theory and Table 1 provides the definitions for these factors offered by Schneider and McGrew (2012). It should be noted these definitions are provided to act more as general descriptions rather than explicit definitions and that cognitive factors associated with spatial ability are more typically described as spatial factors (Uttal et al., 2013).

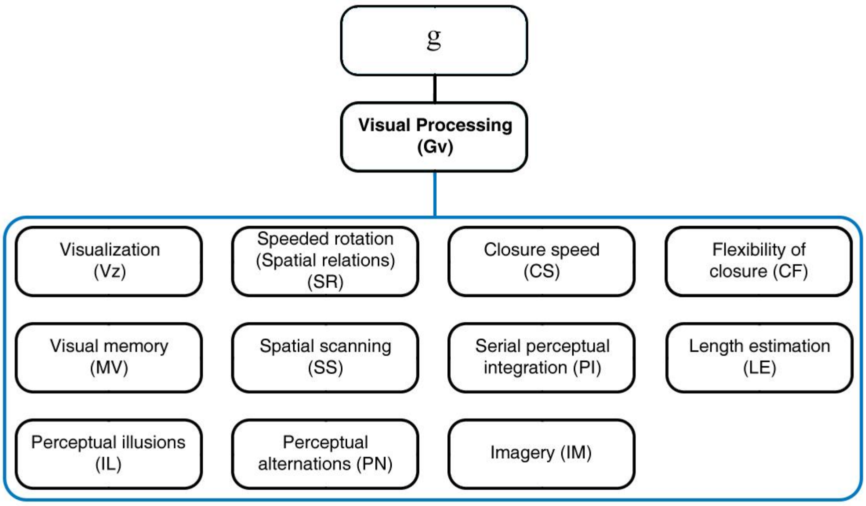

Figure 6. Factor structure of the visual processing (spatial ability) within the CHC theory illustrating the third-order factor of g, the second-order factor of visual processing (Gv) (spatial ability) and the 11 first-order factors associated with spatial ability.

Table 1. Definitions of the visual processing (spatial ability) second-order factor and associated first-order factors from the CHC theory (Schneider & McGrew, 2012).

Factor	Definition
Visual processing (Spatial Ability) (Gv)	The ability to make use of simulated mental imagery (often in conjunction with currently perceived images) to solve problems.
Visualisation (Vz)	The ability to perceive complex patterns and mentally simulate how they might look when transformed (e.g. rotated, changed in size, partially obscured).
Speeded rotation (Spatial relations) (SR)	The ability to solve problems quickly by using mental rotation of simple images.
Closure speed (CS)	The ability to quickly identify a familiar and meaningful visual object from incomplete (e.g., vague, partially obscured, disconnected) visual stimuli, without knowing in advance what the object is.
Flexibility of closure (CF)	The ability to identify a visual figure or pattern embedded in a complex distracting or disguised visual pattern or array, when one knows in advance what the pattern is.
Visual memory (MV)	The ability to remember complex images over short periods of time (less than 30 seconds).
Spatial scanning (SS)	The ability to visualise a path out of a maze or a field with many obstacles.
Serial perceptual integration (PI)	The ability to recognise an object after only parts of it are shown in rapid succession.
Length estimation (LE)	The ability to visually estimate the length of objects.
Perceptual illusions (IL)	The ability to not be fooled by visual illusions.
Perceptual alternations (PN)	Consistency in the rate of alternating between different visual perceptions.
Imagery (IM)	The ability to mentally produce very vivid images.

2.4.2. The role of spatial ability within STEM education disciplines

Since its inception, spatial ability has been one of the more studied domains of human cognitive functioning (Carroll, 1993). Despite this, Lohman (1996) noted that it has long been relegated to a secondary status within human intelligence research. This is evidenced through recent calls for it to be considered in conjunction with mathematical and verbal abilities in STEM talent searches (Lubinski, 2010; NSB, 2010; Wai et al., 2009). Among other reasons, Lohman (1996) attributes this second class status in part as being due to inconsistencies of spatial abilities as predictors for educational success, other cognitive domains such as fluid (Gf) and crystallised (Gc) intelligences being better predictors of educational success, and existing psychometric tests of spatial ability being potentially poor measures of spatial abilities. Lately however, interest in spatial ability has seen a resurgence as it is becoming increasingly linked with educational performance specifically in STEM disciplines (Höffler, 2010; Lubinski, 2010; McGrew & Evans, 2004; Wai et al., 2009). Snow (1999, p.136), acknowledging the neglect of spatial ability in applied educational circles, noted that “there is good evidence that [spatial ability] relates to specialized achievements in fields such as architecture, dentistry, engineering, and medicine... Given this plus the longstanding anecdotal evidence on the role of visualization in scientific discovery... it is incredible that there has been so little programmatic research on admissions testing in this domain”. Examples of the anecdotal evidence Snow (1999) was referring to include Albert Einstein’s claim to achieving insights by means of thought experiments on visualized systems of waves and physical bodies in states of relative motion and other physicists (such as James Clerk Maxwell, Michael Faraday, and Herman Von Helmholtz), inventors (such as Nikola Tesla and James Watt), and generalists (such as Benjamin Franklin, John Herschel, Francis Galton, and James Watson) also displaying high levels of spatial abilities and reporting that they played an important role in their most creative accomplishments (Lohman, 1993). The empirical evidence Snow (1999) was referring to includes findings showing associations between spatial ability and specific STEM disciplines. This type of evidence continues to emerge with spatial ability now being shown to be relevant to many STEM disciplines including biology (Rochford, 1985; Russell-Gebbett, 1985), chemistry (Small & Morton, 1983; Wu & Shah, 2004), physics (Kozhevnikov, Motes, & Hegarty, 2007), mathematics (Cheng & Mix, 2014; Pittalis & Christou, 2010; Sorby et al., 2013), computer programming (Jones & Burnett, 2008), design (Lin, 2016), engineering graphics (Marunic & Glazar, 2013), geometry (Suzuki, Wakita, & Nagano, 1990), and engineering (Alias, Black, & Gray, 2002; Sorby, 2009).

Substantial longitudinal evidence now exists cementing the importance of spatial ability within STEM. Shea, Lubinski and Benbow (2001) tracked 563 talent search participants identified with the Scholastic Assessment Test (SAT) by age 13 as intellectually talented (top 0.5% for their age-group) who were also assessed on spatial ability. Relative to the humanities and other disciplines, participants who subsequently identified Mathematics or Science as their favourite high school subject, earned undergraduate and graduate degrees in STEM, and ultimately ended up in a STEM career 20 years later, typically displayed higher levels of spatial ability at age 13. Additionally, spatial ability was found to account for a statistically significant amount of additional variance beyond SAT-Mathematical and SAT-Verbal in predicting these math–science criteria. Subsequently, Webb, Lubinski and Benbow (2007), with a more general sample of 1,060 adolescents (top 3% in ability), provided evidence corroborating the results of Shea, Lubinski and Benbow (2001). Again they found that spatial ability possessed incremental validity over both SAT scales and comprehensive educational-occupational preference questionnaires over a 5-year interval for predicting favourite high school course, leisure activities relevant to STEM, college major, and intended occupation.

Another piece of longitudinal evidence has emerged from an analysis of the data from project TALENT (Flanagan et al., 1962). The participants from the project consisted of a random sample of the USA's high school population. The entire sample included approximately 50,000 males and 50,000 females across the four levels between the 9th and 12th grade giving a total sample size of 400,000. Included in the tests were a number of measures designed to assess cognitive abilities. Project TALENT also included longitudinal data taken one, five and 11 years after graduation from high school (Wise, McLaughlin, & Steel, 1979). A number of longitudinal studies based on Project TALENT's 11-year follow-up emphasise the importance of spatial ability for accomplishments in STEM disciplines (Austin & Hanisch, 1990; Gohm, Humphreys, & Yao, 1998; Humphreys, Lubinski, & Yao, 1993; Humphreys & Yao, 2002). One specific study comparing this data to modern longitudinal findings from the Study of Mathematically Precocious Youth (Webb et al., 2007), is especially relevant to understanding the development of STEM talent (Wai et al., 2009). Wai et al. (2009) present results from project TALENT which, unlike the previous two longitudinal studies, were based on a random cohort rather than comprising of intellectually gifted youths, therefore allowing for the results to be more easily generalised. Specifically, Wai et al. (2009) aimed to determine the extent to which spatial ability has operated consistently for decades in the prediction of educational and occupational criteria with particular emphasis on STEM domains, to determine the extent to which early manifestations of exceptional spatial ability portend the development of STEM expertise, and to demonstrate how neglect of this important dimension of cognitive functioning leads to untapped pools of talent for STEM domains. Their findings solidify the importance of spatial ability in STEM. Specifically they found that "spatial ability is a salient psychological characteristic among adolescents who subsequently go on to achieve advanced educational and occupational credentials in STEM… [that] spatial ability plays a critical role in structuring educational and occupational outcomes in the general population as well as among intellectually talented individuals… [and that] contemporary talent searches miss many intellectually talented students by restricting selection criteria to mathematical and verbal ability measures" (Wai et al., 2009, p.821). Lubinski (2010, p.348) generalised these results stating that "individual differences in spatial ability contribute to learning, the development of expertise, and securing advanced educational and occupational credentials in STEM".

Uttal & Cohen (2012), commenting on the results of Wai et al.'s (2009) study noted that there is no upper limit on the relationship between STEM and spatial ability. Additionally, at all levels of expertise there is a strong relationship between spatial ability and STEM performance. However, the evidence for a relationship between spatial ability and STEM occupations and performance is weaker and less consistent in STEM experts. For example, whether expert geologists succeed or fail on an authentic geology task seems to have little to do with their level of spatial ability (Hambrick et al., 2012). Stieff (2007) identified this as being a result of spatial ability either limiting or enhancing people's ability to think spatially in a way that is appropriate for STEM thinking. Investigating the role of spatial ability between novices and experts in geoscience, Hambrick et al. (2012) found that it only significantly affected performance for participants with low geospatial knowledge whereby people with low geospatial knowledge but high levels of spatial ability performed nearly as well as participants with high geospatial knowledge. This resulted in Hambrick et al. (2012) formulating the circumvention-of-limits hypothesis. This suggests that the acquisition of domain-specific knowledge eventually reduces or even eliminates the effects of individual differences in cognitive abilities. This hypothesis is supported by similar findings in chemistry (Stieff, 2007) and in physics (Kozhevnikov & Thornton, 2006). While these findings suggest that high levels of discipline specific knowledge alleviate the need for high levels of spatial ability, Miller (1984) identifies that experts are benefitted by spatial ability when coming up with new insights where available discipline specific knowledge is limited or not available. Uttal and Cohen (2012, p.168) summarise this research suggesting that "spatial skills may be a gatekeeper or barrier for success early on in STEM majors, when (a) classes are particularly challenging, and (b) students do not yet have the necessary content knowledge that will allow them to circumvent the limits that spatial ability imposes. Early on, some students may face a Catch-22: they do not yet have the knowledge that would allow them to succeed despite relatively low spatial skills, and they can't get that knowledge without getting through the early classes where students must rely on their spatial abilities". This hypothesis is supported by a large scale study showing high dropout rates (≈40%) in STEM majors (Price, 2010) and further research specifically in engineering showing this is most likely to occur around the third semester (Min, Zhang, Long, Anderson, & Ohland, 2011), after students should have acquired necessary foundational knowledge in their 1st year.

2.4.3. Training spatial ability

There is a very specific need to discuss the capacity to train spatial ability. Given that it has been categorically demonstrated as important in STEM, if it could not be trained, there would be no educational significance other than to determine the potential of novice learners. Fortunately, substantial research has established that spatial skills are malleable and that they respond positively to life experiences, and educational interventions (Baenninger & Newcombe, 1989; Terlecki, Newcombe, & Little, 2008; Wright, Thompson, Ganis, Newcombe, & Kosslyn, 2008). Piaget and Inhelder (1956) describe the process by which spatial abilities naturally manifest in young children and there is considerable evidence that certain activities such as playing with construction toys as a child, engaging with classes including craft work, drafting or mechanics in post-primary education, playing 3-dimensional videogames, and participating in certain sports involving hand-eye coordination can aid the development of spatial skills (Deno, 1995; Sorby, 2009). Additionally, there is evidence which illustrates that freehand sketching can also help foster the development of spatial ability (McKim, 1980; Mohler & Miller, 2008; Olkun, 2003; Sorby & Baartmans, 1996; Sorby & Gorska, 1998).

While this research highlights how a person's experience can impact the development of spatial ability, there is also much research demonstrating the positive effects which educational interventions aiming to train spatial ability can have (Uttal et al., 2013). However, while there is a clear positive effect, caution should be taken when interpreting this result as the true effect on cognition is not fully understood. There is a need for longitudinal evidence to determine the long term effects of such training, randomised control trials to determine the effects independent of a test-retest effect, and studies which examine the transfer of spatial ability training to other related but untrained cognitive factors and educational performance. While many interventions have been created which aspire to enhance spatial ability (e.g. Dimitriu, 2015; July, 2001; Sorby, 2009; Sorby & Baartmans, 2000), perhaps the most widely adopted is the intervention created by Sorby (Sorby, 1999, 2009, Sorby & Baartmans, 1996, 2000). Giving cognisance to how having lower levels of spatial ability can negatively impact novice STEM learners, Sorby's intervention was designed specifically to support students with low spatial ability. Her intervention consists of ten sections ranging from isometric and orthographic sketching, to examining cross sections and intersections of solids. The progression of the course is based on the Piagetian theory of spatial ability development (Bishop, 1978; Piaget, 1970; Piaget & Inhelder, 1956) with results showing statistically significant performance gains in STEM disciplines and improved retention rates (Sorby, 2009). Critically, while the results have proven the positive effects of such interventions in both spatial ability and STEM education, research studies illustrating a causal effect remain outstanding (Stieff & Uttal, 2015). Therefore, until this relationship can be uncovered, there is a limitation on the capacity to scientifically refine and develop the efficacy of cognitive interventions in STEM educational practice.

In summary, there are four critical findings relative to this thesis from spatial ability research concerning its relationship with STEM education:

1. The importance of spatial ability in STEM has been categorically determined
2. There are multiple unique factors which describe components of spatial ability
3. It is most important in novice students, where novices are defined relative to task specific content knowledge, prior to the acquisition of knowledge which can be used as a support to acquire further knowledge
4. It is malleable and can be positively affected by targeted interventions which can subsequently result in increased performance and retention

2.5. Technology education as a unique context for spatial ability research in STEM

As mentioned, the situational context of this thesis is in technology education. However, the agenda is to contribute knowledge relative to the relationship between spatial ability and STEM education as a whole so as to support educational practices associated with learning in STEM. While the importance of spatial ability has been categorically determined for STEM in general, the majority of spatial ability research in education has been conducted in Science, Mathematics and Engineering. However, technology education is fundamentally different in terms of its epistemology and the way in which the utility of knowledge is conceived. Considering the relationship between knowledge and spatial ability in learning, this is a critical variable. While there may be other potential differences between technology education and other STEM disciplines, this variance is the most pertinent to this thesis. To describe this difference, there is a need to consider technological capability and technological knowledge from a philosophical and epistemological perspective in the context of learning.

Firstly, it is important to reaffirm the position taken in this thesis, that learning is defined as "a change in long-term memory" (Kirschner, Sweller, & Clark, 2006, p.75) and "involves the acquisition of knowledge" (Mayer, 2002, p.226). Knowledge, much like intelligence, is not a singular construct. There are multiple types of knowledge, often described as "ways of knowing" (cf. Liou, 2015; McCormick, 1997; Pirttimaa, Husu, & Metsärinne, 2017). Gorman (2002) describes four such ways of knowing as knowing what, knowing how, knowing when, and knowing why. Additionally, knowledge can be either explicit or tacit where explicit knowledge refers to knowledge which can be explicated and tacit knowledge refers to knowledge which cannot (Collins, 2010; Polanyi, 1969).

Considering knowledge in this way has implications for technology education as the overall aim of technology education is regularly acknowledged to mean the development of technological capability (Black & Harrison, 1985; Davies & Rogers, 2000; Gibson, 2008; Kimbell, 1994; Liou, 2015; Norman, 1998; Rauscher, 2011; Shaw, 2002; Tairab, 2001). Due to its subjectivity, technological capability has traditionally been difficult to define (Gagel, 2004) which has resulted in many definitions now existing in the pertinent literature. Despite this, there are more prominent definitions. Perhaps most widely adopted is the model put forward by Gibson (2008) which describes the components of technological capability as knowledge, skills, values and problem solving. Gibson (2008) is relatively clear in his descriptions of each of these except for values which he conflates with ethics. From a knowledge perspective, each of these align almost perfectly with the knowledge types described by Gorman (2002). Furthermore, without trying to conflate technological capability with technological literacy, as this is another aim commonly associated with technology education, a similar perspective can be taken of technological literacy. Williams (2009, p.246) notes that technological literacy usually consists of “an ability/use dimension, a knowledge and understanding dimension and an awareness or appreciation of the relationships between technology, society and the environment”. Again, there is substantial overlap between these characteristics and types of knowledge. These definitions can be useful but there is a problem with them in that if you substitute another subject area into the descriptions in place of Technology, for example Science, the descriptions still make sense. Therefore from this perspective, all that is being contributed by the definitions is that aims of technology education involve the acquisition of knowledge, which includes various different types of knowledge, in a technological context. As described similarly with intelligence, such verbal definitions are inadequate in many ways (Meehl, 2006). As a result it becomes more important to consider what the nature of technological knowledge is to describe what is meant by attributes such as knowledge, skills, values and problem solving.

De Vries (2016) provides a description of technological knowledge noting that when scientific knowledge crosses the boundary into application, a transition into technology has occurred. He further notes the differentiating characteristics of technological knowledge as being its normativity, collective acceptance, non-propositionality and context-specificity. To consider these characteristics, namely that it is an applied knowledge, makes it impossible to explicate a strict epistemological boundary of technological knowledge, thus making it impossible to describe technological capability in much further detail. The perspectives of other pertinent researchers corroborate this idea. McCormick (1997) suggests that explicit technological knowledge will be relative to specific tasks and circumstances and Kimbell (2011) argues that technological knowledge is inherently different to scientific knowledge whereby scientific knowledge is concerned with literal truths and technological knowledge is more aptly associated with usefulness. Furthermore, Kimbell (2011) suggests that provisional knowledge is more aligned with the discipline and that learners reside in an “indeterminate zone of activity where hunch, half-knowledge and intuition are essential ingredients” (p.7) in using their provisional knowledge to support further inquiry in response to particular tasks. Finally, Williams (2009, pp. 248-249) argues that “the domain of knowledge as a separate entity is irrelevant; the relevance of knowledge is determined by its application to the technological issue at hand. So the skill does not lie in the recall and application of knowledge, but in the decisions about, and sourcing of, what knowledge is relevant”.

This fluidity of knowledge in technology education changes the nature of teaching and learning that occurs in the subject relative to other STEM disciplines. For this reason, investigating spatial ability in technology education is likely to be very different to investigating it in other STEM areas. Spatial ability is a domain general cognitive ability which works with knowledge to support learners. When the type of knowledge is different, the role of spatial ability will likely have to change also. To clarify, when considering the research surrounding the circumvention-of-limits hypothesis (Hambrick et al., 2012), as more pertinent discipline knowledge is accumulated, the effect of domain general abilities such as spatial ability reduces. In technology education, the fluidity of knowledge means that content knowledge is less transferable between tasks or problems than it is in other STEM disciplines, i.e. in one task students may be designing a form of technology for a specific person and in the next they may be designing for general use. The specific declarative knowledge associated with each task is quite different and largely unrelated and because of this, the accumulation and storage of such knowledge has little relevance. Such declarative knowledge acts as a medium for the acquisition of more general procedural knowledge. Therefore developing expertise relative to such declarative knowledge in technology education is possible but likely to be limited, and it may vary greatly across individual classrooms and students. As such, spatial ability is theorised to have a more sustained effect over time in technology education relative to other STEM disciplines where declarative knowledge is more transferable over time. Therefore, it is likely that exploring spatial ability in technology education will contribute a new dimension to spatial ability research and through its independence from an explicit knowledge base, a higher order intelligence factor may become apparent as a causal factor for the relationship between spatial ability and STEM as a whole.

3. METHODOLOGY

3.1. Methodological framework

The paradigm in which intelligence research is conducted affects how it is conceived within a study, the type of research questions which can be answered and the nature of evidence which can be gathered. The research described in this thesis explores spatial ability within the context of technology education to support future causal investigations in STEM education. As such, conceiving spatial ability as a component of human intelligence and to investigate it in an applied context requires the adoption of a methodological framework. For example, neuroscientific research requires the use of methods which are different to the methods employed in cognitive psychology. Despite this, the results from different paradigms can often be synthesised to give a more coherent contribution to knowledge. Therefore, the purpose for creating a methodological framework in this thesis was to ensure a consistent interpretation of spatial ability and intelligence, and to allow results attained from different methods across different studies to be synthesised. To achieve this, a synthesis of the various approaches to human intelligence research described by Sternberg's (2000b) as identifiable metaphors was adopted as a methodological framework. These include:

- The geographic metaphor
- The biological metaphor
- The anthropological metaphor
- The computational metaphor
- The genetic-epistemological metaphor
- The sociological metaphor
- The systems metaphor

The following sections briefly describe how intelligence is broadly interpreted and investigated in these paradigms. The sociological metaphor describes intelligence from a social perspective with notable theorists including Vygotsky (1978a) and Feuerstein (1980). This perspective isn’t considered in this thesis so it is not described below. Additionally, the systems metaphor describes the synthesis of the others so while the work compiled in this thesis aligns with it, there is no merit in describing it in more detail. Subsequent to this, the approach sub-section describes explicitly how each perspective of intelligence research was integrated into the explicit research described in this thesis.

3.1.1. The geographic metaphor

The geographic paradigm was named in response to agendas aiming to determine a cognitive map of the mind. Intelligence is interpreted to consist of individual cognitive factors. The most contemporary framework in this field is the CHC theory of intelligence (Schneider & McGrew, 2012) and the most prominent research method includes the administration of psychometric tests with subsequent analysis through correlations, factor analyses and structural equation modelling.

3.1.2. The biological metaphor

The biological paradigm views human intelligence from a neuroscientific perspective to examine its relationship with neural activity. The use of such neuro-imaging techniques offers the possibility for objective assessments of intelligence (Haier, 2009, 2011), with psychometric measures receiving new validity based on their relationships to brain structures and functions (Haier, 2011). Pertinent results emerging from this work include the neural efficiency hypothesis which describes how increased intelligence is associated with more efficient brain activity (Haier et al., 1988), and evidence to suggest a different cognitive architecture between males and females (Haier, Jung, Yeo, Head, & Alkire, 2005; Neubauer & Fink, 2009).

3.1.3. The anthropological metaphor

The anthropological view of intelligence is of particular importance as it brings an individual's specific cultural context to the forefront of intellectual interpretation. This includes interpreting intelligence relative to demographic variables, value systems, and biological variables such as age. Sternberg (2000b, p.11) argues the merits of this paradigm as being the "recognition of cultural roles in determining what constitutes intelligent behaviour and possibly even the nature of intelligence, greater potential for cross-cultural applicability of theorising, and the recognition of the need to gear testing of intelligence to the cultural context". While it is argued that the definition of intelligence is ambiguous and continues to evolve (Detterman, 1986), it is also posited that intelligence cannot be understood outside of a cultural context (Greenfield, 1997; Sternberg, 2004).

3.1.4. The computational metaphor

The computational paradigm, according to Sternberg (2000b, p.10), typically describes the use of "reaction-time analysis, protocol analysis and computer simulation" to study and explain human intelligence. Intelligence is typically viewed from a behaviourist perspective. Early work by Newell and Simon (1972) presented the constructs of a problem space and task environment which describe the mental and physical space respectively that a problem occurs within. This agenda now often refers to what are called fast and frugal heuristics which act as components of a larger system known as the adaptive toolbox (Raab & Gigerenzer 2005). The heuristics are fast as they can help solve problems quickly and frugal as they require little information (Gigerenzer 2004).

3.1.5. The genetic-epistemological metaphor

Genetic epistemology refers to the study of the origins of knowledge, a theory conceptualised by Piaget (1950a; 1950b; 1950c) through the study of child development. Piaget describes the construction of knowledge as the development of cognitive schema. These schema refer to organised networks of information into which new information can be accommodated or assimilated. Identifying this process as cognitive adaption, Piaget (1970) defines assimilation as "the integration of external elements into evolving or completed structures" (p.706) and accommodation as "any modification of an assimilatory scheme or structure by the elements it assimilates" (p.708). Emerging from this and of particular importance within this thesis is the related work on cognitive load theory (Sweller, 1988), specifically the evidence illustrating the temporal and capacity limitations of the human working memory (Cowan, 2001; G. Miller, 1956; Peterson & Peterson, 1959)

3.1.6. Synthesising perspectives of human intelligence

Exploring spatial ability in the context of technology education required the consideration of each of the aforementioned metaphors to different degrees across the appended studies. Due to their methodological appropriateness, every paradigm is not explicitly represented in every paper. The geographic paradigm was the primary contributor of methodological tools and data analysis techniques. Evidence from this perspective was also the primary source reviewed when attending to the objective of defining spatial ability relative to contemporary research. Working within this paradigm was necessary from a pragmatic perspective as it offered appropriate and useful methodological tools for which to objectively study spatial ability in the typically relativist context of education. The research in the biological metaphor provided objective evidence supporting the validity of the psychometric tests utilised in this thesis. The anthropological paradigm guided the selection of participants for each study and highlighted the need to ensure sociocultural validity in the selection of methodological tools from the geographic metaphor (Sternberg, 2000a). The need to elicit an implicit theory of intelligence in STEM from the perspective of technology education students emerged through this ontology. The computational paradigm provided a position which, when synthesised with the geographic paradigm, allowed a greater insight to be attained when investigating problem solving strategies relative to levels of spatial ability attainment. Finally, from the genetic-epistemological perspective, research findings which emerged from psychometric testing were able to be interpreted within the scope of mental ability, memory capacity, and human behaviour.

3.2. Approach

The previously described methodological framework was designed to support the conduction of intelligence research in the applied context of technology education. The approach to this synthesis involved collecting data related to both intelligence and educational performance. The educational performance data was associated both with approaches taken to solving educational problems and performance scores attained. Details of the specific methods used are described in the following sub-sections.

3.2.1. The use of educational performance measures

Considering the epistemological fluidity in technology education (Norman, 2013), the difficulty in defining capability in technology education (Gagel, 2004) and the variance in what is taught and pedagogical practices in technology education (Atkinson, 2017), it is difficult to design a valid task which could be considered representative of practice in technology education. When examining technological knowledge (Paper I) a cohort study was conducted whereby performance in the Irish Leaving Certificate was analysed to examine differences between students studying different subjects with an emphasis on technology education. There are many reasons that this particular dataset was deemed appropriate. First, the Leaving Certificate is a national examination in Ireland which is taken at the end of post-primary education and serves as the country's primary matriculation system for entry into higher education. For students, it is a high stakes examination and it can therefore be assumed that for most, there is sufficient motivation to engage for its duration. Second, there are separate examinations created for every subject, and these are created externally by a government body and distributed nationally. Therefore everyone who is engaging with a subject at the same level takes the same test. Third, the examinations are designed to reflect each subject's curriculum. Some subjects merit the use of coursework as an element of the examination, others do not. Therefore, the examinations could be considered reflective of a subject's nature and its associated knowledge types. As a result, each examination can be considered a valid reflection of what capability in the subject represents, even if articulating this is difficult to do explicitly. Acknowledging the potential for bias in specific tests, a five year cohort study was conducted to reduce the potential effect of this. Finally, each examination is assessed in accordance with a marking scheme to ensure consistency, and grades are associated with a standardised point system enabling comparability between subjects. These characteristics meant that, at least in this context, there was a broad yet valid representation of what is considered to be important in technology education used as a measure of educational performance.

The computational perspective of intelligence research is represented in Paper II where performance in an educational task was examined relative to levels of spatial ability. In this circumstance, performance referred to both the score achieved in the task and also the behaviours exhibited. The behaviour element is a direct reflection of the computational metaphor while the interpretation of results and discussion was also informed by the genetic-epistemological metaphor. The design of this task is arguably not representative of a typical task in technology education as it was an abstract geometric problem solving task, but it was necessary to use a task of this nature given the paucity of research examining intelligence within technology education. Given the applied nature of technological knowledge (de Vries, 2016; Gibson, 2008; Norström, 2014, 2015) an authentic or typical technological task should involve a craft element or the consideration towards future craft (Ankiewicz & De Swardt, 2006; McCormick & Davidson, 1996; Pirttimaa et al., 2017). Unfortunately, to consider this would involve the conflation of intelligence and expertise as craft skill is synonymous with procedural knowledge (Gibson, 2008; Leonard & Sensiper, 1998; Mason & Houghton, 2002; McCormick, 1997, 2004; Norström, 2014; Stevenson, 2004) and as previously discussed it is important to be cautious of this depending on the research question. To add a variable of craft proficiency to control for this knowledge would not have permitted an accurate depiction of how spatial ability manifested in the task as there would be residual influence of knowledge of craft which would be difficult to explicitly control. Therefore, a task which was largely knowledge independent but tangibly related to technology education was designed as a proxy for a purely technological task. The relationship existed as it was a graphical task. Correlations between the Irish technology subjects, of which graphics is considered a part of, from the results of Paper I (also see Table 2 in this kappa) suggested graphics as an appropriate proxy for technology education at this foundational stage. Additionally, graphics is often considered as an appropriate language for technology education (Baynes, 2017; Danos, 2017). As such, a task was created independent of knowledge with the exception of an accessible language, in which spatial ability could be examined as a variable relative to a graded performance and behaviours exhibited by technology students. This allowed for a behaviourist perspective of intelligence to be examined and interpreted through the additional lens of cognitive load stemming from the genetic-epistemological metaphor and provides a basis for future work where more authentic technological tasks can be examined.

3.2.2 Determining the sociocultural validity of psychometric tests in the study cohort

All of the psychometric tests used throughout the studies described in this thesis had been previously validated as measures of the factors they were designed to represent (CEEB, 1939; Ekstrom, French, Harman, & Derman, 1976; Finke, Pinker, & Farah, 1989; Guay, 1977; Hegarty & Waller, 2004; Kozhevnikov & Hegarty, 2001; Raven, Raven, & Court, 1998; Vandenberg & Kuse, 1978). However, an additional dimension to validity, what could be called sociocultural validity, is often needed. Validity can be defined as "the degree to which the test actually measures what it purports to measure" (Anastasi & Urbina, 1997, p.8) however, particularly for intelligence tests, Sternberg (2000a) comprehensively describes how this is not often enough. As the process of validation often involves correlating a new test with other similar tests or external criteria, often school grades, this can be problematic. Correlations with other similar tests creates a closed system (Sternberg, 1997) whereby the more similar a test looks to an existing test the better, even if the old test has particular weaknesses. Correlations with educational performance can also be problematic. This has been a concern since the early work of Spearman (1927) who noted that scholastic tests do not appear to have any correlation with *g*, perhaps because of the many non-intellectual variables impacting on educational performance. This places psychometricians in a precarious position in terms of designing, validating and utilising psychometric tests. Fortunately, advances in statistical methods such as regression analyses, knowledge of the non-intellectual variables impacting on educational performance such as socioeconomic background and personality type, and contemporary understandings of what intelligence means have positioned the psychometric method as a valid and useful psychological tool to facilitate educational development. These advances have resulted in the determination of cognitive ability being able to explain almost all variance in educational performance relative to many other variables including personality measures, birthweight, handedness, socio-economic background, parental education, home language, child-rearing practices such as breast-feeding and access to video-games (e.g. O'Connell, 2018). In terms of reconceptualising what intelligence means, Sternberg (2000a, p.164) notes that "intelligence is in the match between a person's talents and the talents that are valued in a sociocultural context". This idea gives rise to the concept of intelligence as being prototypical in nature (Neisser, 1979) where the prototype of a concept is “that instance (if there is one) which displays *all* the typical properties” (p.182). This infers that an intelligent person, or by extension intelligence, can be prototypically defined through the extrapolation of typical descriptive properties ascribed by people within a specific cultural context. Collectively what this means is that the descriptors of intelligence offered by a particular group of people representative of a cultural context can be consolidated into a definition of intelligence which is valued within that context. Should valid intelligence tests then exist which align with this definition, they can be considered both valid in the traditional sense, but also socioculturally valid in that particular context.

3.2.3. Measuring cognitive ability through psychometric tests

Throughout the studies described in this thesis, there was a need to establish levels of cognitive ability in terms of specific cognitive factors. Based on the research predominantly from the geographic metaphor but also from biological neuroscientific validation studies, psychometric tests were selected as the most appropriate tool to achieve this aim. Psychometric tests, once validated, are capable of eliciting a person’s cognitive ability relative to a specific cognitive factor at a specific point in time. Typically they are paper and pencil based tests, however modern technological advances and pragmatic needs have resulted in the development of computerised versions of tests of certain factors. These were not used in this thesis due to limitations in their comparability to traditional paper and pencil psychometric tests (McDonald, 2002; Shermis & Lombard, 1998). A psychometric test will often be designed to measure a single first-order cognitive factor (e.g. Guay, 1977), however some batteries contain subscales with this aim while the test as a whole may be for a single or multiple second-order factors (e.g. Wechsler, 2014). Occasionally, as it the case with the Raven’s Advanced Progressive Matrices (RAPM) test (Raven et al., 1998), the test can act as a single measure of a second-order factor due to substantial research identifying its validity and high loading on that factor (Alderton & Larson, 1990; Bors & Stokes, 1998; Carpenter, Just, & Shell, 1990; Choi et al., 2008; Marshalek, Lohman, & Snow, 1983; Schweizer, Goldhammer, Rauch, & Moosbrugger, 2007; Snow, Kyllonen, & Marshalek, 1984). There are a number of uses for psychometric tests including aiding in the identification of mental deficiencies such as mild cognitive impairment (Nasreddine et al., 2005) and neurocognitive disorders such as Alzheimer’s (Ihl, Frölich, Dierks, Martin, & Maurer, 1992), adding a cognitive dimension to job recruitment (Furnham, 2008; Olea & Ree, 1994), and identifying mental abilities associated with educational success (Lubinski, 2010; Park, Lubinski, & Benbow, 2008; Wai et al., 2009; Webb et al., 2007). The later of these was at the core of the use of psychometric tests in this thesis. In terms of attending to the specific research objectives, results from psychometric tests were the predominant evidence used to offer a contemporary definition of spatial ability and to identify its relationship with STEM education. They were also used as objective measures of spatial ability which was an independent variable in an examination of problem solving performance and behaviours. Finally, they were used in the final study included in this thesis as objective measures of a variety of domain-free general capacities to allow for a valid determination of relationships between these factors.

3.3. Ethical considerations

Ethical approval for each study within this thesis was sought and approved by the University of Limerick Science and Engineering ethics board under the decision reference 2016_12_13_S&E. Ethical considerations varied across studies due to different cohorts being included as the study samples. In all cases, participation was voluntary when it required activity which was not integrated into participants regular educational activity i.e. module engagement. Where possible, participants were informed of the research aims and methods, they were given the option to withdraw participation at any time throughout a study, and they were given the option to withdraw their personal data from the study therefore excluding it from data analysis and publication. In Paper I, longitudinal data was collected on performance in a national state administered examination at post-primary level in Ireland.

This data was anonymised prior to being received by the researchers. The only demographic information received was the approximate school capacity and type, which is not regarded as sensitive information as it is publically available. In Paper II, performance data was collected based on an undergraduate module assessment mechanism. Participants were aware that module performance was subject to further analysis, however the explicit details of this research was not disclosed prior to the assessment. Anonymity was paramount both in data collection and publication. As this data was being compared with performance in psychometric assessments of spatial ability, participant names were collected to allow both datasets to be aligned. Paper III served as a literature review and synthesis and as such no ethical considerations were required. In Paper IV, two surveys were administered on a voluntary basis to all students in two undergraduate university courses. Demographic information pertaining to the students' year of education, gender, and age was collected voluntarily within the surveys. No information was collected which could be used to identify participants. Finally, in Paper V, participants voluntarily engaged with multiple psychometric tests. All participants were undergraduate university students, were fully aware of the purpose of the research, and were assigned unique identifier codes to anonymise the data. In return, participants requested a breakdown of their performance in each test which was granted at an individual level. No information from any dataset has or will be published which could lead to the identification of any participant.

4. SUMMARY OF PAPERS

The following section presents summaries of the five appended papers preceded by their bibliographic information and current publication status. For each paper, the associated aim, method, findings and contributions are presented. The results and implications are subsequently discussed in the context of spatial ability, technology education, and STEM education from the perspectives of epistemology and philosophy, supporting STEM learners, and future methodological implications.

I. Buckley, J., Seery, N., Power, J. & Phelan, J. (2018). The importance of supporting technological knowledge in post-primary education: A cohort study. *Research in Science and Technological Education.* https://doi.org/10.1080/02635143.2018.1463981

II. Buckley, J., Seery, N., & Canty, D. (2018). Investigating the use of spatial reasoning strategies in geometric problem solving. *International Journal of Technology and Design Education*. http://doi.org/10.1007/s10798-018-9446-3

III. Buckley, J., Seery, N., & Canty, D. (2018). A heuristic framework of spatial ability: A review and synthesis of spatial factor literature to support its translation into STEM education. *Educational Psychology Review*. http://doi.org/10.1007/s10648-018-9432-z

IV. Buckley, J., O'Connor, A., Seery, N., Hyland, T., & Canty, D. (2018). Implicit theories of intelligence in STEM education: Perspectives through the lens of technology education students. *International Journal of Technology and Design Education*. http://doi.org/10.1007/s10798-017-9438-8

V. Buckley, J., Seery, N., Canty, D. (2018). Visualization, inductive reasoning and memory span as components of fluid intelligence: Implications for technology education. *International Journal of Educational Research.* http://doi.org/10.1016/j.ijer.2018.05.007

4.1. Paper I: The importance of supporting technological knowledge in post-primary education: A cohort study

4.1.1. Aim

This paper aimed to examine the position of technology education within STEM education from an epistemological perspective as an empirical difference would have implications for spatial ability research in technology education.

4.1.2. Method

An epistemological stance that capability within a discipline is associated with the acquisition of pertinent disciplinary knowledge was adopted. It is argued that comparing educational performance from standardised and valid examinations across disciplines can provide empirical evidence of variances between them. To achieve a general representation of educational disciplines, and to ensure the data was objective, standardised and valid, this study examined educational performance at post-primary level in Ireland. Longitudinal data of Leaving Certificate performance was collected from five schools over a five year period (n = 1761). In Ireland, the Leaving Certificate is a state examination which is taken at the end of the post-primary education. It serves as the matriculation system to third level education and exams are designed and administered by an independent body, the State Examination Commission (SEC). Subjects are offered at both Higher level and Ordinary level, with an additional Foundation level option available for Mathematics and Irish and a common level for the Leaving Certificate Vocational Programme (LCVP). Pupils can take as many examinations as they wish and are awarded points based on performance. Only students' six highest scoring grades are considered for overall performance and matriculation purposes.

4.1.3. Findings

The findings of this study illustrate the relationships between the technology subjects in Ireland and the other subjects available at post-primary level (Table 2). As technology education at upper post-primary level in Ireland consists of four unique subjects; Engineering, Construction Studies, Technology, and Design and Communication Graphics (DCG), correlations between these subject areas were examined to determine if there was a relationship between them. All subjects, with the exception of Engineering and Technology as no participant in the sample studied both simultaneously, showed statistically significant correlations ranging from moderate (r = .588, p <.05) to very strong (r = .918, p <.01) (Table 2) (Evans, 1996) suggesting commonality between the subjects.

Table 2. Pearson's r correlations between the four technology subjects at Higher level in Irish post-primary education from Paper I.

		Engineering	Construction	Technology	DCG
Engineering	*r*	_			
	N				
Construction	*r*	.768**	_		
	N	64			
Technology	*r*	-	.918**	_	
	N	0	34		
DCG	*r*	.691**	.702**	.588*	_
	N	40	90	18	

Note. **. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed).

Additional analyses examined the relationship between performance in the technology subjects and overall performance in the Leaving Certificate. To achieve this, the sample was divided into quartiles based on overall performance in the Leaving Certificate. A chi-square analysis was conducted to examine the association between subject uptake and quartile. The results for the Higher level subjects are illustrated in Figure 7.

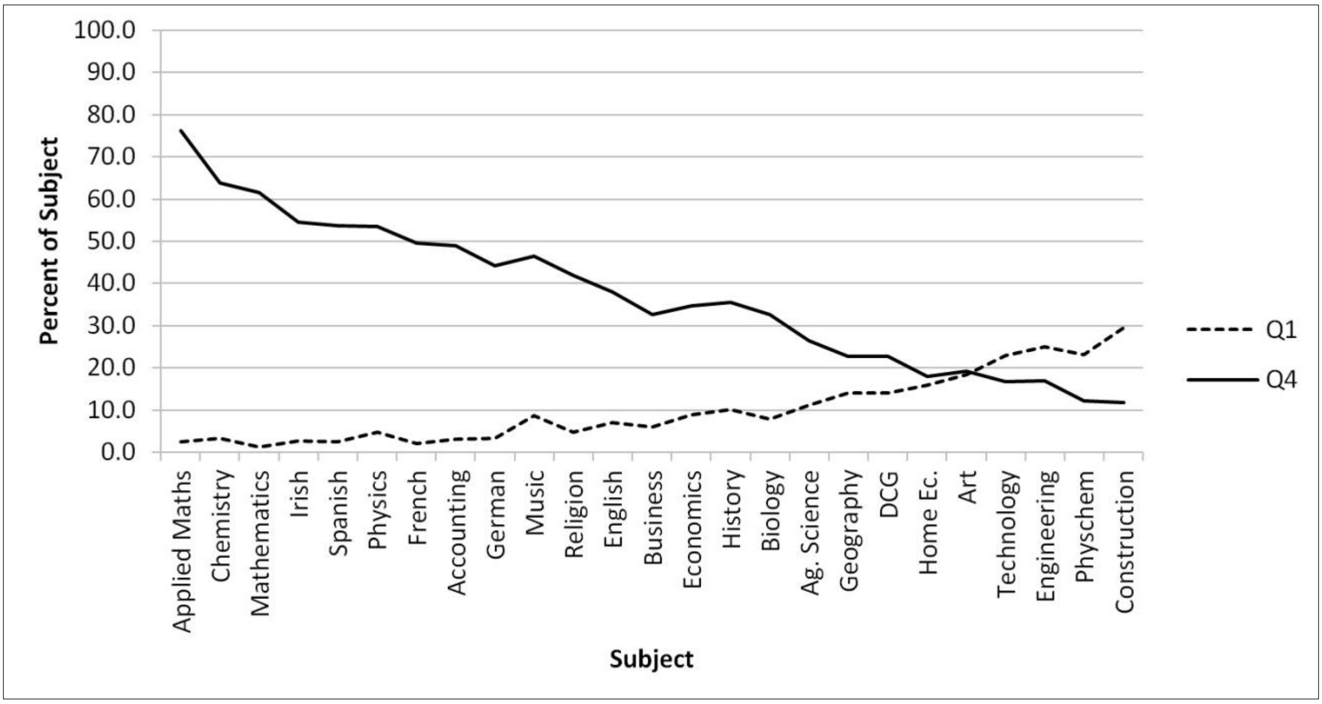

Figure 7. Statistically significant distributions between Q1 and Q4 for Higher level subjects. Subjects are ordered (left to right) based on the variance between the percentage of students in Q1 and Q4 from Paper I.

The results of this analysis show the technology subjects at one end of the continuum indicating that students taking these subjects were more likely to end up in the lowest quartile overall than in the highest quartile. At the opposite end of the continuum were the subjects of Applied Mathematics, Chemistry and Mathematics. Based on this, it is posited that the nature of knowledge in subjects may be a causal factor in the variance between the technology subjects and mathematical and science related disciplines. While the mathematical disciplines, languages, and natural sciences are concerned with explicit knowledge based on factual information, the technology subjects are more applied and speculative in nature where the knowledge base is arguably provisional seeing students work with half-knowledge, hunches, and intuition (Kimbell, 2011). Further analysis in the paper corroborates these findings and illustrates that although students taking the technology subjects are likely to be in the lowest quartile overall, they ultimately perform the best in these subjects relative to any other subjects they take.

4.1.4. Contribution to knowledge

Contribution 1. Taking the epistemological stance that knowledge governs capability in a discipline, empirical evidence is presented that technology education is epistemologically different from other STEM disciplines.

4.2. Paper II: Investigating the use of spatial reasoning strategies in geometric problem solving

4.2.1. Aim

In the previous paper, technology education was demonstrated to be epistemologically different to Mathematics and Science. The correlation between STEM and spatial ability is most often investigated in these disciplines. Therefore, this paper aimed to determine if the correlation was maintained in technology education to support further pertinent investigations.

4.2.2. Method

A repeated cross-sectional study design was implemented to gather longitudinal data of student performance and approaches to solving graphical reasoning problems relative to their level of spatial ability attainment. Graphical education was selected due to its relationship with the other technology subjects (Table 2), the need to eliminate variables associated with disciplinary knowledge, and as it serves as a common language throughout technology education (Baynes, 2017; Danos, 2017). The study was conducted across two cohorts of 3rd year of Initial Technology Teacher Education (ITTE) students. The cohorts came from consecutive years, 2014 (N = 112) and 2015 (N = 103).

Participants completed a battery of psychometric tests designed to measure different spatial factors and a battery of graphical reasoning problems. Correlations were examined between each of the psychometric tests and graphical problems. Participants were divided into quartiles based on performance in the Purdue Spatial Visualization Test: Visualization of Rotations (PSVT:R) (Bodner & Guay, 1997; Guay, 1977) to support further analysis pertaining to problem solving approaches relative to spatial ability attainment. One graphical problem common to both cohorts was selected for an in depth analysis. Relative to each quartile, the study examined performance in the graphical task, the correlation between spatial ability and performance in the graphical task, and problem solving approaches and behaviours in the graphical task.

4.2.3. Findings

Many correlations between the psychometric tests and graphical tasks were not statistically significant. This suggests that additional variables are affecting performance in graphical problem solving. A trend was observed between levels of spatial ability and performance in the common graphical task whereby having increased spatial skills resulted in increased task performance (Figure 8). When examining the correlations between spatial ability and graphical task performance, statistical significance was only observed in the highest quartile of spatial ability suggesting that this group was the only group to use a spatial approach.

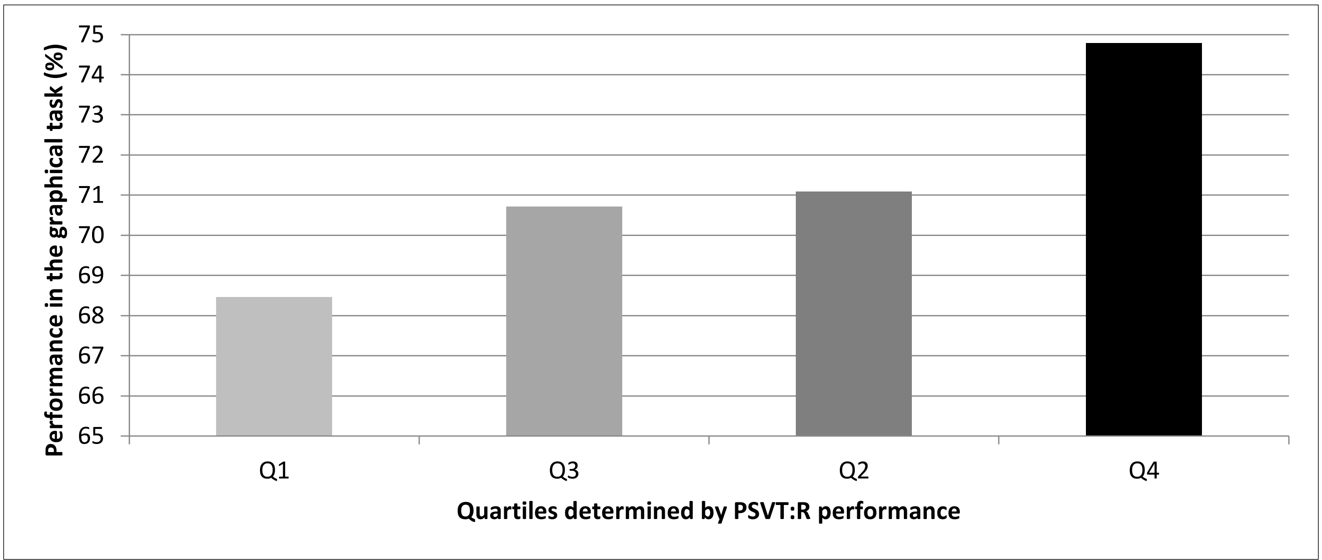

Figure 8. Trend between levels of spatial ability and graphical problem solving task performance from Paper II.

Furthermore, corroborating the results of the correlational analysis, an analysis between the problem solving approaches between the 1st and 4th quartiles revealed more external thinking methods were used by participants with lower levels of spatial ability (Figure 9). Interestingly, the type of methods used most by participants' with lower spatial ability such as creating a 3-dimensional isometric sketch suggest strategies which can either scaffold the use of spatial reasoning or circumvent the need for it.

These results suggest that elevated spatial ability may give students access to a more efficient strategy when engaging with educational problems, but also that behaviours may be a useful indicator of cognitive ability or perceived cognitive ability. This behavioural lens could be adopted with more representative tasks in technology education where craft and psychomotor skill are prevailing learning outcomes as heuristic frameworks can be used to observe cognitive functions (e.g. Buckley, Seery, & Canty, 2017a).

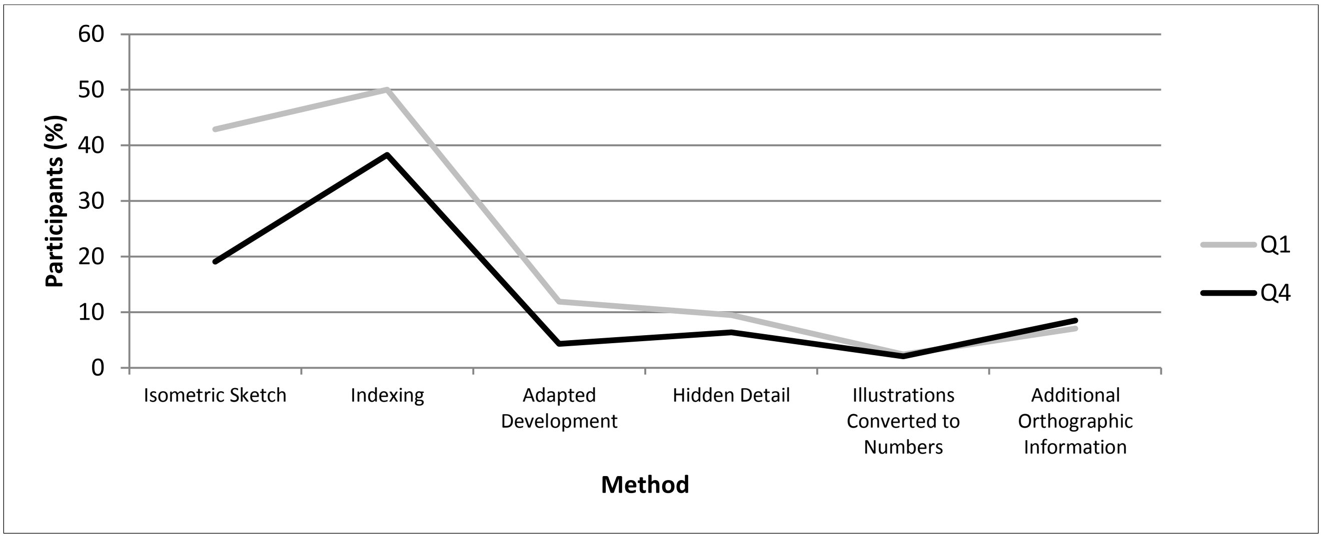

Figure 9. Analysis of external modelling methods utilised during the graphical problem solving task by participants in Q1 and Q4 from Paper II.

4.2.4. Contributions to knowledge

Contribution 2. Empirical evidence is presented that spatial ability does have a statistically significance correlation with technology education, but only with students with high levels of spatial ability.

Contribution 3. When problem solving, the use of external modelling can scaffold the use of spatial reasoning or alleviate the need for it. The need to externally model can manifest when there is an insufficient level of spatial ability relative to the task.

4.3. Paper III: A heuristic framework of spatial cognition: A review and synthesis of spatial factor literature to support its translation into STEM education

4.3.1. Aim

In the previous paper, a correlation between technology education and spatial ability was demonstrated providing merit in further exploring spatial ability in the discipline. However, there is much contention in how spatial ability is conceived in the pertinent research due to the use of verbal definitions. Therefore, this paper aimed to present an empirically based definition relative to cognitive factors to aid in the coherency of future investigations as otherwise a causal explanation cannot be determined. Furthermore, as this thesis aimed to derive a causal theory between spatial ability and STEM education, examining spatial factors empirically has the potential to give such a theory more pragmatic educational impact.

4.3.2. Method

The most recent comprehensive review of spatial factor literature was conducted by Carroll (1993). However, since then, a number of additional and related research agendas emerged based on work such as Carroll's (1993) which consolidated the field and advances in technology making new methodologies possible. A review and synthesis of literature, largely based on psychometric research, and was carried out from the perspective of a splitter theorist (McKusick, 1969). The review aimed to consolidate this contemporary research and synthesise it with Carroll's (1993) findings, which are now represented within the CHC theory (Schneider & McGrew, 2012), to create an up to date heuristic framework of spatial cognition.

4.3.3. Findings

The current status of the CHC theory contains 11 first-order spatial factors (see Table 1) and no factors are described with any conceptual or functional relationships. The findings from this paper present 25 unique first-order factors divided between dichotomous categories of static and dynamic spatial factors (Figure 10). These categories are based on stimulus type, i.e. static is non-moving and dynamic is moving. Connections are also postulated between factors which share similar cognitive actions such as mental rotation (spatial relations and speeded rotation). Where possible, the paper describes empirical evidence illustrating where each factor has been shown as important within STEM and a theoretical discussion is included where such research doesn't yet exist. Based on the evidence reviewed, spatial skills, which are defined in the paper, are observed to have the most importance and there is also direct evidence of the importance of memory factors. Perceptual factors illustrate less significance however they may be important underlying components of spatial skills. Furthermore, spatial skills associated with less cognitive power such as speeded rotations seem more significant in young children whereas those requiring more cognitive power such as spatial relations are more significant from adolescence.

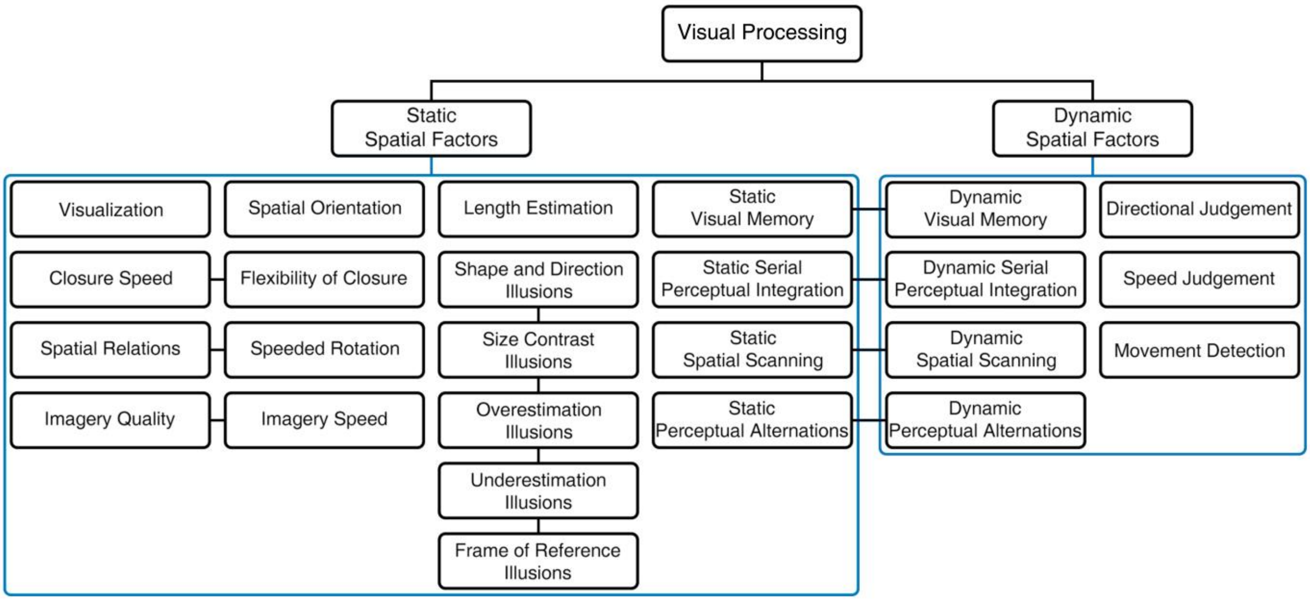

Figure 10. Spatial factor framework presented in Paper III.

4.3.4. Contributions to knowledge

Contribution 4. A new working definition for spatial ability is presented through a framework of 25 spatial factors which provides additional utility in spatial ability research.

4.4. Paper IV: Implicit theories of intelligence in STEM education: Perspectives through the lens of technology education students

4.4.1. Aim

Through examining spatial ability in the context of technology education, the previous papers identified knowledge and external modelling as potential covariates on the relationship between spatial ability and educational performance. Additionally, the definition of spatial ability was also broadened introducing additional covariates. However to enable a causal theory to be derived, the remit of perceived covariates must be investigated. This paper aimed to achieve this by exploring implicit theories of intelligence in STEM from the perspective of ITTE students.

4.4.2. Method

The method employed in this study was derived from Sternberg's investigations into implicit theories of intelligence (Sternberg, 1985b, 2000a; Sternberg, Conway, Ketron, & Bernstein, 1981). The difference between Sternberg's method and the method employed in this study is that Sternberg examined general theories of intelligence with general cohorts whereas the context of STEM education was included in this study and it was a disciplinary cohort. Two surveys were administered on a voluntary basis to a cohort of undergraduate ITTE students (N = 404). Not all students participated in each survey. The first survey asked participants' to offer a list of all behaviours they believed to be characteristic of STEM intelligence. The results of this were synthesised into a list of all unique behaviours offered by the cohort sample (n = 205). The second survey asked the same participant population to rate each behaviours importance to their conception of STEM intelligence on a 5-point Likert scale. The results of this study (n = 213) were examined through a series of Exploratory Factor Analyses (EFA), Confirmatory Factor Analyses (CFA) and Structural Equation Models (SEM) to create a model representing the implicit theory of intelligence in STEM education from the perspective of technology education students.

4.4.3. Findings

The findings of this study illustrate that three factors constitute the cohort's implicit theory of STEM intelligence. These include a social competence factor, a general competence factor, and a technological competence factor (Figure 11). Both the social and general factors were found by Sternberg et al., (1981) but the technological competence factor was not. This suggests that implicit theories of intelligence may reveal discipline specific factors which, in conjunction with general factors, constitute what it means to be intelligent in particular disciplines. From an anthropological perspective, spatial ability proved to be important to this cohorts understanding of intelligence in STEM. Additional factors determined as important included creativity, reasoning, and technological capability. It is therefore important to examine how these factors manifest and how they are operationalised by an intelligent person in technology and STEM education. Importantly, the technological competence factor shows that even though the context was STEM education, the participants' specific disciplinary background was an influential factor in their conceptions. Therefore, it could be inferred that this model is not only representative of their conceptions of intelligence in STEM education but more specifically in technology education as well.

4.4.4 Contributions to knowledge

Contribution 5. Social and general competence factors were observed as important, corroborating the findings of Sternberg (1985b), and suggesting their importance in technology education.

Contribution 6. A technological competence factor was also observed as important. This contributes the existence of discipline specific factors as important to understanding intelligence contextually. This factor corroborated spatial ability as implicitly important as well as technological capability and craft.

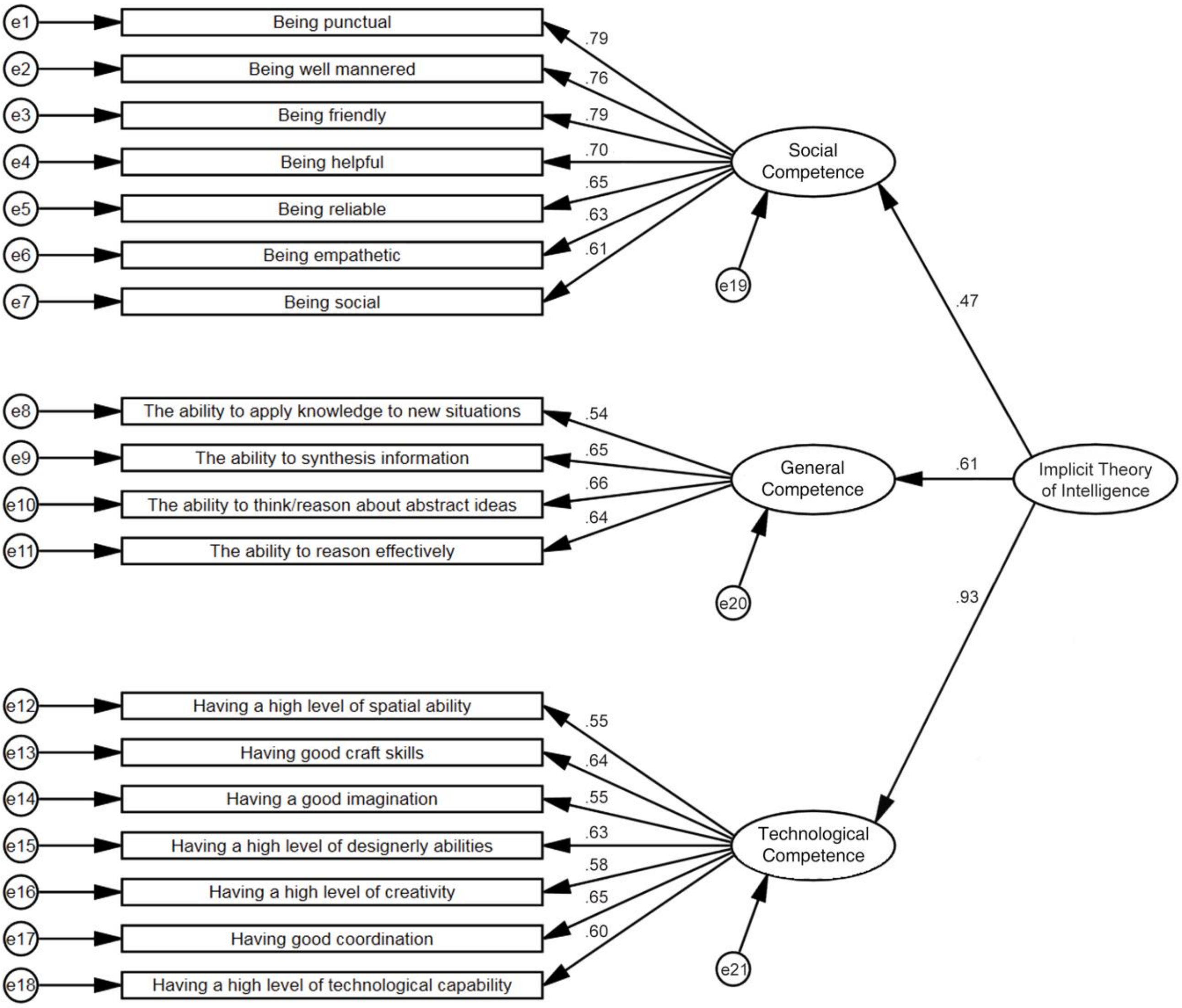

Figure 11. SEM Model of the implicit theory of intelligence from the perspective of technology education from Paper IV.

4.5. Paper V: Visualization, inductive reasoning and memory span as components of fluid intelligence: Implications for technology education

4.5.1. Aim

Using the CHC theory as a theoretical framework of individual cognitive differences, this paper aimed to investigate how the factors perceived to be of importance from the implicit theory of STEM intelligence in the previous paper were psychometrically related. Aligning with the factors perceived to be important, only domain general factors and spatial factors were investigated.

4.5.2. Method

Two studies were designed with two separate cohorts of ITTE students as the cognitive factors being examined in this study were shown to have sociocultural validity within the discipline. In the first experiment, a selection of 16 domain general factors and spatial factors were examined to determine their predictive capacity for fluid intelligence (Gf). The domain general factors were selected based on their conceptual grouping with fluid intelligence (Gf) (Figure 12) and the spatial factors were selected to broadly represent the multifactorial nature of spatial ability (Paper III). In Study 1, the first cohort (n = 85) were administered 17 psychometric tests. The results of these were analysed and the factors shown to have statistically significant predictive capacity for fluid intelligence (Gf) were incorporated into a second study. In Study 2, the second cohort (n = 87) were administered seven psychometric tests based on the results of the first study. Data analysis through multiple linear regression analyses was conducted to confirm the results of Study 1.

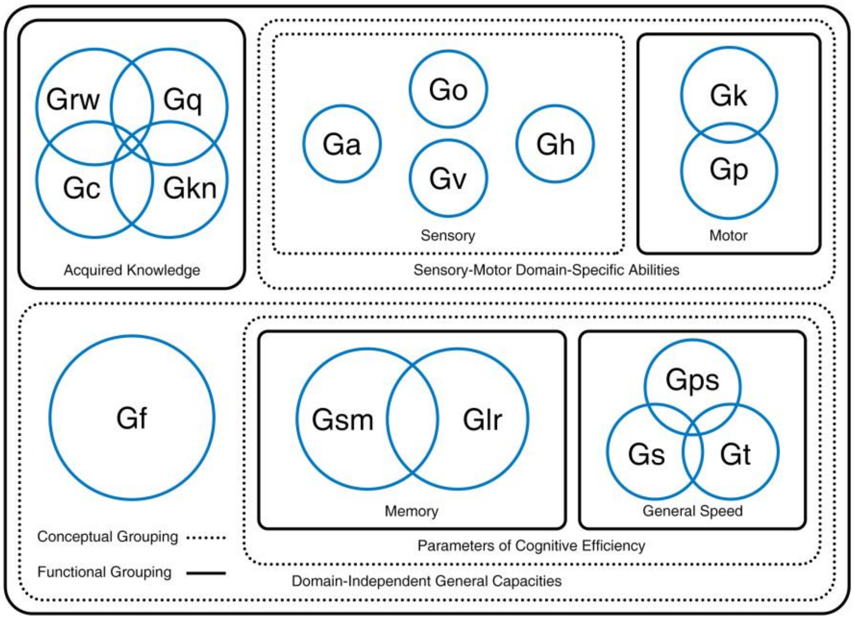

Figure 12. Conceptual and functional groupings of the second-order factors from the CHC theory from Schneider and McGrew (2012).

4.5.3. Findings

The findings of this paper identify three factors as statistically significant predictors of fluid intelligence (Gf). These included visualization (Vz), inductive reasoning (I), and memory span (MS). Important for the interpreting of these findings are the results of neuroimaging studies highlighting that there is unique variance between each of these factors and fluid intelligence (Gf) (Ebisch et al., 2012). Critically, the findings of this study are theoretically sound as memory span (MS) allows people to store pertinent information in the working memory while problem solving, visualization (Vz) allows for information to be generated and manipulated, and inductive reasoning (I) allows inferences to be made based on this information. The identification of visualization (Vz) as a component of fluid intelligence (Gf) also serves to identify the type of spatial factor which is important within STEM education. Visualization (Vz) is associated with cognitive power (Larson, 1996) whereas there are also spatial factors associated with cognitive speed and perception which were not observed as statistically significant predictors of fluid intelligence (Gf).

4.5.4. Contributions to knowledge

Contribution 7. Using the CHC theory as a theoretical framework but acknowledging that knowledge and perceptual factors are not attributable to a causal model suggests that the causal cognitive factor must be a domain general factor. Acknowledging the dichotomy of fluid (Gf) and crystallised (Gc) intelligence, this presents fluid intelligence (Gf) as a possible causal variable underlying the relationship between spatial ability and both technology and STEM educational performance.

Contribution 8. Visualization, the closest spatial factor to spatial ability, only accounts for some of the variance in fluid intelligence. Inductive reasoning and memory span are also salient predictors of variance in fluid intelligence.

5. DISCUSSION

5.1. The epistemological position of technology education in STEM

The contributions from each of the papers within this thesis are relevant to the scientific advancement of pedagogical practices in both technology and STEM education. While the primary aim of this work was to establish the foundational knowledge needed to underpin causal investigations between spatial ability and STEM, the contributions also have broader pedagogical implications in terms of practice. Many of the contributions directly relate to the nature of technology education, particularly to its epistemological position within STEM. For clarity of interpretation, it is critical that the epistemological stance which is taken in this thesis is clear. The definition of learning which is subscribed to is that it is "a change in long-term memory" (Kirschner, Sweller, & Clark, 2006, p.75) and "involves the acquisition of knowledge" (Mayer, 2002, p.226). Discourse pertaining to technological capability implies that there is much more associated with learning than just declarative knowledge acquisition, i.e. that developing skills, values, and problem-solving abilities are also important (Gibson, 2008). This is not being contested but it does serve as an example of the inadequacy of verbal definitions for multifaceted constructs. The types of knowledge described by Gorman (2002), knowing what, knowing how, knowing when, and knowing why, align almost perfectly with the components of Gibson's (2008) model of technological capability. This is important as although skills, for example, are often considered separate to knowledge (Hetherington, 2011; Stanley & Williamson, 2001), from the epistemological stance taken in this thesis they are both considered as knowledge but with skills being considered as procedural knowledge whereas the knowledge referred to in the context of technological capability is declarative or conceptual knowledge. From this perspective, what constitutes as capability in technology education can holistically be described as technological knowledge. However, the qualities of knowledge, skills, values and problem solving are also important in Science, Engineering and Mathematics. This means what is considered to determine capability in these disciplines, namely knowledge, skills, values, and problem solving, cannot be the epistemological difference. Instead, the epistemological difference relates to the nature of this knowledge in that technological knowledge is applied, normative, and context specific whereas scientific knowledge is absolute and context invariant (de Vries, 2016).

This difference has implications for conducting intelligence based research in STEM and positions technology education as an auspicious context in which to do this. Based on the contributions of this thesis, this can be broadly described in two ways. The first of which is the effect that the type of knowledge at the core of a learning objective has on the associated teaching and learning methodologies (de Vries, 2016). One of the contributions from this thesis is that learners can rely on external modelling if they have too low a level of spatial ability relative to the level required in solving a problem. This specific relationship will be described in more detail later in the discussion in relation to supporting learning in STEM. External modelling as a sense-making tool exists ubiquitously across STEM, however, the finding presents an implication associated with craft as it is still a form of externalisation but it is often done with a different agenda to modelling. The prevalence of craft in technology education and its absence in Science and Mathematics means there are opportunities to examine intelligence in technology education which do not exist in these subjects.

The second implication of the epistemological position of technology education within STEM concerns its contextual capacity to examine causal variables. Technology education, where an explicit epistemological boundary doesn't exist and instead the focus is on knowledge application, is fundamentally different to other STEM disciplines. Purely from the perspective of intelligence, having knowledge can't be a causal variable for why intelligence predicts performance as it is used with intelligence, among other factors, when engaging with learning tasks. It can however describe when intelligence is important and additionally, the capacity to acquire knowledge, or crystallised intelligence (Gc), could be conceived as a possible causal variable. The contribution from the implicit theories studies in Paper IV, which presented abstract reasoning as an important intellectual component in STEM education but with no perceived importance being attributed to any factor resembling crystallised intelligence (Gc), possibly only occurred as a result of the applied nature of technology education. Had the context being studied been Mathematics, Science, or arguably Engineering, it would have been probable that a crystallised intelligence factor would have emerged meaning the consideration of fluid intelligence as a potential causal variable in the subsequent study would not have been empirically rational.

5.2. Progressing towards determining a causal relationship between spatial ability and STEM

In addition to the contributions associated with the epistemological positioning of technology education within STEM from the perspective of intelligence, this thesis provides further empirical contributions which can be used to support investigations pertaining to the causal relationship between spatial ability and STEM. Research examining spatial ability within STEM has provided a number of critical findings pertinent to STEM learning. These include categorically illustrating the importance of spatial ability in STEM (Wai et al., 2009), providing evidence that it can be developed through targeted interventions (Stieff & Uttal, 2015), and showing that using interventions to develop spatial ability can result in increased STEM performance and retention (Sorby, 2009). There is clear evidence that it is advantageous to develop spatial ability in STEM learners and this is particularly important in novices. Considering the effect of spatial ability on performance decreases as pertinent knowledge increases (Hambrick et al., 2012), Uttal and Cohen (2012) hypothesised that spatial ability is most critical early in STEM learning when learners do not have sufficient knowledge to engage with content.

While this thesis does not provide an empirically tested causal explanation, two pertinent contributions to knowledge are made. One of which is directly related to the hypothesis provided by Uttal and Cohen (2012). One of the most important agendas for educational research is put forward by Kirschner and van Merriënboer (2013, p.179) when they note that “research should not simply try to find out ‘what works’ (cf. Chatterji, 2005; Olson, 2004) but should be aimed at explaining why particular methods help and why others do not help to reach particular goals in particular types of education under particular conditions”. Uttal and Cohen (2012) begin to address this agenda for spatial ability and STEM by considering a temporal dimension relative to knowledge acquisition, i.e. that spatial ability is important when a learner does not have sufficient knowledge to engage in a task. This perspective needs to be more nuanced and describe when spatial ability is relevant in a specific type of task. This will require examining spatial ability through individual spatial factors to accurately describe specific cognitive abilities. To answer how a spatial factor is important will require the provision of a cognitive explanation for a specific activity, and finally determining why it is important relates to the construct validity of a spatial factor and its capacity to align with the mental operations associated with an element of a task. The work in this thesis contributed a framework consisting of 25 spatial factors to support this exact agenda. The variety of spatial factors describes a broader remit of cognitive processes than what is depicted in the CHC theory. As a result there is an increased capacity to theoretically account for mental processes in educational tasks. Furthermore, the discussion on the significance of the framework (see Paper III) demonstrates how specific spatial factors have been empirically observed to be related to specific elements of educational tasks.

The second associated contribution involves the formulation of an empirically based theoretical model describing fluid intelligence (Gf) as the causal factor between spatial ability and STEM learning. As previously discussed, the hypothesis that fluid intelligence (Gf) may be the causal variable emerged from the contributions associated with the epistemology of technology education. Further empirical evidence is contributed in this thesis illustrating that visualization (Vz), inductive reasoning (I) and memory span (MS) are salient predictors of fluid intelligence (Gf). This particular contribution describes a theoretical causal model depicting individual differences in cognitive abilities. An illustration of this model, which is not scientifically accurate, is presented in Figure 13.

Its purpose is to provide a visual representation of how the results are interpretable to facilitate intelligence research in STEM education.

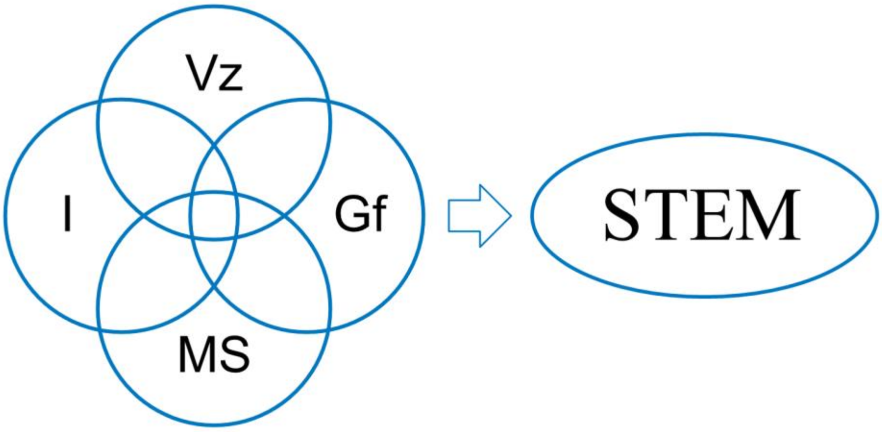

Figure 13. Empirically based theoretical and relational model of visualization (Vz), inductive reasoning (I), memory span (MS) and fluid intelligence (Gf) to support causal investigations in STEM.

It is paramount that the factors included in the model are not only empirically derived but also theoretically sound within STEM education. Perhaps the most important factor in this model is fluid intelligence (Gf). Fluid intelligence (Gf) has general educational significance (Lohman, 1996) as it has been identified as a causal factor in general learning as it supports the acquisition of knowledge (Kvist & Gustafsson, 2008; Primi et al., 2010). It is also recognised as the closest second-order factor to general intelligence (Carroll, 1993; Ebisch et al., 2012). In addition, correlations between fluid intelligence (Gf) and constructs such as divergent thinking, an index of creativity (Batey, Chamorro-Premuzic, & Furnham, 2009; Batey, Furnham, & Safiullina, 2010; Furnham, Batey, Anand, & Manfield, 2008; Nusbaum & Silvia, 2011; Silvia, 2008), further indicate the significance of fluid intelligence (Gf) within STEM as it is considered a creative domain (Cooper & Heaverlo, 2013; Park et al., 2008). Within specific STEM disciplines, the results of this thesis suggest the importance of fluid intelligence (Gf) in technology education, however it has also been shown to be important in Mathematics (Primi et al., 2010; Xin & Zhang, 2009) and Science (Yuan, Steedle, Shavelson, Alonzo, & Oppezzo, 2006).

In conjunction with fluid intelligence (Gf), there are unique roles and mental operations afforded by the first-order factors of memory span (MS), visualization (Vz) and inductive reasoning (I). Memory span (MS) affords the capacity to retrieve and hold chunks of information in the working memory while engaging with a problem or task. Based on the work of Miller (1956) who identified the importance of having large schema available to problem solvers, the importance of memory span (MS) directly relates to the educational importance of cognitive load theory (Chen, Castro-Alonso, Paas, & Sweller, 2017; Kirschner, 2002; Paas, Renkl, & Sweller, 2003, 2004, Sweller, 1988, 1994). The importance of visualization (Vz) builds on the capacity of the working memory system as while memory span (MS) allows information to be held in a usable cognitive space, visualization (Vz) allows for this information to be generated, represented and manipulated (Schneider & McGrew, 2012). This is supported by the evidence that adopting a spatial strategy in problem solving is advantageous (Linn & Petersen, 1985; Stieff, Hegarty, & Dixon, 2010) and by the wealth of evidence identifying the importance of spatial ability in STEM education. The additional link between spatial ability and creativity further adds to the evidence that it is associated with fluid intelligence (Gf) (Kell, Lubinski, Benbow, & Steiger, 2013). Finally, inductive reasoning (I) allows for inferences to be drawn based on the available information (Carpenter et al., 1990; Embretson, 1998; Klauer, Willmes, & Phye, 2002; Primi, 2002; Sternberg, 1977). By allowing for information to be retrieved, stored, generated, represented, manipulated and inferred, this model, both empirically and theoretically, can account for all of the necessary mental operations presented in established problem solving frameworks (Carlson & Bloom, 2005; Gigerenzer, 2001; Gigerenzer & Todd, 1999; Novick & Bassok, 2005; Schraw, Dunkle, & Bendixen, 1995; Wang & Chiew, 2010). As this model can account for the necessary processes, it is now important to examine exactly how they are employed in practice at discipline specific and task specific levels as it is posited that the significance of each factor will be situationally dependant.

5.3. Supporting learning in STEM

There are still many questions which need to be answered to progress this research towards the determination of a causal relationship between spatial ability and STEM, many of which have emerged from this thesis. The most pertinent of these, if the model in Figure 13 is considered, is to determine which part of the venn diagram is the most predictive of STEM performance. In other words, there is a need to go beyond just examining correlations between the cogntive factors and determine their predictive capacity for STEM achievement. But it is important to also consider the way's that the current state of knowledge, as a result of this thesis, can directly support STEM learning by informing pedagogical practices. Broadly, this thesis can contribute in two ways, by informing cognitive interventions to support STEM learners and by informing pedagogical practices which reduce the reliance on relatively high levels of cognitive abilities.

In relation to informing cognitive interventions, there is currently contention surrounding the possibility of developing fluid intelligence (Gf) (Au et al., 2015), however if it can be developed there would be significant implications for academic, professional, and personal success (Gottfredson, 1997; Ritchie, 2015). Some studies have shown promise in fluid intelligence (Gf) training (Rudebeck, Bor, Ormond, O'Reilly, & Lee, 2012; Stephenson & Halpern, 2013) while others have failed to find transfer between training and performance (Redick et al., 2013; Thompson et al., 2013). Based on this evidence, Au et al. (2015) conducted a systematic meta-analysis of the entire pertinent literature to estimate an overall average effect size and to explore moderators associated with deviations from the overall average. They concluded that several weeks of *n*-back training (*n*-back tasks require participants to identify stimuli presented a specified number 'n' of steps previously in a sequence) can have small but statistically significant effects on fluid intelligence (Gf) performance and that this can have profound societal effects due to the range of life functions which it underpins. These results are further reinforced by evidence demonstrating that at least two the first-order factors this thesis shows as having predictive power for fluid intelligence (Gf) can be significantly developed by training interventions. Sorby (2009) has shown that visualization (Vz) can be statistically significantly improved over 20 hours of cognitive training. A meta-analysis conducted by Klauer and Phye (2008) has shown that inductive reasoning (I) can also be developed and can result in better academic learning and positive transfer to problem-solving. Finally, Harrison et al. (2013) have examined working memory training with results tentatively showing improvement at a construct level. Taken together, the results from this thesis, the meta-analysis by Au et al. (2015), and nuanced findings from the studies examined in their meta-analysis could provide a foundation for training fluid intelligence (Gf) which would benefit STEM learners.

However, should it prove impossible to affect fluid intelligence (Gf) validly and meaningfully through training interventions, there is still the potential to develop visualization (Vz) and inductive reasoning (I) and perhaps memory span (MS). The intervention described by Sorby (2009) can be used as an example for this in practice. As discussed, there is a need for longitudinal evidence to determine the long term effects of such training, randomised control trials to determine the effects independent of a test-retest effect, and studies which examine the transfer of spatial ability training to other related but untrained cognitive factors and educational performance. However, Sorby's intervention contains ten sections which are designed to be delivered across 20 hours. Upon identifying a causal relationship between spatial ability and STEM education, or perhaps more accurately causal relationships between spatial factors and STEM activities, this intervention could be refined and developed, perhaps in a modular way to align with particular disciplines. The contributed framework of 25 spatial factors in this thesis could be used in the creation of new sections for spatial ability interventions. One example could be the inclusion of targeted dynamic spatial skill training as these factors are linked with the capacity to comprehend text describing dynamic movement which is common in problems across each STEM sub-discipline. If this agenda was emulated for memory span (MS) (or working memory in general) and inductive reasoning (I), an intervention could be created as a synthesis of these with the potential to have a greater effect than interventions targeting individual factors.

Furthermore, there is a need to acknowledge an additional dimension to STEM performance other than knowledge and spatial ability. Even if spatial ability is generalised to describe any mental ability, this dichotomy neglects to account for situated or environmental variables. The work in this thesis contributed empirical evidence illustrating that external modelling, described as external to differentiate it from cognitive modelling, can act as a scaffold when there is a relative deficit in spatial ability. It is posited that this is an effective approach for learners with relatively low spatial ability as it circumvents the cognitive limitations relative to their need to maintain a vivid mental image. External modelling can allow learners to manipulate information physically which they may not be able to manipulate mentally. Furthermore, external modelling can act as a communicative process for sharing thoughts and ideas, however as the social dynamics of learning were not the focus of this thesis this will not be discussed. It needs to be considered that external modelling is not just a tool for negotiating cognitive deficits. External modelling itself could be considered as the physical manifestation of generative cognitive activity[2] whereby although physical action occurs, the need to model and the implications of modelling are entirely cognitive as a thought or idea is generated or developed. In this way it can be differentiated to making, which could be described as a generative physical activity. Kirsh (2010), while acknowledging the obvious explanation for external modelling as being to save internal memory when processing information, comprehensively describes a number of ways in which modelling acts as a significant aid to thinking and learning. When describing models he notes that:

- they change the cost structure of the inferential landscape
- they provide a structure that can serve as a shareable object of thought
- they create persistent referents
- they facilitate re-representation
- they are often a more natural representation of structure than mental representations
- they facilitate the computation of more explicit encoding of information
- they enable the construction of arbitrarily complex structure; and they lower the cost of controlling thought - they help coordinate thought

Essentially, Kirsh (2010, p.441) summarises the utility of models by noting how “they allow us to think the previously unthinkable”. By extension of thinking the previously unthinkable, modelling allows students to learn the previously unlearnable.

While contributing to STEM learning ultimately means supporting the acquisition of more knowledge, it is not just a case of addressing cognitive deficits to meet this aim. While it is certainly beneficial to do this, it is also possible to provide the tools and opportunity for learners to use modelling to support knowledge acquisition when they do not have access to the required cognitive capacities. It is posited within the classical theory of problem solving that framing a problem involves building a mental representation of the problem’s structure known as the problem space (Newell & Simon, 1972). This is directly applicable to learning through direct instruction as well. Acknowledging the complexity of both problem solving and learning, they both share a similar characteristic of cognitive adaption (Piaget, 1970) as knowledge is being acquired, albeit through

---

[2] The idea of modelling as being cognitively generative was provided by Professor Emeritus Richard Kimbell of Goldsmiths, University of London, during the 90% seminar of this thesis.

different processes, which needs to be assimilated into pre-existing schema. In both of these situations, it needs to be acknowledged that learning and cognition are fundamentally situated (Brown, Collins, & Duguid, 1989). Therefore, the task environment also needs to be acknowledged (Newell & Simon, 1972). Larkin and Simon (1987) suggest that problem states can be partially encoded internally and partially encoded externally through the use of external representations, or models, of the problem. Chambers and Reisberg (1985) illustrated that people can explore external models differently to how they explore cognitive models of the same entity. Considering this work, and the contribution that external modelling can circumvent the need for spatial reasoning or scaffold its use, it needs to be acknowledged that STEM learning can be supported by providing tools for modelling.

To summarise, considering learning to involve the acquisition of knowledge, then to support STEM learning involves facilitating leaners in acquiring knowledge. This can be achieved in two ways; (1) tasks can be changed to reduce their difficulty in terms of cognitive processing making them more accessible or (2) learners can be provided with the tools necessary to negotiate tasks. These tools can be considered from both a cognitive and physical perspective. If learners have the required level of cognitive ability to negotiate and make sense of knowledge, the provision of physical tools may be helpful but may not be necessary. In relation to this thesis, these cognitive abilities are posited to refer to visualization (Vz), inductive reasoning (I), memory span (MS) and fluid intelligence (Gf) when the context is taken to be technology education and aspects of STEM education. However, if learners do not have the required level of metal resources available, physical tools can act as a scaffold to support sense making and learning.

6. CONCLUSION

6.1. Conclusions

This was a multifaceted research project investigating spatial ability as a factor of human intelligence within technology education to support STEM education. The aim of this thesis was to put forward an empirically based theoretical model to support a causal investigation into the relationship between spatial ability and STEM education. In achieving this aim, the following conclusions were made.

1. The research set out to empirically illustrate the epistemological differences between technology education and other STEM disciplines. By examining educational performance at post-primary level, it was concluded that there is a statistically significant difference between technology education and mathematics and science education which is most likely influenced by their treatment of knowledge.

2. The thesis investigated whether and to what extent the correlation between spatial ability and STEM educational performance is observable in technology education. Findings showed that the correlation was only observed in learners with high levels of spatial ability. Furthermore, learners with low levels of spatial ability utilised more external modelling methods to aid in problem solving.

3. The need emerged to establish an empirically based working definition for spatial ability through a review of contemporary spatial factor literature. Through the conduction of a literature review, it was concluded that verbal definitions for spatial ability are largely inadequate and empirically derived factor structures are more appropriate. A model including 25 spatial factors was put forward through this literature review.

4. The research aspired to empirically determine the sociocultural validity of spatial ability for technology education students. Through an analysis of technology education students' implicit theories of intelligence, spatial ability was determined to be a socioculturally valid construct.

5. Finally, the research sought to develop an empirically based model which can theoretically describe the causal relationship between spatial ability and STEM education. Through a psychometric study this was achieved with the causal variable being considered as fluid intelligence (Gf). As well as visualization (Vz), memory span (MS) and inductive reasoning (I) were found to have predictive capacity for fluid intelligence (Gf).

6.2. Limitations

While it is important to describe the potential applicability of this work for practice, it is equally important to acknowledge the limitations of the work. Perhaps the biggest limitation of this thesis is that no evidence is presented which examines the final model relative to STEM achievement. This research could be undertaken through an analysis of the potential relationship between fluid intelligence (Gf), visualization (Vz), memory span (MS) and inductive reasoning (I), with STEM educational performance at an individual task level, individual discipline level and holistic course level.

A second limitation relates to the study cohort. Based on the anthropological paradigm of intelligence research, a homogenous cohort of technology education students was selected for this thesis. While this allowed for a more scientific and valid contextual examination of the relationships between cognitive factors, there is a need to examine this work in the context of other educational disciplines both related and not related to STEM and in general samples.

Related to this, a third limitation is associated with the gender distribution of the study samples. The overrepresentation of males and underrepresentation of females in some of the samples is representative of technology education in Ireland where the data was gathered. It would be advantageous to ensure a more equal gender distribution in future replication studies. This would be important as there are notable sex differences in cognition with females performing better on verbal tasks and males on spatial tasks (D. Miller & Halpern, 2014). However, as has been noted, the relationships between factors do not vary in general (Bickley, Keith, & Wolfle, 1995) and this thesis was predominantly concerned with relationships rather than effect sizes. Therefore, for the purposes of this research, the gender distribution in the study samples is acknowledged as a limitation but not as an invalidation.

A forth limitation concerns the influence of additional factors. While this thesis acknowledges other variables such as discipline specific knowledge and external modelling which impact on problem solving and learning, this thesis was limited by not examining their impact. It is therefore important to examine the interaction between these variables and the cognitive factors which form the focus of this work.

A final limitation is associated with educational environments, in particular the exclusion of the sociological ontology of intelligence research in this thesis. While it was not the aim of this particular investigation, it is important to be cognisant of how learning and problem solving occur in education. Learning is a demand driven and social act (Brown & Duguid, 2000) and Vygotsky's (1978b) sociocultural theory describes it as a social process where learning is seen to occur on two levels: "first on the social level, and later, on the individual level; first, between people (interpsychological) and then inside the child [learner] (intrapsychological)" (p.57). This theory further describes the learner as a co-constructor of knowledge within their environment and as such students learn to negotiate problems and tasks in the situations they exist within. Therefore, in the progression of this research agenda, the impact of other students, educators, and other stakeholders in students' educational transactions should be investigated in terms of engagement, motivation, performance, retention and cognitive development.

6.3. Future work

Throughout the thesis a number of research questions which merit investigation have been alluded to and directly specified. Below is a list of research agendas related to intelligence and both technology and STEM education which have emerged from this thesis. Most of these are directly related to furthering the specific agenda described in this thesis while others are related to specific points of discussion in the appended papers.

- Primarily, there is a need for an analysis of the relationship between fluid intelligence (Gf) and STEM education. This is needed across all disciplines of STEM and needs to account for the factors of visualization (Vz), inductive reasoning (I) and memory span (MS). Investigations should take the form of large scale statistical analyses to determine effect sizes and small scale qualitative studies which identify the utilization of these abilities in practice. Other covariates such as knowledge, modelling, and those considered by O'Connell (2018) should also be considered.
- Causal effects of this work should be examined. While not discussed explicitly in the thesis, considering the evidence that a reduced cognitive load has on learning (Brunken, Plass, Leutner, Brünken, & Plass, 2003; Kirschner, 2002; Sweller, 1988; Sweller, Ayres, & Kalyuga, 2011), the relationship between elevated cognitive abilities and cognitive load induced by learning tasks should be examined. If elevated cognitive abilities result in reduced cognitive load, this could explain the mechanism underlying the transfer of cognitive training to increased learning.
- There is a need to determine the long-term effects of cognitive training in terms of both elevated cognitive ability and increased educational potential. Considering the effect of spatial ability on educational performance reduces relative to increased discipline specific knowledge, the question of the necessity of spatial ability for discipline experts also needs to be contextually answered. Elevated cognitive abilities may be more pertinent in technology education considering its fluid epistemology.
- Research efforts need to focus on the pragmatic optimisation of cognitive interventions. This includes both the determination of appropriate intelligence factors to target and the specific nature of training activities.
- In terms of the framework of spatial factors presented in this thesis, empirical evidence should be sought to validate the existence of the included framework and scientifically determine the functional relationships between the included factors to increase its utility.
- Further research efforts should be invested in designing representative and authentic technological tasks for use in objective research on the effects of different variables on learning and performance in technology education.
- Implicit theories of intelligence have the capacity to underpin the development of explicit theories. The results of this thesis provide an implicit theory of intelligence from ITTE students. It would be beneficial to do the same for technology education educators, academics and post-primary students internationally on both intelligence and technological capability. This could lead to a more explicit definition of technological capability and a more coherent disciplinary epistemological boundary. Furthermore, this research should be continued in other STEM disciplines to create a model of perceived STEM intelligence.
- Finally, there is insufficient evidence to conduct large scale studies between spatial ability and non-STEM disciplines such as social science and the humanities. Small scale studies should be conducted initially to determine the applicability of the research described throughout this thesis for learning in general.

6.4. Related work

Acknowledging the breadth of human intelligence paradigms and the prevalence of psychometric testing in this thesis, below is a list of other variables and factors which were examined parallel to this thesis which informed much of the discussion and thinking within it:

- The components of fluid intelligence (Gf) (Buckley, Seery, & Canty, 2017a, 2018)
- Spatial working memory in mental rotations (Buckley, Canty, & Seery, 2018)
- Defining spatial ability (Buckley & Seery, 2016b; Buckley et al., 2017c)
- The natural development and gender differences in spatial ability in young adolescents (Seery, Buckley, Bowe, & Carthy, 2016)
- The bifurcation of static and dynamic cognitive processes (Buckley & Seery, 2016c)
- The assessment of dynamic spatial ability (Buckley, O'Neill, & Seery, 2016)
- Online testing of spatial ability (Buckley, Seery, & Canty, 2016)
- The relationship between self-efficacy and spatial ability performance (Power, Buckley, & Seery, 2016)
- Visual perception and virtual reality (Buckley, Phelan, Seery, & Canty, 2016)
- Self-report assessments of cognitive abilities (Seery, Buckley, Hyland, & Canty, 2016)
- Problem solving in graphical education (Buckley & Seery, 2016a)
- The use of heuristics in discipline specific problem solving (Buckley et al., 2017b)
- Cognitive and behavioural approaches to problem solving (Buckley, Howley, & Seery, 2016)

7. REFERENCES

Alderton, D., & Larson, G. (1990). Dimensionality of Raven's advanced progressive matrices items. *Educational and Psychological Measurement*, *50*(4), 887–900.

Alias, M., Black, T., & Gray, D. (2002). Effect of instructions on spatial visualisation ability in civil engineering students. *International Education Journal*, *3*(1), 1–12.

Anastasi, A., & Urbina, S. (1997). *Psychological testing*. Upper Saddle River, New Jersey: Prentice Hall.

Ankiewicz, P., & De Swardt, E. (2006). Some implications of the philosophy of technology for Science, Technology and Society (STS) studies. *International Journal of Technology and Design Education*, *16*(2), 117–141.

Atkinson, S. (2017). So what went wrong and why? In E. Norman & K. Baynes (Eds.), *Design Epistemology and Curriculum Planning* (pp. 13–17). Leicestershire: Loughborough Design Press.

Au, J., Sheehan, E., Tsai, N., Duncan, G., Buschkuehl, M., & Jaeggi, S. (2015). Improving fluid intelligence with training on working memory: A meta-analysis. *Psychonomic Bulletin & Review*, *22*(2), 366–377.

Austin, J., & Hanisch, K. (1990). Occupational attainment as a function of abilities and interests: A longitudinal analysis using Project TALENT data. *The Journal of Applied Psychology*, *75*(1), 77–86.

Baenninger, M., & Newcombe, N. (1989). The role of experience in spatial test performance: A meta-analysis. *Sex Roles*, *20*(5–6), 327–344.

Batey, M., Chamorro-Premuzic, T., & Furnham, A. (2009). Intelligence and personality as predictors of divergent thinking: The role of general, fluid and crystallised intelligence. *Thinking Skills and*

Creativity, *4*(1), 60–69.

Batey, M., Furnham, A., & Safiullina, X. (2010). Intelligence, general knowledge and personality as predictors of creativity. *Learning and Individual Differences*, *20*(5), 532–535.

Baynes, K. (2017). Meaning without words. In E. Norman & K. Baynes (Eds.), *Design Epistemology and Curriculum Planning* (pp. 47–63). Leicestershire: Loughborough Design Press.

Bickley, P., Keith, T., & Wolfle, L. (1995). The three-stratum theory of cognitive abilities: Test of the structure of intelligence across the life span. *Intelligence*, *20*(3), 309–328.

Bishop, J. (1978). Developing students' spatial ability. *The Science Teacher*, *45*(8), 20–23.

Black, P., & Harrison, G. (1985). *In place of confusion: Technology and science in the school curriculum*. London: Nuffield-Chelsea Curriculum Trust and the National Centre for School Technology.

Bodner, G., & Guay, R. (1997). The purdue visualization of rotations test. *The Chemical Educator*, *2*(4), 1–17.

Bors, D., & Stokes, T. (1998). Raven's advanced progressive matrices: Norms for first-year university students and the development of a short form. *Educational and Psychological Measurement*, *58*(3), 382–398.

Brown, J. S., Collins, A., & Duguid, P. (1989). Situated cognition and the culture of learning. *Educational Researcher*, *18*(1), 32–42.

Brown, J. S., & Duguid, P. (2000). *The social life of information*. Cambridge, Massachusetts: Harvard Business Press.

Brunken, R., Plass, J. L., Leutner, D., Brünken, R., & Plass, J. L. (2003). Direct measurement of cognitive load in multimedia learning. *Educational Psychologist*, *38*(1), 53–61.

Buckley, J., Canty, D., & Seery, N. (2018). Spatial working memory in mental rotations: A Case for exploring neural efficiency and cognitive strategies. In S. Sorby & M. Sadowski (Eds.), *ASEE Engineering Design Graphics Division 72nd Mid-Year Conference*. Montego Bay, Jamaica: EDGD.

Buckley, J., Howley, U., & Seery, N. (2016). An exploratory study into the cognitive and behavioural influences on problem solving performance. In P. Tiernan (Ed.), *33rd International Manufacturing Conference*. Limerick, Ireland: University of Limerick.

Buckley, J., O'Neill, C., & Seery, N. (2016). Technology mediated assessment of dynamic spatial ability. In P. Tiernan (Ed.), *33rd International Manufacturing Conference*. Limerick, Ireland: University of Limerick.

Buckley, J., Phelan, J., Seery, N., & Canty, D. (2016). Assessing visual perception in virtual reality environments. In P. Tiernan (Ed.), *33rd International Manufacturing Conference*. Limerick, Ireland: University of Limerick.

Buckley, J., & Seery, N. (2016a). An investigation into problem solving approaches adopted during graphical reasoning episodes. In M. de Vries, A. Bekker-Holtland, & G. van Dijk (Eds.), *PATT2016: Technology Education for 21st Century Skills* (pp. 118–128). Utrecht, Netherlands: PATT.

Buckley, J., & Seery, N. (2016b). Framing spatial cognition: establishing a research agenda. In L. Sun, H. Steinhauer, & D. Lane (Eds.), *ASEE Engineering Design Graphics Division 70th Mid-Year Conference* (pp. 118–122). Daytona Beach, Florida: EDGD.

Buckley, J., & Seery, N. (2016c). The potential bifurcation of static and dynamic spatial cognitive processes. In J. Birchman (Ed.), *ASEE Engineering Design Graphics Division 71st Mid-Year Conference* (pp. 97–103). Nashua, New Hampshire: ASEE.

Buckley, J., Seery, N., & Canty, D. (2016). The validity and reliability of online testing for the assessment of spatial ability. In J. Birchman (Ed.), *ASEE Engineering Design Graphics Division 71st Mid-Year Conference* (pp. 11–16). Nashua, New Hampshire: ASEE.

Buckley, J., Seery, N., & Canty, D. (2017a). An exploratory analysis into the relationships between spatial factors, domain-free general capacities and general fluid intelligence. In S. Warner & L. Litowitz (Eds.), *PATT2017: Technology & Engineering Education – Fostering the Creativity of Youth Around The Globe*. Philadelphia: PATT.

Buckley, J., Seery, N., & Canty, D. (2017b). Heuristics and CAD modelling: An examination of student behaviour during problem solving episodes within CAD modelling activities. *International Journal of Technology and Design Education*. https://doi.org/10.1007/s10798-017-9423-2

Buckley, J., Seery, N., & Canty, D. (2017c). Spatial cognition in engineering education: Developing a spatial ability framework to support the translation of rheory into practice. *European Journal of Engineering Education*. https://doi.org/10.1080/03043797.2017.1327944

Buckley, J., Seery, N., & Canty, D. (2018). Examining the components of fluid intelligence: Implications for STEM education. In S. Sorby & M. Sadowski (Eds.), *ASEE Engineering Design Graphics Division 72nd Mid-Year Conference*. Montego Bay, Jamaica: EDGD.

Burt, C. (1909). Experimental tests of general intelligence. *British Journal of Psychology*, *3*(1–2), 94–177.

Burt, C. (1911). Experimental tests of higher mental processes and their relation to general intelligence. *Journal of Experimental Pedagogy and Training*, *1*(1), 93–112.

Burt, C. (1949). The structure of the mind. *British Journal of Educational Psychology*, *19*(3), 176–199.

Carlson, M., & Bloom, I. (2005). The cyclic nature of problem solving: An emergent multidimensional problem-solving framework. *Educational Studies in Mathematics*, *58*(1), 45–75.

Carpenter, P., Just, M., & Shell, P. (1990). What one intelligence test measures: A theoretical account of the processing in the raven progressive matrices test. *Psychological Review*, *97*(3), 404–431.

Carroll, J. (1993). *Human cognitive abilities: A survey of factor-analytic studies*. New York: Cambridge University Press.

Cattell, R. (1943). The measurement of adult intelligence. *Psychological Bulletin*, *40*(3), 153–193.

Cattell, R. (1963). Theory of fluid and crystallized intelligence: A critical experiment. *Journal of Educational Psychology*, *54*(1), 1–22.

Cattell, R., & Horn, J. (1978). A check on the theory of fluid and crystallized intelligence with description of new subtest designs. *Journal of Educational Measurement*, *15*(3), 139–164.

CEEB. (1939). *Special aptitude test in spatial relations*. New York: College Entrance Examination Board.

Chambers, D., & Reisberg, D. (1985). Can mental images be ambiguous? *Journal of Experimental Psychology: Human Perception and Performance*, *11*(3), 317–328.

Chatterji, M. (2005). Evidence on "what works": An argument for extended-term mixed-method (ETMM) evaluation designs. *Educational Researcher*, *34*(5), 14–24.

Chen, O., Castro-Alonso, J., Paas, F., & Sweller, J. (2017). Extending cognitive load theory to incorporate working memory resource depletion: Evidence from the spacing effect. *Educational Psychology Review*. https://doi.org/10.1007/S10648-017-9426-2

Cheng, Y., & Mix, K. (2014). Spatial training improves children's mathematics ability. *Journal of Cognition and Development*, *15*(1), 2–11.

Choi, Y. Y., Shamosh, N. A., Cho, S. H., DeYoung, C. G., Lee, M. J., Lee, J.-M., … Lee, K. H. (2008). Multiple bases of human intelligence revealed by cortical thickness and neural activation. *The Journal of Neuroscience*, *28*(41), 10323–10329.

Collins, H. (2010). *Tacit and explicit knowledge*. Chicago and London: University of Chicago Press.

Cooper, R., & Heaverlo, C. (2013). Problem solving and creativity and design: What influence do they have on girls' interest in STEM subject areas? *American Journal of Engineering Education*, *4*(1), 27–38.

Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences*, *24*(1), 87–114.

Cronbach, L. (1957). The two disciplines of scientific psychology. *American Psychologist*, *12*(11), 671–684.

Danos, X. (2017). Graphicacy and a taxonomy. In E. Norman & K. Baynes (Eds.), *Design Epistemology and Curriculum Planning* (pp. 64–84). Leicestershire: Loughborough Design Press.

Das, J., Naglieri, J., & Kirby, J. (1994). *Assessment of cognitive processes*. Boston: Allyn & Bacon.

Davidson, J., & Kemp, I. (2011). Contemporary models of intelligence. In R. Sternberg & S. B. Kaufman (Eds.), *The Cambridge Handbook of Intelligence* (pp. 58–84). Cambridge: Cambridge University Press.

Davies, D., & Rogers, M. (2000). Pre-service primary teachers' planning for science and technology activities: Influences and constraints. *Research in Science & Technological Education*, *18*(2), 215–225.

de Vries, M. (2016). *Teaching about technology: An introduction to the philosophy of technology for non-philosophers*. Switzerland: Springer.

Deno, J. (1995). The relationship of previous experiences to spatial visualization ability. *Engineering Design Graphics Journal*, *59*(3), 5–17.

Detterman, D. (1986). Qualitative integration: The last word? In R. Sternberg & D. Detterman (Eds.), *What is Intelligence? Contemporary Viewpoints on its Nature and Definition* (pp. 163–166). New Jersey: Ablex.

Detterman, D. (2016). Education and intelligence: Pity the poor teacher because student characteristics are more significant than teachers or schools. *The Spanish Journal of Psychology*, *19*(e93), 1–11.

Dimitriu, D. (2015). *A, B, See... in 3D: A workbook to improve 3-D visualization skills*. Vermont: Morgan & Claypool Publishers.

Ebisch, S., Perrucci, M., Mercuri, P., Romanelli, R., Mantini, D., Romani, G. L., … Saggino, A. (2012). Common and unique neuro-functional basis of induction, visualization, and spatial relationships as cognitive components of fluid intelligence. *NeuroImage*, *62*(1), 331–342.

Ekstrom, R., French, J., Harman, H., & Derman, D. (1976). *Kit of factor-referenced cognitive tests*. Princeton, New Jersey: Educational Testing Service.

Embretson, S. (1998). A cognitive design system approach to generating valid tests: Application to abstract reasoning. *Psychological Methods, 3*(3), 380–396.

Evans, J. (1996). *Straightforward statistics for the behavioral sciences*. California: Brooks/Cole Publishing Company.

Feuerstein, R. (1980). *Instrumental enrichment: An intervention program for cognitive modifiability*. Baltimore, Maryland: University Park Press.

Finke, R., Pinker, S., & Farah, M. (1989). Reinterpreting visual patterns in mental imagery. *Cognitive Science*, *13*(1), 51–78.

Flanagan, J., Dailey, J., Shaycoft, M., Gorham, W., Orr, D., & Goldberg, I. (1962). *Design for a study of american youth*. Boston: Houghton Mifflin Company.

Furnham, A. (2008). HR professionals' beliefs about, and knowledge of, assessment techniques and psychometric tests. *International Journal of Selection and Assessment*, *16*(3), 300–305.

Furnham, A., Batey, M., Anand, K., & Manfield, J. (2008). Personality, hypomania, intelligence and creativity. *Personality and Individual Differences*, *44*(5), 1060–1069.

Gagel, C. (2004). Technology profile: An assessment strategy for technological literacy. *The Journal of Technology Studies*, *30*(4), 38–44.

Galton, F. (1879). Generic images. *The Nineteenth Century*, *6*(1), 157–169.

Gardner, H. (1983). *Frames of mind: The theory of multiple intelligences*. London: Heinemann.

Gibson, K. (2008). Technology and technological knowledge: A challenge for school curricula. *Teachers and Teaching*, *14*(1), 3–15.

Gigerenzer, G. (2001). The adaptive toolbox. In G. Gigerenzer & R. Selten (Eds.), *Bounded Rationality: The Adaptive Toolbox* (pp. 37–50). Cambridge, Massachusetts: The MIT Press.

Gigerenzer, G. (2004). Fast and frugal heuristics: The tools of bounded rationality. In D. Koehler & N. Harvey (Eds.), *Blackwell Handbook of Judgment and Decision Making* (pp. 62–88). Oxford, UK: Blackwell.

Gigerenzer, G., & Todd, P. M. (1999). Fast and frugal heuristics: The adaptive toolbox. In G. Gigerenzer, P. Todd, & A. R. Group (Eds.), *Simple Heuristics That Make Us Smart* (pp. 3–34). New York: Oxford University Press.

Gohm, C., Humphreys, L., & Yao, G. (1998). Underachievement among spatially gifted students. *American Educational Research Journal*, *35*(3), 515–531.

Gorman, M. (2002). Types of knowledge and their roles in technology transfer. *Journal of Technology Transfer*, *27*(3), 219–231.

Gottfredson, L. (1997). Why g matters: The complexity of everyday life. *Intelligence*, *24*(1), 79–132.

Greenfield, P. (1997). You can't take it with you: Why ability assessments don't cross cultures. *American Psychologist*, *52*(1), 1115–1124.

Guay, R. (1977). *Purdue spatial visualization test: Rotations*. West Lafayette, Indianna: Purdue Research Foundation.

Guilford, J. P. (1967). *The nature of human intelligence*. New York, St. Louis, San Francisco, Toronto, London and Sydney: McGraw-Hill Book Company.

Haier, R. (2009). Neuro-intelligence, neuro-metrics and the next phase of brain imaging studies. *Intelligence*, *37*(2), 121–123.

Haier, R. (2011). Biological basis of intelligence. In R. Sternberg & S. B. Kaufman (Eds.), *The*

Cambridge Handbook of Intelligence (pp. 351–368). Cambridge: Cambridge University Press.

Haier, R., Jung, R., Yeo, R., Head, K., & Alkire, M. (2005). The neuroanatomy of general intelligence: Sex matters. *NeuroImage*, *25*(1), 320–327.

Haier, R., Siegel, B., Nuechterlein, K., Hazlett, E., Wu, J., Paek, J., … Buchsbaum, M. (1988). Cortical glucose metabolic rate correlates of abstract reasoning and attention studied with positron emission tomography. *Intelligence*, *12*(2), 199–217.

Hambrick, D., Libarkin, J., Petcovic, H., Baker, K., Elkins, J., Callahan, C., … LaDue, N. (2012). A test of the circumvention-of-limits hypothesis in scientific problem solving: The case of geological bedrock mapping. *Journal of Experimental Psychology: General*, *141*(3), 397–403.

Harrison, T., Shipstead, Z., Hicks, K., Hambrick, D., Redick, T., & Engle, R. (2013). Working memory training may increase working memory capacity but not fluid intelligence. *Psychological Science*, *24*(12), 2409–2419.

Hegarty, M., & Waller, D. (2004). A dissociation between mental rotation and perspective-taking spatial ability. *Intelligence*, *32*(2), 175–191.

Hetherington, S. (2011). *How to know: A practicalist conception of knowledge*. West Sussex, UK: Wiley & Sons.

Holzinger, K. J., & Harman, H. (1938). Comparison of two factorial analyses. *Psychometrika*, *3*(1), 45–60.

Holzinger, K. J., & Swineford, F. (1939). A study in factor analysis: The stability of a bi-factor solution. *Supplementary Educational Monographs*, *48*(1), xii+91.

Horn, J. (1985). Remodelling old models of intelligence. In B. Wolman (Ed.), *Handbook of Intelligence: Theories, Measurements, and Applications* (pp. 267–300). New Jersey: Wiley.

Horn, J. (1998). A basis for research on age differences in cognitive abilities. In J. McArdle & R. Woodcock (Eds.), *Human Cognitive Abilities in Theory and Practice* (pp. 57–91). Mahwah, New Jersey: Erlbaum.

Horn, J., & Blankson, B. (2005). Foundations for a better understanding of cognitive abilities. In D. Flanagan & P. Harrison (Eds.), *Contemporary Intellectual Assessment: Theories, Tests, and Issues* (2nd Ed., pp. 41–68). New York and London: Guilford Press.

Horn, J., & Cattell, R. (1966). Refinement and test of the theory of fluid and crystallized general intelligences. *Journal of Educational Psychology*, *57*(5), 253–270.

Horn, J., & Noll, J. (1997). Human cognitive capabilities: Gf-Gc theory. In D. Flanagan, J. Genshaft, & P. Harrison (Eds.), *Contemporary Intellectual Assessment: Theories, Tests, and Issues* (1st Ed., pp. 53–91). New York: Guilford Press.

Humphreys, L., Lubinski, D., & Yao, G. (1993). Utility of predicting group membership and the role of spatial visualization in becoming an engineer, physical scientist, or artist. *Journal of Applied Psychology*, *78*(2), 250–261.

Humphreys, L., & Yao, G. (2002). Prediction of graduate major from cognitive and self-report test scores obtained during the high school years. *Psychological Reports*, *90*(1), 3–30.

Höffler, T. (2010). Spatial ability: Its Influence on learning with visualizations—a meta-analytic review. *Educational Psychology Review*, *22*(3), 245–269.

Ihl, R., Frölich, L., Dierks, T., Martin, E.-M., & Maurer, K. (1992). Differential validity of psychometric tests in dementia of the Alzheimer type. *Psychiatry Research*, *44*(2), 93–106.

Jensen, A. (1998). *The g factor: The science of mental ability*. Connecticut: Greenwood Publishing

Group.

Johnson, W., & Bouchard Jr., T. (2005). The structure of human intelligence: It is verbal, perceptual, and image rotation (VPR), not fluid and crystallized. *Intelligence*, *33*(4), 393–416.

Jones, S., & Burnett, G. (2008). Spatial ability and learning to program. *Human Technology: An Interdisciplinary Journal on Humans in ICT Environments*, *4*(1), 47–61.

July, R. (2001). *Thinking in three dimensions: Exploring students' geometric thinking and spatial ability with geometer's sketchpad*. Florida International University.

Kane, M. (2005). Fluid intelligence. In N. Salkind (Ed.), *Encyclopedia of Human Development* (pp. 528–529). California: SAGE Publications.

Kaufman, A., & Kaufman, N. (1983). *Kaufman assessment battery for children*. New Jersey: John Wiley and Sons, Inc.

Kell, H., Lubinski, D., Benbow, C., & Steiger, J. (2013). Creativity and technical innovation: Spatial ability's unique role. *Psychological Science*, *24*(9), 1831–1836.

Kimbell, R. (1994). Progression in learning and the assessment of children's attainments in technology. *International Journal of Technology and Design Education*, *4*(1), 65–83.

Kimbell, R. (2011). Wrong ... but right enough. *Design and Technology Education: An International Journal*, *16*(2), 6–7.

Kirschner, P. (2002). Cognitive load theory: Implications of cognitive load theory on the design of learning. *Learning and Instruction*, *12*(1), 1–10.

Kirschner, P., Sweller, J., & Clark, R. (2006). Why minimal guidance during instruction does not work: An analysis of the failure of constructivist, discovery, problem-based, experiential, and inquiry-based teaching. *Educational Psychologist*, *41*(2), 75–86.

Kirschner, P., & van Merriënboer, J. (2013). Do learners really know best? Urban legends in education. *Educational Psychologist*, *48*(3), 169–183.

Kirsh, D. (2010). Thinking with external representations. *AI and Society*, *25*(4), 441–454.

Klauer, K. J., & Phye, G. (2008). Inductive reasoning: A training approach. *Review of Educational Research*, *78*(1), 85–123.

Klauer, K. J., Willmes, K., & Phye, G. (2002). Inducing inductive reasoning: Does it transfer to fluid intelligence? *Contemporary Educational Psychology*, *27*(1), 1–25.

Kozhevnikov, M., & Hegarty, M. (2001). A dissociation between object manipulation spatial ability and spatial orientation ability. *Memory & Cognition*, *29*(5), 745–756.

Kozhevnikov, M., Motes, M., & Hegarty, M. (2007). Spatial visualization in physics problem solving. *Cognitive Science*, *31*(4), 549–579.

Kozhevnikov, M., & Thornton, R. (2006). Real-time data display, spatial visualization ability, and learning force and motion concepts. *Journal of Science Education and Technology*, *15*(1), 111–132.

Kvist, A., & Gustafsson, J.-E. (2008). The relation between fluid intelligence and the general factor as a function of cultural background: A test of cattell's investment theory. *Intelligence*, *36*(5), 422–436.

Larkin, J., & Simon, H. (1987). Why a diagram is (sometimes) worth ten thousand words. *Cognitive Science*, *11*(1), 65–99.

Larson, G. (1996). Mental rotation of static and dynamic figures. *Perception & Psychophysics*, *58*(1), 153–159.

Leonard, D., & Sensiper, S. (1998). The role of tacit knowledge in group innovation. *California Management Review*, *40*(3), 112–132.

Lin, H. (2016). Influence of design training and spatial solution strategies on spatial ability performance. *International Journal of Technology and Design Education*, *2016*(1), 123–131.

Linn, M., & Petersen, A. (1985). Emergence and characterization of sex differences in spatial ability: A meta-analysis. *Child Development*, *56*(6), 1479–1498.

Liou, P.-Y. (2015). Developing an instrument for assessing students' concepts of the nature of technology. *Research in Science and Technological Education*, *33*(2), 162–181.

Lohman, D. (1979). *Spatial ability: A review and reanalysis of the correlational literature*. Stanford, California: Office of Naval Research.

Lohman, D. (1993). Spatial ability and g. In *The First Spearman Seminar* (pp. 1–19). Iowa: University of Plymouth.

Lohman, D. (1996). Spatial ability and g. In I. Dennin & P. Tapsfield (Eds.), *Human Abilities: Their Nature and Measurement* (pp. 97–116). New Jersey: Lawrence Erlbaum Associates.

Lubinski, D. (2010). Spatial ability and STEM: A sleeping giant for talent identification and development. *Personality and Individual Differences*, *49*(4), 344–351.

Luria, A. (1980). *Higher cortical functions in man*. New York: Basic Books.

Major, J., Johnson, W., & Deary, I. (2012). Comparing models of intelligence in Project TALENT: The VPR model fits better than the CHC and extended Gf-Gc models. *Intelligence, 40*(6), 543–559.

Manichander, T. (2016). *Psychology of the learner*. North Carolina, USA: Lulu Press Inc.

Marshalek, B., Lohman, D., & Snow, R. (1983). The complexity continuum in the radex and hierarchical models of intelligence. *Intelligence, 7*(2), 107–127.

Marunic, G., & Glazar, V. (2013). Spatial ability through engineering graphics education. *International Journal of Technology and Design Education*, *23*(3), 703–715.

Mason, R., & Houghton, N. (2002). The educational value in making. In S. Sayers, J. Morley, & B. Barnes (Eds.), *Issues in Design and Technology Teaching* (pp. 43–66). London: RoutledgeFalmer.

Mayer, R. (2002). Rote versus meaninful learning. *Theory into Practice*, *41*(4), 226–232.

McCormick, R. (1997). Conceptual and procedural knowledge. *International Journal of Technology and Design Education*, *7*(1–2), 141–159.

McCormick, R. (2004). Issues of learning and knowledge in technology education. *International Journal of Technology and Design Education*, *14*(1), 21–44.

McCormick, R., & Davidson, M. (1996). Problem solving and the tyranny of product outcomes. *Journal of Design & Technology Education*, *1*(3), 230–245.

McDonald, A. (2002). The impact of individual differences on the equivalence of computer-based and paper-and-pencil educational assessments. *Computers and Education*, *39*(3), 299–312.

McGrew, K. (1997). Analysis of the major intelligence batteries according to a proposed comprehensive Gf-Gc framework. In D. Flanagan, J. Genshaft, & P. Harrison (Eds.), *Contemporary Intellectual Assessment: Theories, Tests, and Issues* (pp. 151–179). New York: Guilford Press.

McGrew, K. (2005). The Cattell-Horn-Carroll theory of cognitive abilities: Past, present and future. In D. Flanagan & P. Harrison (Eds.), *Contemporary Intellectual Assessment: Theories, Tests, and Issues* (2nd ed., pp. 136–181). New York: Guilford Press.

McGrew, K. (2009). CHC theory and the human cognitive abilities project: Standing on the shoulders of the giants of psychometric intelligence research. *Intelligence*, *37*(1), 1–10.

McGrew, K., & Evans, J. (2004). *Internal and external factorial extensions to the Cattell-Horn-Carroll (CHC) theory of cognitive abilities: A review of factor analytic research since Carroll's seminal 1993 treatise*. Carroll Human Cognitive Abilities (HCA) Project Research Report #2.

McKim, R. (1980). *Experiences in Visual Thinking* (2nd ed.). Boston, Massachusetts: PWS Publishers: Cengage Learning.

McKusick, V. (1969). On lumpers and splitters, or the nosology of genetic disease. *Perspectives in Biology and Medicine*, *12*(2), 298–312.

Meehl, P. (2006). The power of quantitative thinking. In N. Waller, L. Yonce, W. Grove, D. Faust, & M. Lenzenweger (Eds.), *A Paul Meehl Reader: Essays on the Practice of Scientific Psychology* (pp. 433–444). Mahwah, New Jersey: Erlbaum.

Miller, A. (1984). *Imagery in scientific thought: Creating 20th century physics*. Boston: Birkhquser.

Miller, D., & Halpern, D. (2014). The new science of cognitive sex differences. *Trends in Cognitive Sciences*, *18*(1), 37–45.

Miller, G. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review*, *63*(2), 81–97.

Min, Y., Zhang, G., Long, R., Anderson, T., & Ohland, M. (2011). Nonparametric survival analysis of the loss rate of undergraduate engineering students. *Journal of Engineering Education*, *100*(2), 349–373.

Mohler, J., & Miller, C. (2008). Improving spatial ability with mentored sketching. *Engineering Design Graphics Journal*, *72*(1), 19–27.

Nasreddine, Z., Phillips, N., Bédirian, V., Charbonneau, S., Whitehead, V., Collin, I., … Chertkow, H. (2005). The montreal cognitive assessment, MoCA: A brief screening tool for mild cognitive impairment. *Journal of the American Geriatrics Society*, *53*(4), 695–699.

Neisser, U. (1979). The concept of intelligence. In R. Sternberg & D. Detterman (Eds.), *Human Intelligence: Perspectives on its Theory and Measurement* (pp. 179–189). New Jersey: Ablex.

Neubauer, A., & Fink, A. (2009). Intelligence and neural efficiency: Measures of brain activation versus measures of functional connectivity in the brain. *Intelligence*, *37*(2), 223–229.

Newell, A., & Simon, H. (1972). *Human problem solving*. New Jersey: Prentice-Hall.

Norman, E. (1998). The Nature of Technology for Design. *International Journal of Technology and Design Education, 8*(1), 67–87.

Norman, E. (2013). Design epistemology and curriculum planning. *Design and Technology Education: An International Journal*, *18*(2), 3–5.

Norström, P. (2014). How technology teachers understand technological knowledge. *International Journal of Technology and Design Education*, *24*(1), 19–38.

Norström, P. (2015). Knowing how, knowing that, knowing technology. *Philosophy & Technology, 28*(4), 553–565.

Novick, L., & Bassok, M. (2005). Problem solving. In K. Holyoak & R. Morrison (Eds.), *The*

Cambridge Handbook of Thinking and Reasoning (pp. 321–349). New York: Cambridge University Press.

NSB. (2010). *Preparing the next generation of STEM innovators: Identifying and developing our nation's human capital*. Virginia: National Science Foundation (NSB 10-167).

Nusbaum, E., & Silvia, P. (2011). Are intelligence and creativity really so different? Fluid intelligence, executive processes, and strategy use in divergent thinking. *Intelligence*, *39*(1), 36–45.

O'Connell, M. (2018). The power of cognitive ability in explaining educational test performance, relative to other ostensible contenders. *Intelligence*, *66*(1), 122–127.

Olea, M. M., & Ree, M. J. (1994). Predicting pilot and navigator criteria: Not much more than g. *Journal of Applied Psychology*, *79*(6), 845–851.

Olkun, S. (2003). Making connections: Improving spatial abilities with engineering drawing activities. *International Journal of Mathematics Teaching and Learning*, *3*(1), 1–10.

Olson, D. (2004). The triumph of hope over experience in the search for "what works": A response to slavin. *Educational Researcher*, *33*(1), 24–26.

Paas, F., Renkl, A., & Sweller, J. (2003). Cognitive load theory and instructional design: Recent developments. *Educational Psychologist*, *38*(1), 1–4.

Paas, F., Renkl, A., & Sweller, J. (2004). Cognitive load theory: Instructional implications of the interaction between information structures and cognitive architecture. *Instructional Science*, *32*(1), 1–8.

Park, G., Lubinski, D., & Benbow, C. (2008). Ability differences among people who have commensurate degrees matter for scientific creativity. *Psychological Science*, *19*(10), 957–961.

Paterson, D. (1957). The conservation of human talent. *American Psychologist*, *12*(3), 134–144.

Peterson, L., & Peterson, M. (1959). Short-term retention of individual verbal items. *Journal of Experimental Psychology*, *58*(3), 193–198.

Piaget, J. (1950a). *Introduction à l'épistémologie génétique, Volume I: Le pensée pathematique*. Paris: Presses Universitaires de France.

Piaget, J. (1950b). *Introduction à l'épistémologie génétique, Volume II: Le pensée physique*. Paris: Presses Universitaires de France.

Piaget, J. (1950c). *Introduction à l'épistémologie génétique, Volume III: Le pensée biologique, psychologique et sociologique*. Paris: Presses Universitaires de France.

Piaget, J. (1970). Piaget's theory. In P. H. Mussen (Ed.), *Carmichael's Manual of Child Psychology* (3rd Editio, pp. 703–732). New York: Wiley.

Piaget, J., & Inhelder, B. (1956). *The child's conception of space*. London: Routledge.

Pirttimaa, M., Husu, J., & Metsärinne, M. (2017). Uncovering procedural knowledge in craft, design, and technology education: A case of hands-on activities in electronics. *International Journal of Technology and Design Education*, *27*(2), 215–231.

Pittalis, M., & Christou, C. (2010). Types of reasoning in 3D geometry thinking and their relation with spatial ability. *Educational Studies in Mathematics*, *75*(2), 191–212.

Polanyi, M. (1969). *Knowing and being: Essays*. Chicago: Chicago University Press.

Power, J., Buckley, J., & Seery, N. (2016). Visualizing success: Investigating the relationship between ability and self-efficacy in the domain of visual processing. In L. Sun, H. Steinhauer, & D. Lane

(Eds.), *ASEE Engineering Design Graphics Division 70th Mid-Year Conference* (pp. 73–79). Daytona Beach, Florida: EDGD.

Price, J. (2010). The effect of instructor race and gender on student persistence in STEM fields. *Economics of Education Review*, *29*(6), 901–910.

Primi, R. (2002). Complexity of geometric inductive reasoning tasks contribution to the understanding of fluid intelligence. *Intelligence*, *30*(1), 41–70.

Primi, R., Ferrão, M. E., & Almeida, L. (2010). Fluid intelligence as a predictor of learning: A longitudinal multilevel approach applied to math. *Learning and Individual Differences*, *20*(5), 446–451.

Raab, M., & Gigerenzer, G. (2005). Intelligence as smart heuristics. In R. Sternberg & J. Pretz (Eds.), *Cognition & Intelligence* (pp. 188–207). Cambridge: Cambridge University Press.

Rauscher, W. (2011). The technological knowledge used by technology education students in capability tasks. *International Journal of Technology and Design Education*, *21*(3), 291–305.

Raven, J., Raven, J. C., & Court, J. H. (1998). *Raven manual: Section 4, advanced progressive matrices, 1998 edition*. Oxford: Oxford Psychologists Press Ltd.

Redick, T., Shipstead, Z., Harrison, T., Hicks, K., Fried, D., Hambrick, D., … Engle, R. (2013). No evidence of intelligence improvement after working memory training: A randomized, placebo-controlled study. *Journal of Experimental Psychology: General*, *142*(2), 359–379.

Ritchie, S. (2015). *Intelligence: All that matters*. London: John Murray Learning.

Rochford, K. (1985). Spatial learning disabilities and underachievement among university anatomy students. *Medical Education*, *19*(1), 13–26.

Rudebeck, S., Bor, D., Ormond, A., O’Reilly, J., & Lee, A. (2012). A potential spatial working memory training task to improve both episodic memory and fluid intelligence. *PLoS ONE*, *7*(11), e50431.

Russell-Gebbett, J. (1985). Skills and strategies–pupils’ approaches to three-dimensional problems in biology. *Journal of Biological Education*, *19*(4), 293–298.

Schneider, J., & McGrew, K. (2012). The Cattell-Horn-Carroll model of intelligence. In D. Flanagan & P. Harrison (Eds.), *Contemporary Intellectual Assessment: Theories, Tests, and Issues* (3rd ed., pp. 99–144). New York: Guilford Press.

Schneider, J., & Newman, D. (2015). Intelligence is multidimensional: Theoretical review and implications of specific cognitive abilities. *Human Resource Management Review*, *25*(1), 12–27.

Schraw, G., Dunkle, M., & Bendixen, L. (1995). Cognitive processes in well-defined and ill-defined problem solving. *Applied Cognitive Psychology*, *9*(6), 523–538.

Schweizer, K., Goldhammer, F., Rauch, W., & Moosbrugger, H. (2007). On the validity of Raven’s matrices test: Does spatial ability contribute to performance? *Personality and Individual Differences*, *43*(8), 1998–2010.

Seery, N., Buckley, J., Bowe, B., & Carthy, D. (2016). Spatial ability in education: A national study. In P. Tiernan (Ed.), *33rd International Manufacturing Conference*. Limerick, Ireland: University of Limerick.

Seery, N., Buckley, J., Hyland, T., & Canty, D. (2016). MIND strengths: The unique cognitive architecture of engineering and technology students. In P. Tiernan (Ed.), *33rd International Manufacturing Conference*. Limerick, Ireland: University of Limerick.

Shaw, K. (2002). Education and technological capability building in the Gulf. *International Journal of*

Technology and Design Education, *12*(1), 77–91.

Shea, D., Lubinski, D., & Benbow, C. (2001). Importance of assessing spatial ability in intellectually talented young adolescents: A 20-year longitudinal study. *Journal of Educational Psychology*, *93*(3), 604–614.

Shermis, M., & Lombard, D. (1998). Effects of computer-based test administrations on test anxiety and performance. *Computers in Human Behavior*, *14*(1), 111–123.

Silvia, P. (2008). Another look at creativity and intelligence: Exploring higher-order models and probable confounds. *Personality and Individual Differences*, *44*(4), 1012–1021.

Small, M., & Morton, M. (1983). Research in college science teaching: Spatial visualization training improves performance in organic chemistry. *Journal of College Science Teaching*, *13*(1), 41–43.

Smith-woolley, E., Pingault, J.-B., Selzam, S., Rimfeld, K., Krapohl, E., Stumm, S. von, … Plomin, R. (2018). Differences in exam performance between pupils attending selective and non-selective schools mirror the genetic differences between them. *Npj Science of Learning*, *3*(3), 1–7.

Snow, R. (1999). Commentary: Expanding the breadth and depth of admissions testing. In S. Messick (Ed.), *Assessment in Higher Education* (pp. 133–140). Mahwah, New Jersey: Lawrence Erlbaum Associates.

Snow, R., Kyllonen, P., & Marshalek, B. (1984). The topography of ability and learning correlations. In R. Sternberg (Ed.), *Advanced in the Psychology of Human Intelligence* (pp. 47–103). Hillsdale, New Jersey: Erlbaum.

Sorby, S. (1999). Developing 3-D spatial visualization skills. *Engineering Design Graphics Journal*, *63*(2), 21–32.

Sorby, S. (2009). Educational research in developing 3-D spatial skills for engineering students. *International Journal of Science Education*, *31*(3), 459–480.

Sorby, S., & Baartmans, B. (1996). A course for the development of 3-D spatial visualization skills. *Engineering Design Graphics Journal*, *60*(1), 13–20.

Sorby, S., & Baartmans, B. (2000). The development and assessment of a course for enhancing the 3-D spatial visualization skills of first year engineering students. *Journal of Engineering Education*, *89*(3), 301–307.

Sorby, S., Casey, B., Veurink, N., & Dulaney, A. (2013). The role of spatial training in improving spatial and calculus performance in engineering students. *Learning and Individual Differences*, *26*(1), 20–29.

Sorby, S., & Gorska, R. (1998). *The effect of various courses and teaching methods on the improvement of spatial ability*. *Proceedings of the 8th ICECGDG*. Austin, Texas, 31 July-3 August: International Society for Geometry and Graphics.

Spearman, C. (1904). "General intelligence," objectively determined and measured. *The American Journal of Psychology*, *15*(2), 201–292.

Spearman, C. (1927). *The abilities of man, their nature and measurement*. London, Bombay, Calcutta, Madras, Melbourne: Macmillan.

Spearman, C. (1939). Thurstone's work re-worked. *The Journal of Educational Psychology*, *30*(1), 1–16.

Stanley, J., & Williamson, T. (2001). Knowing how. *The Journal of Philosophy*, *98*(8), 411–444.

Stephenson, C., & Halpern, D. (2013). Improved matrix reasoning is limited to training on tasks with a visuospatial component. *Intelligence*, *41*(5), 341–357.

Sternberg, R. (1977). Component processes in analogical reasoning. *Psychological Review*, *84*(4), 353–378.

Sternberg, R. (1985a). *Beyond IQ: A triarchic theory of human intelligence*. Cambridge: CUP Archive.

Sternberg, R. (1985b). Implicit theories of intelligence, creativity, and wisdom. *Journal of Personality and Social Psychology*, *49*(3), 607–627.

Sternberg, R. (1997). *Successful intelligence*. New York: Plume.

Sternberg, R. (2000a). Implicit theories of intelligence as exemplar stories of success: Why intelligence test validity is in the eye of the beholder. *Psychology, Public Policy, and Law*, *6*(1), 159–167.

Sternberg, R. (2000b). The concept of intelligence. In R. Sternberg (Ed.), *Handbook of Intelligence* (pp. 3–15). Cambridge: Cambridge University Press.

Sternberg, R. (2004). Culture and intelligence. *American Psychologist*, *59*(1), 325–338.

Sternberg, R., Conway, B., Ketron, J., & Bernstein, M. (1981). People’s conceptions of intelligence. *Journal of Personality and Social Psychology*, *41*(1), 37–55.

Stevenson, J. (2004). Developing technological knowledge. *International Journal of Technology and Design Education*, *14*(1), 5–19.

Stieff, M. (2007). Mental rotation and diagrammatic reasoning in science. *Learning and Instruction*, *17*(2), 219–234.

Stieff, M., Hegarty, M., & Dixon, B. (2010). Alternative strategies for spatial reasoning with diagrams. In A. . Goel, M. Jamnik, & N. . Narayanan (Eds.), *Diagrammatic Representation and Inference* (pp. 115–127). Berlin Keidelberg: Springer.

Stieff, M., & Uttal, D. (2015). How much can spatial training improve STEM achievement? *Educational Psychology Review*, *27*(4), 607–615.

Suzuki, K., Wakita, S., & Nagano, S. (1990). Improvement of spatial ability through descriptive geometry education. *Journal of Graphic Science of Japan*, *24*(1), 21–28.

Sweller, J. (1988). Cognitive load during problem solving: Effects on learning. *Cognitive Science*, *12*(2), 257–285.

Sweller, J. (1994). Cognitive load theory, learning difficulty, and instructional design. *Learning and Instruction*, *4*(4), 295–312.

Sweller, J., Ayres, P., & Kalyuga, S. (2011). *Cognitive load theory*. New York: Springer.

Tairab, H. (2001). How do pre-service and in-service science teachers view the nature of science and technology? *Research in Science & Technological Education*, *19*(2), 235–250.

Terlecki, M., Newcombe, N., & Little, M. (2008). Durable and generalized effects of spatial experience on mental rotation: Gender differences in growth patterns. *Applied Cognitive Psychology*, *22*(7), 996–1013.

Thompson, T., Waskom, M., Garel, K.-L., Cardenas-Iniguez, C., Reynolds, G., Winter, R., … Gabrieli, J. (2013). Failure of working memory training to enhance cognition or intelligence. *PLoS ONE*, *8*(5), e63614.

Thorndike, E. (1927). *The Measurement of Intelligence*. New York: Bureau of Publications, Teachers College, Columbia University.

Thurstone, L. L. (1938). *Primary mental abilities*. Chicago: Chicago University Press.

Tversky, B. (2005). Functional significance of visuospatial representations. In P. Shah & A. Miyake (Eds.), *The Cambridge Handbook of Visuospatial Thinking* (pp. 1–34). Cambridge, Massachusetts: Cambridge University Press.

Uttal, D., & Cohen, C. (2012). Spatial thinking and STEM education: When, why, and how? *Psychology of Learning and Motivation*, *57*(1), 147–181.

Uttal, D., Meadow, N., Tipton, E., Hand, L., Alden, A., Warren, C., & Newcombe, N. (2013). The malleability of spatial skills: A meta-analysis of training studies. *Psychological Bulletin*, *139*(2), 352–402.

Vandenberg, S., & Kuse, A. (1978). Mental rotations, A group test of three-dimensional spatial visualization. *Perceptual and Motor Skills, 47*(2), 599–604.

Vernon, P. (1950). *The structure of human abilities*. New York: Wiley.

Vygotsky, L. (1978a). *Mind in society*. Cambridge, Massachusetts and London, England: Harvard University Press.

Vygotsky, L. (1978b). *Mind in society: The development of higher psychological processes*. Cambridge: Harvard University Press.

Wai, J., Lubinski, D., & Benbow, C. (2009). Spatial ability for STEM domains: Aligning over 50 years of cumulative psychological knowledge solidifies its importance. *Journal of Educational Psychology*, *101*(4), 817–835.

Wang, Y., & Chiew, V. (2010). On the cognitive process of human problem solving. *Cognitive Systems Research*, *11*(1), 81–92.

Wasserman, J., & Tulsky, D. (2005). A history of intelligence assessment. In D. Flanagan & P. Harrison (Eds.), *Contemporary Intellectual Assessment: Theories, Tests, and Issues* (pp. 3–22). New York and London: The Guilford Press.

Webb, R., Lubinski, D., & Benbow, C. (2007). Spatial ability: A neglected dimension in talent searches for intellectually precocious youth. *Journal of Educational Psychology, 99*(2), 397–420.

Wechsler, D. (2014). *Wechsler adult intelligence scale - Fourth edition (WAIS-IV)*. San Antonio, Texas: Psychological Corporation.

Williams, P. J. (2009). Technological literacy: A multliteracies approach for democracy. *International Journal of Technology and Design Education*, *19*(3), 237–254.

Willis, J., Dumont, R., & Kaufman, A. (2011). Factor-analytic models of intelligence. In R. Sternberg & S. B. Kaufman (Eds.), *The Cambridge Handbook of Intelligence* (pp. 39–57). Cambridge: Cambridge University Press.

Wise, L., McLaughlin, D., & Steel, L. (1979). *The Project TALENT data bank handbook*. California: American Institutes for Research.

Wright, R., Thompson, W., Ganis, G., Newcombe, N., & Kosslyn, S. (2008). Training generalized spatial skills. *Psychonomic Bulletin & Review*, *15*(4), 763–771.

Wu, H.-K., & Shah, P. (2004). Exploring visuospatial thinking in chemistry learning. *Science Education*, *88*(3), 465–492.

Xin, Z., & Zhang, L. (2009). Cognitive holding power, fluid intelligence, and mathematical achievement as predictors of children's realistic problem solving. *Learning and Individual Differences*, *19*(1), 124–129.

Yuan, K., Steedle, J., Shavelson, R., Alonzo, A., & Oppezzo, M. (2006). Working memory, fluid intelligence, and science learning. *Educational Research Review*, *1*(2), 83–98.