A STUDY OF BEHAVIOURAL, COGNITIVE AND NEURAL MARKERS UNDERLYING VISUOSPATIAL LEARNING

A thesis submitted for the Degree of

DOCTOR OF PHILOSOPHY

By

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Abstract

Visuospatial (VS) learning is an education format noted for encouraging an individual to use visual exploration and their innate spatial ability in constructing a flexible ‘internal mental representation’ of three-dimensional information. Being a discipline reliant upon this informed consideration, VS methods have found particular application in anatomy education – with tangential evidence linking the inclusion of these methods to greater student understanding of anatomical concepts. Building on these findings, this thesis investigates: (i) the extent of individual and group learning benefits that accompany VS instruction within anatomy education, and (ii) a novel exploration of the cognitive and neuroscientific mechanisms that govern their success.

To chart the success of instructional methodology in our reporting, we selected an array of academic performance and accompanying engagement indices. These items had been expressed by numerous modestly-powered prior studies, encompassing a diversity of anatomy cohorts, to be heightened under VS learning. Our initial work in Chapter 2 was therefore to determine if these effects were preserved when VS instruction was introduced within a substantially larger undergraduate anatomy cohort. Findings substantiated the wider applicability of this teaching method, with academic scores in each of the examined categories (didactic, spatial, and extrapolation) being superior to standard course delivery. Conflictingly, lower engagement and desire for VS inclusion was noted in the group receiving this instruction – leading us to attribute this to prevailing misconceptions about the nature of VS learning.

In order to determine whether benefits found to characterise VS teaching in anatomy were universally applicable, or attributable to a myriad of demographic and cognitive factors, Chapter 3 explored variation in individual spatial capacity. Interestingly, the prevailing advantage of raw spatial aptitude in males was not associated with improved practical performance. This subsequently allowed a component of underlying psychological reasoning, namely visualisation (Vz) ability, to be highlighted as the clearest indicator of one’s ability to transfer raw spatial intelligence into practical VS understanding. Accompanying the misconceptions of VS learning reported in Chapter 2, participants were found to be poor estimators of their VS ability.

Having established that spatial reasoning in anatomy possesses a physiological basis, we conducted a novel exploration of the neuroscientific mechanism evoked in VS learning using electroencephalography (EEG) technology (Chapter 4). This was evaluated by monitoring the neural signals of individuals engaged in two anatomical education workshops (featuring standard or VS instruction). No significant differences in oscillatory power accounted for the influence of VS instruction within any of the assessed frequency ranges (2-45Hz). Objective task outcomes were consistent with those in Chapter 2, finding a similarly elevated ability to address spatial questions following VS instruction.

When placed together, the results of Chapters 2, 3 and 4 demonstrate the explicit advantages present for VS instruction in anatomy education. Though further work is required to isolate the specific underlying neural pathways, this appears linked to passive changes in how the human brain processes and later consolidates this information. Findings have important implications for advancing medical educational strategy (Appendix Descriptive Review), and wider understanding of the mechanisms that govern learning.

Declaration

I, Toby Branson, certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint award of this degree.

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Signed …………………….

Date ………16/02/2022…..

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Aims and General Introduction

Developing accurate consideration of structural human form is a skill of paramount importance to anatomy students. When properly refined, competence in this domain enables the successful reasoning within a variety of clinical situations. Arts-based approaches have long shown an ability to develop this topological understanding within anatomy education – heightening initial comprehension and commitment to memory of pertinent information. A particular directive titled 'visuospatial (VS) learning' is thought to best exemplify these conventions. This approach harnesses feedback gained from physical (haptic) manipulation and visual observation to build holistic three-dimensional (3D) awareness of a target structure. This aids both an understanding of the isolated anatomical feature and how it interacts with surrounding physiology. While distinct advantages for VS education have been found in small-group cohorts, little is known of the merits for utilising this method in large-group anatomical instruction.

Success in VS education appears contingent on individual spatial ability. Though difficult to encapsulate, this intelligence is contingent on the bi-directional relation of two-dimensional (2D) and 3D information - generating a complex working understanding of applicable material. Understandably, this principle is rooted in governing cognitive architecture, with an assortment of processing mechanisms likely related to VS learning proclivity. Of these, visualisation (Vz) ability shows notable promise. Although prior studies have explored independent associations, it remains unknown how readily isolated spatial ability translates to integrated anatomical understanding.

Beyond inherent psychological capacity, a myriad of neuroscientific subtleties are thought to account for benefits obtained through VS learning. Although a complex process involving the interplay of disparate neural regions, 3D reasoning ability is a function predominantly assigned to the parietal lobe. Initial investigations into VS properties have been guided by different neuroimaging methods, of which functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) find prominence. While these approaches allow sophisticated exploration of brain sites showing activation during VS learning, they provide limited insight into the nature and wider connectivity of these responses. In monitoring electrical activity across the cortex, electroencephalography (EEG) is an excellent adjudicator of these shortcomings, with scant prior literature having explored its ability to capture neural signalling mechanisms throughout VS instruction.

Following an initial review of the surrounding literature in Chapter 1, the following three experimental chapters will sequentially outline the benefits of VS education methods and begin exploring the underlying mechanisms that afford them. Specifically, I will begin by examining the effect of VS learning directives on learning outcomes, within a significantly large cohort of anatomy students (Chapter 2). Specifically, I will examine the accompanying responses in learning outcomes for the inclusion of VS learning directives within this cohort of anatomy students (Chapter 2). Thereafter, these changes will be related to items of individual processing capability, with Chapter 3 exploring how an array of cognitive and demographic factors might be associated with assorted spatial abilities. In the final experimental chapter, attention will shift to understanding whether EEG technology can uncover any differences in neural sequencing that accompany VS learning (Chapter 4). This thesis will conclude with a discussion of the main findings, highlighting their relevance to advancing medical education, and proposing next steps for uncovering their neural basis in future research.

CHAPTER I

A Review of the Literature

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1 A Review of the Literature

In this review, I will initially provide a brief recount of the historical association between artistic description of human form and the study of anatomy, highlighting modern methods that preserve this practice in elevating the observational abilities of students. I will then discuss the neuroanatomical structures and physiological processes that are thought to facilitate learning under artistic directive, and explore evidence that these factors coalesce to expedite three-dimensional (3D) conceptualisation. Finally - I will specifically review electroencephalography (EEG) technology, discussing the advantages of this approach in comparison to alternate methods of examining the brain, and describing the neural oscillations that are known to accompany facets of learning.

1.1 The historical connection between illustration and anatomy

Illustration, as utilised in resources such as textbooks, has become an integral method used to explain the intricacies of anatomical content. This has emerged as a relatively modern application of the long-standing association held between artistic observation of human form, and its subsequent depiction for use in conveying anatomical knowledge. While this practice has seemingly progressed linearly in complexity alongside human evolution, a well-recognised era of heightened sophistication occurred during the Renaissance period – where artists and anatomists of the day documented human form in a way that maintains applicability to modern teaching. This section will highlight this key period, as well as those that proceeded and followed, in a manner that adequately surmises conformational shifts in the approaches used. Further explanation of these events, including a more succinct timeline of occurrence, can be found within several existing comprehensive descriptive articles (Cavalcanti *et al.*, 2009; Ghosh, 2015; Sealy and Lee, 2020).

1.1.1 Pre-Renaissance period

Our earliest description of anatomical consideration can be found in 4th century BC Greece, where authors such as Aristotle, Herophilus of Chalcedon and Galen of Pergamum (200 years later) provided textual reports resulting from cadaveric dissection of both animal and human material (Singer, 1957; Blits, 1999; Marx, 2013). Owing to prevailing religious and societal beliefs of the day, it is believed that restrictions were imposed upon the ‘contentious’ examination of human remains, thus hindering extensive anatomical study and description throughout this period (Di Ieva *et al.*, 2007). This was ultimately rectified in the Late Middle Ages, where the emergence of universities throughout Europe fostered an organised academic environment that persuaded the Catholic Church and Roman Emperor to de-stigmatise this work and promote enhancements in the diagnostic understanding of medicine (Rengachary *et al.*, 2009; Ghosh, 2015). This engendered the first formally approved methodical dissection of human anatomy - performed by Mondino de Liuzzi (Crivellato and Ribatti, 2006). Outcomes of this work were collated and published by de Liuzzi in 1316 as the seminal text *Anathomia Mondini*, which would prove invaluable in conveying anatomical understanding for an estimated 200 years (Choulant and Streeter, 1920; Crivellato and Ribatti, 2006). While information had to this point been conveyed using descriptive text, it was de Liuzzi’s student Guido da Vigevano (1280-1349) who reserves initial credit for incorporating illustrative means within anatomical description (Rengachary *et al.*, 2009). These hand-drawn figures are initially found to compliment the manuscript *Anathomia*, published in 1345, and display the trephination of the scalp to expose an array of constituent tissues of the nervous system (Olry, 1997; Di Ieva *et al.*, 2007). Though lacking in precise anatomical detail, these illustrations would establish a new benchmark for the field, cultivating the production of refined observation that would be completed by contemporaries throughout the next several hundred years during the Renaissance Period (Olry, 1997; Gurunluoglu *et al.*, 2013).

1.1.2 Renaissance period

The political and economic shifts that brought about the "rebirth" of European culture during the Renaissance Period (1400-1600AD) had a profound impact on the artistic landscape and subsequent depiction of anatomical material. It was during this time that illustration became invaluable in conveying detail of human form, with the influence of several prominent artists and scholars being heralded for bringing about this metamorphosis. Perhaps most well-known, Leonardo da Vinci pioneered this culmination of considered anatomical observation with exceptional drawing ability (Reti and Bührer, 1974; Dunn, 1997). The resulting works, generally depicting a broad spectrum of gross anatomy, contained a level of detail and realism that has previously been omitted in favour of text description (Keele and Roberts, 1983; Perloff, 2013). Accompanying this clarity, Da Vinci's illustrations often included differing viewpoints of the same anatomical feature, providing the observer with a better three-dimensional comprehension of the material being displayed (Jose, 2001). Though he produced many hundreds of works, Da Vinci's works were not widely disseminated until nearly 400 years after his death, resulting in debate amongst some historians as to the influence that Da Vinci's work imparted upon the field (Keele and Roberts, 1983). We do know however that this influence is found in the works of Da Vinci's younger contemporary, Michelangelo Buonarroti (1475 – 1564), who incorporated awareness of human anatomy into his many artistic and scholarly pursuits (Summers, 1981; Eknoyan, 2000). This work highlighted the convergence of art and anatomy, and can be seen utilised to convey realism in depicting biblical characters (Eknoyan, 2000). As it explicitly relates to medical education, physician Andreas Vesalius (1514 – 1564) authored the definitive work of this period *De Humani Corporis Fabrica* in 1543 (Vesalius, 1968). Drawn in collaboration with renowned artist Stefan van Calcar, the anthology of texts exhibited a collection of anatomical illustrations of previously undocumented clarity (Benini and Bonar, 1996; Hildebrand, 1996).

Work of this meticulous quality is thought to have transformed the prior conception of anatomical description being used strictly within the context of mythical or religious display, into an empirical science (Lasky, 1990; Toledo-Pereyra, 2008).

1.1.3 Post-Renaissance period

Following the concentrated observation and description of human form that took place throughout the Renaissance Period, the last few hundred years prior to the 20th century centred primarily on honing defined protocols for the description of this information. Perhaps owing to the fervent rediscovery of classical art forms in prior years, anatomists appear to have preferentially stylised their descriptions to incorporate visual flair in the centuries immediately exiting the Renaissance Period. Exemplifying this, Dutch physician Govert Bidloo worked with a compatriot, and gifted painter, Gerard De Lairesse in publishing a compendium of anatomy titled *Anatomia Humani Corporis* in 1685 (Hildebrand, 2005). While this collaboration yielded illustrations with tremendous artistic detail, it was found that the resultant product required explicit understanding of painting techniques in order to comprehend the source material – leading to substantial disorientation amongst fellow anatomists (Bell, 1794; Kemp and Thomas, 1997; IJpma and van Gulik, 2013). This trend of style over substance continued with Bernhard Albinus, a German professor of anatomy, who similarly partnered with an artist Jan Wandelaar in producing illustrations of human form that embodied the “homo perfectus” (Jensen, 1978; Rudakewich, 1998). Clearly discernible within resultant works, this romantic idea of presenting an idealistic representation of the examination omitted key anatomical features that might blemish stoic appearance (Kemp, 2010). This perspective that anatomical description necessitates artistic interpretation is termed “attic perfection”, and epitomizes prevailing consensus amongst contemporaries of the era (Hildebrand, 2005). Towards the end of the 18th century we begin to see a challenging of

this convention, with anatomist William Hunter and artist Jan van Rymsdyk returning to illustrate only absolute findings of anatomical dissection (Thornton, 1982; McCulloch, Russell and McDonald, 2002). Demonstrating a clear viewpoint towards resultant instruction, emphasis was placed upon the exact depiction of human anatomy as it was viewed, uncompromised by any subsequent ‘glorification’ (Hunter, 1774). This approach would come to be termed ‘grand naturalism’ (Kemp, 2010). Contemporaries throughout the 19th century would hone this realistic description, with notable names such as John Bell and Henry Gray publishing works that so accurately portrayed anatomical description and surgical technique that revised editions still feature prominently in modern medical education (Gray *et al.*, 1901; Hiatt and Hiatt, 1995; Kaufman, 2005).

1.2 Modern utilisation and benefits of artistic practice in anatomy

The long-standing use of illustration in conveying anatomical detail is far from the only artistic practice to permeate medical education, with a broad array of approaches having been utilised to promote student understanding. Modern research has attempted to explore the potential benefits associated within these disparate methods, specifically investigating their impact upon (i) academic performance, (ii) qualitative reports, and (iii) skill acquisition. By first providing a brief overview of established methods within anatomical instruction, the following section will outline findings in each of the aforementioned categories that document the inclusion of artistic practices within a wide variety of primary and allied healthcare training programs.

1.2.1 Established methods of anatomical instruction

The study of anatomy is an invaluable central component within medical curricula that provides the understanding of primary human form that then enables the successful development of relevant clinical skills. Though the applications of this anatomical knowledge can be utilised in disparate ways, an established system of conventional curriculum elements can often be found across both degrees of study and the institutions that provide them (Estai and Bunt, 2016). In surmising these prevailing curriculum components, three common teaching strategies will be discussed (Brenner *et al.*, 2003).

(i) Didactic Lectures and Tutorials: Perhaps the central component that combines all that follow, this entails the steady delivery of content through an initial lecture that is reinforced through subsequent small-group tutorial group or workshop meetings (Vazquez *et al.*, 2007). Lectures can be delivered in a multitude of approaches, encompassing series that require no active participation of students to the much discussed flipped-classroom approaches which emphasise it (Lage, Platt and Treglia, 2000). Tutorial groups similarly feature variability, typically highlighting lecture content in a more personalised setting that encourages student interaction using methods that can involve simple question and answer feedback with an instructor or more involved clinical case-based or problem-based scenario learning (Davis, 1999; Kassirer, 2010). Though historically delivered in person, modern technology has allowed students to consume these materials in a variety of online means (Ellaway and Masters, 2008).

(ii) Dissection and Prosection: Often viewed as the primary accompaniment to didactic methods of anatomical instruction, the viewing and interaction with human cadavers provides students with a deep understanding of human physiology (Azer and Eizenberg, 2007). Additionally, this method has supplementary advantages in promoting clinical professionalism, teamwork, systematic manual skill development and providing an otherwise unquantifiable means of introducing and developing comfort at the interface between life and death (Fruhstorfer *et al.*, 2011). Time spent in the laboratory adds real-world emphasis to student learning, explicitly outlining anatomical variability and how it differs from the often-simplified textbook viewpoint of the subject (Sprunger, 2008). While dissection specifically concerns student dismemberment of cadaveric material, prosection describes the displaying of already manipulated anatomical structures that aid specific understanding of a given feature or system. With a number of advantages being present for each of the two variants, the ratio by which students are taught through either method is often dictated by faculty constraints and the level of direct application to required degree outcomes (Leung *et al.*, 2006).

(iii) Medical Imaging: To foster integrated understanding and provide an avenue of direct clinical application, anatomical courses commonly incorporate components of medical imaging into their curriculum. The technique provides unique *in vivo* exploration of target tissues or systems, with the opportunity to highlight how these components differ when compromised by pathology (Gunderman and Wilson, 2005). Images are derived from a variety of established clinical techniques such as ultrasound, computed tomography (CT) and magnetic resonance imaging (MRI) that require students to interpret internal human form in multitude of sections (Gunderman and Wilson, 2005). It is in reconstructing a three-dimensional (3D) understanding from the presentation of a two-dimensional (2D) image that is thought to promote a deeper awareness of the underlying physiology (Miles, 2005; Lufler *et al.*, 2010).

Anatomy education, much like any other field of study, requires continual reconsideration. This ensures that student outcomes remain pertinent to skills required in future positions of employment, and that these skills are taught in a manner that optimally balances student concerns and faculty constraints (Moxham and Plaisant, 2007).

1.2.2 Utilisation of alternative artistic approaches

Though illustration and facets of drawing continue to feature most prominently as supplementary tools in anatomy education, a broad array of both specific and uncategorised artistic measures have been implemented within curriculum design and varying effects measured.

(i) Uncategorised: Proficiency in communication through visual arts remains a consistently identified skill for medical practitioners and scientific evaluators to possess (Naghshineh *et al.*, 2008). It is thought that competence in this field demonstrates valuable empirical qualities of perception and interpretation of emotion and expression, as evidenced in a cohort of medical students that were provided auxiliary artistic tutelage (Bardes, Gillers and Herman, 2001). These attributes have overt applications in assisting clinical examination procedures (Shapiro, Rucker and Beck, 2006; Naghshineh *et al.*, 2008). Further to this, visual arts appear to promote considerable engagement between students and anatomical subject matter (Hake, 1998; Ward and Walker, 2008). In possessing a ‘novelty’ effect, it is believed that visual arts can be implemented to ‘awaken’ previously disinterested students by “breaking the monotony” of a course - this idea having been examined through consideration of class attendance, participation and feedback within a cohort of medical students learning gross-anatomy through either didactic or diagrammatic means (Nayak and Kodimajalu, 2010). In explicitly placing emphasis upon self-directed learning, artistic methods can harness intrinsically activated attention to extract a maximal amount of information (Eagleton, 2015; Choi-Lundberg *et al.*, 2016). This, accompanied by outlined benefits for long-term memory integration, indicate that these methods produce knowledge that will more directly bridge the gap from class-room into clinical application (Collett and McLachlan, 2005; Ainsworth, Prain and Tytler, 2011; Moore *et al.*, 2011; Naug, Colson and Donner, 2011; Balemans *et al.*, 2016). While traditional education techniques possess advantages in their ability to present and display human form in precise detail, extensive shortcomings are encountered upon faculty time, the requirement for specialised facilities and the negotiating of ethical limitations surrounding the institution of a body-donation program (Dyer and Thorndike, 2000; Aziz *et al.*, 2002; Boulware *et al.*, 2004; McLachlan, 2004; Biasutto, Ignacio Caussa and Esteban Criado del Río, 2006). In comparison, artistic practises present both a time and cost-effective means of providing supplementary immersion within an anatomy learning environment (Bennett, 2014; Backhouse *et al.*, 2017).

(ii) Specific: In identifying specific uses for the arts within medical education, we note that a broad range of alternative strategies have been examined for their merits. Of these, a significant portion consider the examination and manipulation of living anatomy. Body painting, in its various forms, is an often-utilised example of this, providing an interactive learning experience that conveys awareness of surface and underling anatomy (Akker *et al.*, 2002). Specifically, this method entails the painting or tracing of bodily structures or systems upon their actual location in the living human body (typically a model of fellow student), allowing students to visualise the otherwise hidden architecture (McMenamin, 2008;

Jariyapong *et al.*, 2016). Aside from offering an interesting experience, body painting has been shown to heighten retention and recall of pertinent anatomical concepts (Finn and McLachlan, 2010). Finding a similarly diverse application within anatomy curricula, the incorporation or creation interaction with models (whether they be physically or graphically generated) appears to also possess cognitive advantage in assimilating anatomical relationships (Hilbelink, 2007; Seixas-Mikelus *et al.*, 2010; Moxham *et al.*, 2011). In presenting a physical depiction of the information being delivered in traditional education techniques, models are able to consolidate spatial awareness of gross anatomy in a cost-effective means (Estevez, Lindgren and Bergethon, 2010; Khot *et al.*, 2013; Yammine and Violato, 2015).

With proficiency in observation being imperative for the application of knowledge within a clinical setting, approaches that highlight the interpretation of emotion through photography, interpretive dance, clay modelling, and conceptual modelling have be shown to be valuable in providing an excellent foundation (Bardes, Gillers and Herman, 2001; Shapiro, Rucker and Beck, 2006; Kirklin *et al.*, 2007; Naghshineh *et al.*, 2008; Chang-Seok, Ji-Young and Yeon Hyeon, 2009). Students are also expected to develop upon their innate empathetical skills, allowing them to appreciate a patient’s perception of the medical treatment they are receiving (Dunbar and Nichols, 2012). While typically being difficult to progress through any other means than experience, artistic methods including the interpretation of still images, canvas painting and consideration of language have shown effectiveness in maturing this trait (Geranmayeh and Ashkan, 2008; Kumagai, 2012). Additionally, the consideration and sketching of comics (graphic works) has been shown useful in evoking and developing feelings of empathy within medical students, with this having inspired the production of specific anatomy based comic strips (Green and Myers, 2010; Park, Kim and Chung, 2011).

1.2.3 Inclusion of drawing within anatomical instruction

Perhaps the most evident artistic strategy to accompany primary methods of instruction, drawing (often described interchangeably with sketching) has been widely implicated in the improvement of student learning outcomes, specifically in relation to both initial anatomical knowledge and fostering connection into clinical application (Pandey and Zimitat, 2007; Jones, 2010; Naug, Colson and Donner, 2011; Jasani and Saks, 2013; Davis *et al.*, 2014; Balemans *et al.*, 2016). It is thought this may potentially derive from an innate ability to encourage considered concentration of material, ultimately allowing for a deeper retention of information (Matern and Feliciano, 2000). This is supported by qualitative data indicating that engagement and participation of medical students is increased under anatomical instruction that includes drawing paradigms (McMenamin, 2008; Kotzé, Mole and Greyling, 2012; Bell and Evans, 2014).

In comparing interventions that utilise drawing in anatomical education, we find two broad categories emerge, (i) Student-generated works (without accompanying instruction), and (ii) Instructor-mediated drawing (typically iterative upon received feedback) (Van Meter and Garner, 2005; Leutner, Leopold and Sumfleth, 2009; Azer, 2011; Noorafshan *et al.*, 2014; Schmeck *et al.*, 2014; Balemans *et al.*, 2016). This initial category of self-directed approaches is less representative of specific procedure, instead epitomising student recreation of figures or images that have been presented in common educational modalities (e.g. lectures, textbooks, or whiteboard/blackboard demonstration) (Clavert *et al.*, 2012). While both classifications have been shown to possess an ability to evoke respective elements of learning, the progressive nature of instructor-mediated drawing methods is thought to better amplify subconscious neural processing through initial creation and subsequent interpersonal reflection (Dempsey and Betz, 2001; Van Meter, 2001). An example of this, the Observe, Reflect, Draw, Edit, Repeat (ORDER) model was developed in alignment with this understanding of experiential education theory (Kolb, 1984; Catterall, 2005; Backhouse *et al.*, 2017). Integrating an additional element of interactivity, the haptico-visual observation and design (HVOD) technique incorporates tactile feedback in optimising ORDER principles to further support spatial awareness of anatomical structures (see section 1.3.2 for further detail) (Stephen Reid, Shapiro and Louw, 2019; Leonard Shapiro *et al.*, 2020). A broader and more pervasive example of this approach considers 'structured life-drawing', whereupon students are encouraged to both survey human form and draw their findings in a prescribed session supervised under both anatomical and visual arts guidance (Phillips, 2000; Mitchell, 2001). This method has been shown to facilitate a greater comprehension of 3D structure within a cohort of medical students, as well as exemplify the positive correlation with engagement (McLachlan *et al.*, 2004; Nayak and Kodimajalu, 2010). In adapting to advancements in modern technology, the necessity for physical interaction between student and instructor is removed, with online methods allowing for remote instructor-mediated interaction. A notable iteration of this virtual learning media is 'screen-cast' recordings, which incorporate both the stepwise following of pre-recorded drawing progression with the opportunity for real-time instructor interaction (Greene, 2018a). This online method appears akin to its in-person counterparts, possessing similar ability to heighten awareness of anatomical relationships in a means that may be more convenient and adaptable for institutions or programs emphasising less on-campus attendance (Pickering, 2017).

These benefits for the implementation of structured drawing regimes within anatomical or medical sciences study extend beyond transient class experiences, with a broad array of initial and longitudinal learning advantages having been found to accompany their inclusion (Nayak and Kodimajalu, 2010; Azer, 2011). Though difficult to classify, value of this method has been described to particularly concern: increased comprehension of anatomical knowledge, overall ability to interpret anatomy, and promotion of deeper learning that aids advanced recall and extension to clinical application (Alhamdani and Hatem, 2017; Borrelli *et al.*, 2018; Greene, 2018a). A prominent example of this literature considers the randomised design of several hundred blinded medical students in demonstrating significant improvements in their ability to recall aspects of facial anatomy through having undergone a sketching session either before or after having completed each session of a seven-week dissection module (Alsaid and Bertrand, 2016). While to highlight that expansive medical application, an alternate study demonstrating that replicating an image (rather than taking notes on it) increased knowledge retention in histological material over a six-week period (Balemans *et al.*, 2016).

1.3 Visuospatial learning in anatomy

In attempting to further explore how artistic practices are able to elicit positive effects upon anatomical comprehension, the fundamental principles by which this these methods operate must be elucidated. Throughout the diverse approaches described in the previous section, a common feature emerges in their requirement for the incorporation of multiple senses throughout interaction. It is this synergistic combination of senses that is thought to underpin advancements in engagement and concentration that ultimately promote interest in learning material. By focusing on the most prominent example of this coalescence, ‘visuospatial learning’, this section will provide: an overview of the educational theory itself, exploration of a particular instruction method governed by its principles, and coverage of modern technologies in anatomical education and clinical practice that utilise it.

1.3.1 Overview of visuospatial learning

Of the artistic methods proposed to enhance anatomy teaching, visuospatial observation and drawing has been advocated most prominently within academic literature (Pandey and Zimitat, 2007; Nayak and Kodimajalu, 2010; Naug, Colson and Donner, 2011; Jasani and Saks, 2013; Balemans *et al.*, 2016; L. Shapiro *et al.*, 2020). These methods have shown ability to foster tangential understanding - channelling initial conceptualisation into long-term memory and application (Collett and McLachlan, 2005; Ainsworth, Prain and Tytler, 2011; Moore *et al.*, 2011; Naug, Colson and Donner, 2011; Balemans *et al.*, 2016; Langlois *et al.*, 2020). Implied within the name, visuospatial teaching methods are those that seek to incorporate both visual and spatial senses throughout each facet of education delivery and subsequent student interaction (Rosenthal, Kennard and Soto, 2010; Lufler *et al.*, 2012; Borella *et al.*, 2014). While the visual component of this dual-approach is fairly implicit, denoting the focused optic inspection of material, it does not alone distinguish a technique that is dissimilar from common traditional methods (e.g. viewing of prosections). However, it is when this latter component (spatial feedback) is introduced that integration of distinct pathways can take-place, affording the aforementioned educational advantages.

Spatial conceptualisation encompasses an individual's capacity to survey the field using a collection of their senses to specifically comprehend features such as size, form and location, that together unveil description of structural relationships (Carroll, 1993a; Nguyen *et al.*, 2014). Further to this, once initial understanding has been reached, spatial awareness consolidates a 'mental representation' of these features, permitting consequent mental manipulation and recall (Carroll, 1993a; Makuuchi, Kaminaga and Sugishita, 2003; Schlegel *et al.*, 2015). A major proponent in accomplishing this spatial awareness is the inclusion of a physical interaction component can be ascertained through the involvement of haptics (incorporating feedback from touch) in further emphasising 3D understanding (Klatzky and Lederman, 2011; Vorstenbosch *et al.*, 2013). Supporting conventional wisdom, this sense of touch has been widely purported in extant literature to possess a crucial role in our perception of the world (Klatzky, Lederman and Matula, 1993). Far from strictly concerning the direct area being felt, the bounds of haptic exploration extend to supplementary factors of the object/feature including the weight, coarseness, distribution of balance, and dynamics by which it moves (Lederman and Klatzky, 1987; Wolfe *et al.*, 2015; Stephen Reid, Shapiro and Louw, 2019). In short, visuospatial directives are less concerned with recreating a 'photographically accurate' image of the human form - instead prioritising consideration of the 3D structure of an anatomical part through visual observation and physical interaction to arrive at subsequent spatial inference of its importance in human physiology (L. Shapiro *et al.*, 2020).

A feature shared by all visuospatial methods is an attempt to facilitate the interchange of 2-D and 3-D information; a skill that is essential for interpreting many aspects of medical imaging and histological examination, but one that is also essential for relating the mostly 2-D information in textbooks to real life situations (Keenan and Powell, 2020; L. Shapiro *et al.*, 2020). Likewise, with increasingly sophisticated modes of anatomy presentation and education delivery (e.g. virtual and augmented reality), it is important that students are able to reverse this process and mentally convert 3D anatomy back into the 2D representations that dominate text learning. Additionally, it is important that students improve their spatial awareness so that they might extrapolate a 2D image to its specific location within the volume of anatomy. In understanding these governing principles, specific methods have been developed to take advantage of the accompanying learning benefits. A particular example of this, employing a variety of instructive tasks to provide guided visuospatial exploration of relevant anatomical structure, is a technique formally referred to as Haptico-Visual Observation and Drawing (HVOD).

1.3.2 Haptico-visual observation and drawing (HVOD)

Building upon this theoretical understanding that both visuospatial learning directives and artistic drawing practices have merit in strengthening aspects of anatomical education, a fair deduction might assume that when used concurrently, aspects of multisensory observation combined with a structured drawing outlet would possess an additive effect that results in a more comprehensive consideration of 3D structure/function relationship than when either component is used in isolation. In identifying education methods that best consider this duality, a distinct concept titled "observational drawing" has been found to exemplify this overlap (Kantrowitz, 2012). This notion concerns an individual's explicit observation of an anatomical structure in 3D space and the transition required to represent their acquired information onto a 2D outlet (paper). Extrapolating upon the central themes of observational drawing, a detailed, adaptable and scalable learning intervention, titled the haptico-visual observation and drawing (HVOD) technique. This method, designed by visual-artist Leonard Shapiro, introduces cross-modal artistry and visuospatial observation practices into anatomical instruction, providing students with skills in 3D structural awareness. Though aesthetically pleasing drawings may result from this method, HVOD places no emphasis upon visual appearance, even discouraging its consideration to mitigate any potential clouding of perceptual understanding (Keenan, Hutchinson and Bell, 2017; Stephen Reid, Shapiro and Louw, 2019). Existing as a two-hour long workshop that can either compliment or replace an opportunity to view cadaveric material, the method is comprised of a series of individual stages (L. Shapiro *et al.*, 2020).

Stage 1:

Prior to interacting with an object, the participant is required to undergo a pair of exercises designed to both focus observational awareness and the ability to make marks that correspond to the discoveries made. By selectively training muscles and behaviors that govern the upper limb and hand in particular, subsequent movement will be made in a more purposeful and direct manner that better facilitates description of 3D form.

(i) Paper Exercise: Participants are asked to use their hands only in identifying how many "different things" they can do with several sheets of paper provided to them. This is left open to interpretation and guidance from the instructor, but could involve any or all of the following actions as an example: touching, folding, scrunching, and tearing. While initially appearing simple, each new piece of paper yields new ideas, with students engaging not only joints of their hands (radiocarpal and intercarpal) to accomplish this but also their ability to make spontaneous, imaginative, and fluid movements.

(ii) Scribble Exercise: Participants are asked to nondescriptly scribble on an additional sheet of paper. The instructor will then assess each of the individual styles of scribble presented to distinguish which have been produced through characteristic repetitive movements, and which have been made in a descriptive manner. The instructor can then provide pragmatic guidance as to improve the detail captured within these marks, presenting the participant with a series of tasks that introduce concepts such as: variable pencil pressure, speed of movement, and direction.

Stage 2:

Having now sufficiently engaged their visual means of observation and physical ability to depict the findings, the next step tasks individuals with adding haptic exploration into this growing list of considerations. This specifically involves the instructor guided employment of a set of deliberate movements termed ‘exploratory procedures’ (EP’s), that were first described by researchers Lederman and Klatzky, to a conventional ball and peen hammer (Lederman and Klatzky, 1987). These eight EP’s, such as “static contact”, “contour following” and “function test”, are designed to transduce information regarding the 3D form of an object. Somewhat arbitrarily, a hammer is utilised as this introductory object for its variety of physical and geometric features (textures, edges, volumes), while also being small and light enough for an individual to hold in one hand. Initially, individuals conduct this haptic exploration with eyes closed, followed by a return to visual observation only, before finally combining the two modalities to palpate the hammer with one hand and use the other to make representative marks with graphite on paper. If executed properly, this sensing hand will provide haptic and visual feedback regarding the hammer that will simultaneously inform the motor movements made by the drawing hand.

Stage 3:

Now that an individual has developed confidence in their ability to observe and draw a practice object, the last step concerns the integration of these skills into an anatomical context. Though adaptable to comply with available resources of the individual, the long-bone of a humerus is often selected to be the model for this exercise. No new techniques are described in this stage, instead the individual is encouraged to apply the distinct strategies gained throughout earlier parts of the workshop to observe the 3D form of this anatomical structure. By rotating the structure into different positions, individuals create overlapping interpretations of what is being observed on paper – not on distinct sheets, but aggregated on one. This provides the instructor a secondary opportunity to view the 'marks of meaning' that have been made, and correct any that may forgo descriptive ability for aesthetic appearance. At workshops completion, the ultimate goal is for the individual to (i) be able to close their eyes and view a mental representation of the anatomical structure they have interacted with, and (ii) possess an ability to visualise the 3D spatial volume of this structure from their 2D observational drawing.

Though there has yet been a been an objective quantitative evaluation of the HVOD method (though partially examined in the later experimental chapter of this thesis), the rationale is supported by qualitative data and anecdotal feedback. Specifically, elevations in both cognitive understanding and 3D memorisation of important anatomical features have been found to accompany the implementation of HVOD, with subsequent phenomenological evaluations suggesting it provides an engaging environment by which the spatial exploration of anatomy is supported (Stephen Reid, Shapiro and Louw, 2019; L. Shapiro *et al.*, 2020). Moreover, individual components of the HVOD are rooted within both educational pedagogy and cognitive neuroscience.

1.3.3 Modern techniques

As alluded to in prior discussion, certain former mainstay methods of anatomy teaching (e.g. cadaveric dissection) are becoming scant in their use within tertiary education. This has been attributed primarily to growing imbalances between expanding cohort sizes and limitations in infrastructure that house this study (Aziz *et al.*, 2002; Sugand, Abrahams and Khurana, 2010). This circumstance is representative of a wider shift towards education methods that are fundamentally ‘learner-centered’ as opposed to being ‘teacher-student’ mediated (Torres *et al.*, 2014; Smith *et al.*, 2016). These methods ascribe that knowledge acquisition be directed by student endeavor, with strategies either re-imagining traditional approaches or utilising innovative novel technologies to encourage this exploration (Kurt, Yurdakul and Ataç, 2013; Singh and Kharb, 2013; Waight, Chiu and Whitford, 2014; Estai and Bunt, 2016; Phillips, Eason and Straus, 2018). Instances of this include: team-based training, case or problem-based learning (PBL or CBL), monitor display of cross-sectional images, flipped-classroom approaches, computer-guided education, simulation software, interactive 3D videos, and an assortment of handheld or centrally available interactive devices (Lufler *et al.*, 2010; DePietro *et al.*, 2017). The incorporation of these practices within anatomy curricula has been demonstrated to make instruction feel more engaging and interesting, with strong ties to accurate memory consolidation and ability to apply this knowledge within a clinical situation (Tubbs *et al.*, 2014; Smith *et al.*, 2016). Accompanying this, an inadvertent secondary benefit of these methods may be lie in shifting the perception of course-specific anatomical revision from being a relatively mundane rote-learning experience, into an engrossing one that reinforces concepts at an individual student’s desired pace (Singh *et al.*, 2019).

With specific regard to interactive devices, a particular advantage afforded to modern methods in providing ‘learner-centered’ education is the ability to present students with an emulation of medical imaging techniques, while exploiting the intrinsic enjoyment of exploring this anatomical material in these novel approaches. With growing need for medical professionals to be proficient in radiological classification, these innovative technological methods have risen in prominence to provide this additional education - with prior studies outlining advantages in motivation and resultant understanding of gross anatomy that occur from their pre-clinical implementation (Murakami *et al.*, 2014; Murphy *et al.*, 2015; Heptonstall, Ali and Mankad, 2016; Paech *et al.*, 2017). Exemplifying these approaches are tools such as: free anatomical image viewing software, e-learning sources, portable ultrasound, applications for personal phone or computer tablet devices (e.g. IPad), and tables for virtual dissection of cadaveric material (e.g. Anatomage or Sectra) (Colucci *et al.*, 2015; Custer and Michael, 2015; Darras *et al.*, 2017; Wilson *et al.*, 2018). Within a clinical environment, a popular addition to these means is the use of simulation technology in the practicing of clinical procedures (Singapogu *et al.*, 2015). Of note, the integration of haptics into the otherwise virtual simulation environments has shown to benefit early career trainees in their navigation of internal landscapes during minimally invasive surgeries (van der Meijden and Schijven, 2009; Pinzon, Byrns and Zheng, 2016).

Emulating their implementation within other fields of education, contemporary research has also explored the use of both augmented reality (whereupon objects are superimposed into an individual's viewpoint of their surrounding) and virtual reality (with complete immersion) in anatomical instruction (Azuma *et al.*, 2001; Birt *et al.*, 2018). Though showing promise in both initial qualitative and quantitative studies of individual reception, large scale analyses have yet verified these methods possess the efficacy of more established technologies (Bork *et al.*, 2019). This necessity for longitudinal investigation is particularly pertinent in this educational research, as individual items of literature that examine these emerging technologies are often plagued with issues surrounding their immediate presentation within established curricula. This phenomenon, described as the 'novelty effect', can be approached from two distinct angles - either causing artificially high results in having temporarily engaged students in an exciting novel method, or lowering results proportional to an increased cognitive load placed upon students trying to process information from this novel method (Moro, Smith and Stromberga, 2019; Wainman *et al.*, 2020).

1.4 Conventional anatomical learning theories and pedagogy

In rounding out discussion of how and why artistic (specifically visuospatial) learning modalities may be implemented within anatomical education, consideration must be paid to the foundational theories that govern these approaches in contrast to more established methods. In each possessing unique strengths, a combination of their intrinsic components is theorised to provide comprehensive instruction - with the consideration of these approaches serving as the basis for curriculum design. After initially chronicling these theories, specifically outlining those utilised in artistic approaches, this section will discuss the notion that different individuals are predisposed to divergent learning approaches, and particular regard paid to a classification system titled ‘VARK’.

1.4.1 Educational theories

Outlined in various formats within preceding sections of this review, modern instruction of anatomy is facing a period of reconsideration whereupon established curriculum methods are being amended. This changing of approaches is indicative of the broader deviation in tertiary education towards ‘learner-centered’ techniques, those which commonly use either integrated traditional means or novel technological methods to place the emphasis of learning upon the student (see section 1.3.3 for further detail). Compounding this are bi-products of shifting institutional direction that can impact an anatomy educator’s ability to provide content, including: larger course sizes, reduction of contact hours, reduction of course funding, infrastructure restrictions, and the need for more integrated content that mirrors advancing clinical expectations. In order adequately meet these challenges, it becomes imperative for educators to consider the intrinsic benefits possessed within each education method, and design a holistic syllabus that meets individual student requirements with respect to institutional constraints. This contemplation can be guided by principles outlined in general educational psychology, a field that represents the inference between the scientific study of human learning and teaching practices. This research encompasses factors such as the manner of problem solving, inherent motivation and memory consolidation. Though being roughly divided into two main approach models, (i) behavioral, and (ii) cognitive, modern literature has strongly favored the further exploration and classification of the latter category, resulting in the branching of several distinct sub-theories.

Behavioral Model:

Having been the dominant approach advocated within educational psychology from its inception in 1906 to the early 1980's, this model considers learning as being a mechanistic response that is periodically strengthened or depleted through observation and interaction within a given environment (Greeno, Collins and Resnick, 1996). With this line of reasoning, the brain could be metaphorically thought of as a sponge that is awaiting the application of information for it to expand (Terrell, 2006). The emphasis of instruction is therefore placed upon the simple presentation of material and the expectation that students will, through different pedagogical methods such as repetition and recitation, 'immerse' themselves within the required knowledge (Morrone and Tarr, 2005). This invariably places supreme emphasis upon the educator, who both possesses the required knowledge and is charged with disseminating it (Halpern and Hakel, 2003). By comparison, students are relegated to passive positions in their own training. Though few examples of this model remain in modern anatomical teaching, its design principles are evident in the demonstration of new clinical skills or procedures, as well as to promote overarching graduate outcomes like professional demeanor and clinical etiquette.

Cognitive Model:

Now considered to be the preeminent approach in educational psychology, this model operates at the opposite end of the spectrum as it's behavioral forbearer in dictating that the input of the learner be paramount within the learning process. By allowing students to interact with material, an educator can seek to activate complex mechanisms of cognition that extend beyond simple passive absorption (Walberg and Haertel, 1992). Though many diverse approaches have been explored, three major theories have emerged to help explain the intrinsic benefit of this cognitive model, as well as outline how it can be specifically utilised within anatomical education.

Information Processing Theory:

This theory considers learning as an active cognitive process whereby novel stimuli undergo interplay at the level of immediate conceptualisation prior to storage in memory. A cognitive architecture classifies this interplay into three distinct subcomponents, sensory memory (SM), working memory (WM), and long-term memory (LTM), that each possess a crucial role in the initial acquisition of knowledge, its processing, potential storage and ability to be subsequently retrieved. Briefly described: SM is the initial acquisition of the incoming information (whether that be auditory, visual, haptic, etc), WM (used interchangeably with short-term memory) then acts as the ‘middle man’ to processes this knowledge and establish the pertinent components for long-term storage, and LTM is this repository of considered intelligence. Though described as the intake of new information, this system is mediated by feedback in both directions, with LTM’s ability to be recalled in temporary WM and subsequently influence SM. Factors such as attention, intensity, similarity to prior knowledge and emotional attachment contribute to WM decision of relevant information to retain – hence they are features emphasised by pedagogy designed under this approach (Bruning, Schraw and Ronning, 1999). The chief goal of information-processing instruction is the ability to consolidate key information into LTM and have it be available for subsequent retrieval. The role of an instructor is therefore to outline a succinct goal, and design a syllabus that reiterates this content through disparate approaches. Principles of this theory have been adopted into modern anatomical education – supplementing purely rote-learning exercises like lectures and text-books with interactive methods within a curriculum. This might include the making of concept maps, student creation of mnemonics, and informal completion of practice examination material (Morrone and Tarr, 2005).

Directly associated with information processing theory is the cognitive theory of multimedia learning (often simply referred to as the ‘Multimedia Theory of Learning’). This conjecture states that successful neural integration of novel information can be enhanced when content is presented in multiple forms (using the example of providing graphics alongside text presentation (Sweller, 1988; Moreno and Mayer, 1999). Specifically, this combined input is thought to necessitate the successful conversion of working memory into long-term memory through reduction of overall cognitive load, consequently improving information processing capabilities (Mayer and Moreno, 2003). This theory is predicated upon three underlying principles of cognition: (i) dual channels – acknowledging that learners have distinct pathways of learning for each sensory modality (Paivio, 1990), (ii) limited capacity – that attention span dictates only a few items can be encoded at one time (Baddeley and Logie, 1999; Sweller, 1999), and (iii) active processing – denoting that engagement heightens the capacity to learn (Wittrock, 1989).

Constructivist Theory:

Primarily charting the impact of progression, the constructivist theory defines learning as an iterative process whereupon a foundational base of knowledge is continuously built-upon (Vygotsky, 1980). The constant comparison of one's own knowledge against the particular level required therefore serves as the chief driving force for learning. It follows that when novel information is met, cognitive architecture must attempt to assimilate this content with reference to two factors, (i) what is currently possessed, and (ii) what is currently valuable to obtain (Saxe, 2015). Guiding the answer to these cognitive questions serves as the primary responsibility of an educator observing this premise. Though expressed in differing ways, the crucial means of addressing this is invariably through fostering social collaboration. In contrast to other approaches, not only is the teaching method and specific content of importance, but also the environment in which it is applied into. In viewing learning within a social context, novel information can be reinforced through interactions that are adaptive, interactive, and progressive to the current knowledge level possessed by an individual (Morrone and Tarr, 2005). Pedagogy adhering to this theory emphasises the subliminal promotion of autonomy within a learner, providing an integrated curriculum that inspires genuine curiosity and a community to support its exploration. An instructor's responsibility is therefore to facilitate this, outlining the required knowledge and providing framing exercises to encourage its analysis (Derry, 1996). Modern anatomical instruction considers this theory in designing small group problem (or case) based learning exercises, that encourage students to collaborate in completing a clinical case study that contains content relevant to learning outcomes.

Metacognitive Theory:

As indicated by the name, this theory concerns the process of "thinking about thinking" and the encouragement of students to take charge in their own learning (Terrell, 2006). By implementing strategies that task students with conceptualising their own learning, it is thought they might take conscious control in their tackling of the content or problem they are faced with and self-adjusting their behavior to combat it appropriately (Svinicki, 1999). Within this context, metacognition is defined as the culmination of two factors: (i) knowledge of cognition (awareness), and (ii) the ability to regulate this cognition (critical assessment) (Brown and Glaser, 1978; Schraw, 1998).

(i) Being itself comprised of three distinct considerations, this initial awareness of knowledge concerns taking stock of one's own cognitive approach to learning. This is accomplished through: 'declarative knowledge' – whereby strategies that contribute to effective performance are identified, 'conditional knowledge' – where the most effective of these are selected, and 'procedural knowledge' - where the means to execute these strategies are outlined (Reynolds, 1992; Schneider and Pressley, 2013).

(ii) Secondary regulation of these considerations is again described in three aspects, together aiming to implement a blueprint that will improve learning. These are: 'planning' – establishing succinct goals in light of the time, effort and materials required; 'monitoring' – ability to make assess adherence and make relevant adjustments, and 'evaluation' – critically assessing whether the learning outcome has been met, and how to potentially improve it for future tasks (Flavell, Weinert and Kluwe, 1987; Schraw, 1998).

Akin to each of the other two theories within the cognitive model, metacognitive-based instruction places primary emphasis upon a student to become more independent. An instructor therefore assumes responsibility to deliver required knowledge before promoting this metacognitive awareness. Within anatomical education, this can include: drawing student attention to how specific information (e.g. lecture content) is relevant to both immediate course outcomes and wider clinical application, overview sessions proceeding each module, and demonstrator circulation within course activities to promote group consideration (Schneider and Pressley, 2013).

Now returning to examine which elements of educational psychology are stressed in visuospatial means, and in particular those instructed-mediated drawing regimes, it appears there is a mutual recognition within both the cognitive and constructivist theories. In particular, a sub-group born out of this overlap between theories is titled the "multimedia model", one which stipulates that learners are being focused to actively integrate new ideas into their memory, this is termed 'generative learning' (Van Meter *et al.*, 2006). By generating new conceptual representations and links between that new information and prior understanding, the learner is able dual encode a non-verbal representation of material and attach it to verbal text that may have already been stored (i.e. lectures, tutorials) (Van Meter *et al.*, 2006; Stephen Reid, Shapiro and Louw, 2019).

1.4.2 Learning predispositions

In addition to the classification of distinct theories that can govern the delivery of education, so too is there belief that learners themselves inherently possess different traits that make them as an individual more susceptible to differing means of education. This thought in pedagogical research is often referred to as the concept of distinct "learning styles" or "learning predispositions", and initially described as the "characteristic cognitive, effective, and psychosocial behaviors that serve as relatively stable indicators of how learners perceive, interact with, and respond to the learning environment" (Curry, 1981). In discovering one's own learning style (or predisposition), it's thought a correlating aspect of educational theory may be emphasised within an individual's study regime, such that this might permit greater success in higher education (Romanelli, Cain and Smith, 2006). This can then further equip an educator with information on the ideal pedagogy to implement within a particular course, tailoring a curriculum that managing both the wider theories of education and also makes particular concession for the individuals strengths (Lubawy, 2003). Supporting this, a great number of articles have reported potential methods by which students can achieve above standard academic outcomes through selective activation of these learning modalities, indicating that teachers should implement strategies within their curriculum that encompass all the variability at play (Fleming and Mills, 1992; Tanner and Allen, 2004; Lujan and DiCarlo, 2006; Wehrwein, Lujan and DiCarlo, 2007).

Exploring the underlying elements of this, disparate items of primary research have proposed numerous examples of the presence of distinct categories of learning styles that exemplify these principles (Felder and Silverman, 1988; Canfield, 1992). Much of the overall direction in the field has been guided by Kolb's seminal model of learning categories, describing a cyclical process whereby experience, reflective observation, and abstract conceptualisation beget one's comfortability in experimentation (Kolb, 1984). Subsequent studies, typically centering on either elements of cognition or evidence observed in practical application, tend to classify learners in accordance with properties such as: their preference or strength to use various sensory modalities, personality type (e.g. extroverted or introverted), cognitive style (e.g. perceptive or described), or prior performance in varying design (Cook and Smith, 2006). Despite this, evidence has yet supported a consensus viewpoint on a particular classification set to be utilised by educators (Rohrer and Pashler, 2012).

This inability to classify distinct learning styles within the population has led to widespread academic discussion as to whether there is really a difference in classification and approach which can dictate an individual's learning style, or whether they are a 'myth' (Hawk and Shah, 2007; Riener and Willingham, 2010; Dekker *et al.*, 2012; Howard-Jones, 2014). A meta-analysis exploring this concept revealed that seldom few items of research in the field contained a requisite control to be valued as concrete scientific evidence, and that the conventional wisdom that had entered the field as a result was largely un-justified (Pashler *et al.*, 2008a). Further to this, a general trend observed in these studies is the ringing endorsement of learning styles despite evidence being provided in their results that might support these claims (Newton, 2015). Instead, many articles expound their endorsement for such a concept having only examined simple questionnaire responses from students categorising their own learning (Willingham, Hughes and Dobolyi, 2015). Indeed, subsequent work had shown that even changing education styles to align with those methods preferred by students did not improve outcomes, while rather resulting in burdens such as a higher average financial cost (Riener and Willingham, 2010; Papanagnou *et al.*, 2016). Despite this, the notion of learning styles has entered popular consensus, and is subsequently still widely considered and implemented by educators in all forms of education (Dekker *et al.*, 2012).

1.4.3 Visual, Aural, Read/Write, Kineasthetic (VARK) learning

Perhaps the most pervasive learning strategy discussed within education, the VARK model was created by Fleming and Mills in 1992, and dictates that students are grouped into either of a few distinct categories of education modalities that are thought to correspond with their preferred learning style (Fleming and Mills, 1992). Though originally designed as a method of instigating discussion surrounding education methods, and not as a diagnostic tool, VARK has been used extensively throughout teaching to ‘categorise’ students into the style they should be structuring their education around (Pashler *et al.*, 2008a; Scott, 2010).

The title of this scheme is itself an anagram for the potential constituent modalities that it proposes an individual can possess, that of being a Visual (V), Auditory (A), Read/Write (R) or Kinaeasthetic (K) learner (Fleming and Mills, 1992). To summarise each component: a visual learner is one who can best reason through and retain information that they can visualise (e.g. diagrams), an auditory learner prefers to hear the delivery of this content (e.g. lectures), a read/write learner enjoys the distillation of material into words (e.g. textbooks), and a kineasthetic learner grasps quickest through practice or simulation (e.g. problem solving). Information on which modality a particular student adheres to is typically guided by a series of multiple-choice questions that task students with responding to ostensibly random queries such as “If you were to go on holiday, and would only have access to one of the following items, which would it be?”. Each option of the multiple-choice response will have then been designed to correlate to a precise VARK modality, and though far from an exact science, an algorithm (in more complex studies) or simple summation of these factors (in basic analysis) provides the results. The VARK model stipulates that learners can adhere strictly to one of the aforementioned categories and be described as ‘unimodal’, but also makes concessions that it’s far more likely that overlap between multiple preferred modalities exist, in which case the term ‘multimodal’ is utilised. According to the exact nature of this overlap, multimodal learners can be further sub-categorised as ‘bimodal’, ‘trimodal’, or even ‘tetramodel’ (Fleming and Mills, 1992). For example, an individual’s aptitude for visuospatial education is colloquially thought to correlate with features in their VARK classification. While has never been demonstrated, bimodal visual and kineasthetic learners would hypothetically be more receptive to material presented in this manner than their counterparts.

In a similar pattern to the wider determinations made of learning predispositions, literature has outlining the disparity between the observed learning style through VARK and both the true enjoyment and academic benefits that result through its implementation (Hawk and Shah, 2007; Husmann and O’Loughlin, 2019). While the classification of students into VARK categories has in some cases been attributed to increases in academic performances amongst undergraduate medical and allied-health courses, an equal number of these studies report either no correlation or a contradictory one between selected approached and outcomes (Wessel *et al.*, 1999; Sandmire, Vroman and Sanders, 2000). A common consensus is reached that while a *concrete* intrinsic learning style for each individual is unlikely, students may have a *preference* for a particular style and more pertinently the way it in way in which the content may be covered (e.g. enthusiasm, engagement). A far better metric than a questionnaire appears to be observing the way in which students currently learn and embracing a class design around the strengths that these modes can provide (i.e. pre-recorded lectures, mobile technology, app development).

1.5 Psychological processing of 3D information

Having discussed evidence supporting the implementation of visuospatial learning within anatomical education and how this can be accomplished through various methods of instruction, attention now turns to classifying the mechanisms by which these benefits are achieved. While qualities such as enhanced knowledge acquisition and subsequent long-term memory retention are inherently desirable outcomes reported to accompany spatial conceptualisation, how is it that the processing of this information facilitates this exchange? The following passage will take the first step in describing our understanding of this system by exploring the psychological principles that govern it. By first discussing the intrinsic features that guide our perception and consolidation of 2D and 3D spatial information, this section will relay how these components are directly emphasised in the perception of functional human anatomy, and provide specific example of a common predictive task that estimates one’s aptitude for accomplishing this interchange.

1.5.1 Consolidation of spatial information

Conceptual mental imagery can be described as the ability to create a transient mental depiction of a particular item or system, informed by the precise detail obtained through multi-faceted visualisation, of both its individual spatial characteristics and interaction within its environment (Guillot *et al.*, 2007). This process is mediated by fundamental components of neurophysiology and anatomical specialisation that culminate in the application of varying elements of cognitive psychology. Perhaps the most essential component of spatial ability, mental rotation requires the initial recall of information about an item, such that cognitive manipulation can then transfer this information into another viewpoint or plane of reference. This newly configured version of the object will retain the original spatial characteristics, and be used to solve a newly presented problem (e.g. navigation) (Gunzelman and Anderson, 2004). It is then unsurprising that a large and diverse number of activities have been described to elicit this spatial visualisation, including the: performance of music, honing of motor-skills, and interpretation of science curricula (Brochard, Dufour and Després, 2004; Peters *et al.*, 2006; Pietsch and Jansen, 2012).

A fundamental step in generating this mental representation is the ability to perform isolated reasoning of both 2D and 3D information, as well as facilitate interchange between them. Within 2D rotation this conversion is limited to a single plane of transformation, allowing reasoning to be conducted with incomplete spatial inferences and simple correlation judgements. When transitioning to a 3D viewpoint, mental rotation inherently requires an additional component of depth to be extracted from the surmised content, adding supplementary complexity to the process. While maintaining a grasp of the rotated objects geometric characteristics, this conversion to 3D rotation must preserve the spatial layout gained through prior exploration of 2D form, simply adding the new 3D spatial information (Moreau, 2013). This transient transformation from 2D conceptualisation to a 3D mental representation is termed ‘dimensionality crossing’ (Voyer, Voyer and Bryden, 1995). Accompanying these concepts is the idea that certain modes of cognition regulate this process, altering and refining neural systems in response to presented afferent stimuli (Honey, Newman and Schapiro, 2017). The two most prominent examples of this are the ‘internally biased’ and ‘externally biased’ modes, which together recognise patterns and utilise feedforward mechanisms to predict required awareness (Hasselmo, 1995).

In outlining the neurophysiological features that govern mental rotation, paramount importance is placed upon the interplay between the motor system and surrounding aspects of higher cognition (particularly the development of the prefrontal 'executive' cortex) (Wexler, Kosslyn and Berthoz, 1998; Wohlschläger and Wohlschläger, 1998; Amorim, Isableu and Jarraya, 2006). Overseeing this exchange, visual working memory (WM) is responsible for the maintenance of temporary visual stimuli in ongoing tasks, executing this function using three distinct subcomponents: (i) central command (dictating attention), and two codependent short-term memory loops, (ii) phonological (concerning language) and (iii) visuospatial (mental manipulation) (Baddeley, 1992; Dube, Emrich and Al-Aidroos, 2017; Ye *et al.*, 2017). Processed information is said to be utilised by the 'inner scribe' (actively processing movement and spatial relationships) or retained in the 'visual cache' (passive storage) (Logie, 2011). While an individual's WM capacity is largely genetically predetermined, representative of broader cognitive intelligence, prior studies have indicated that it is somewhat malleable and responsive to trained experience (Hyun and Luck, 2007). Of note, increased sensorimotor communication within a certain environment has been shown to accelerate WM processing by better promoting communication between the 'visual cache' and 'inner scribe', providing an increased mental rotation ability (Moreau *et al.*, 2011; Steggemann, Engbert and Weigelt, 2011).

In classifying further neural components that facilitate this rotation, evidence has demonstrated the neurological similarities that exist between physical and virtual rotation (Ruddle and Jones, 2001). This suggests that the brain initiates a very similar sequence of neuronal firing whether a manual action is taken or not - outlining our subconscious ability to interpret our surroundings and pre-emptively plan appropriate actions (Waller, 2000). Haptic experiences are thought to provide further mental stimulation, actively transferring referential information gained through physical manipulation to build a more complete virtual picture – for instance, components such as weight or coarseness are only discernable through these means (Janczyk *et al.*, 2012).

1.5.2 Importance within anatomical education

The study of functional human anatomy is a domain of education that is heavily reliant on complex spatial processing and mental transformations. This presents an excellent opportunity to utilise dimensional awareness, and has subsequently served as a platform for a multitude of investigations into visuospatial abilities (Berney *et al.*, 2015). Interpretation of medical imaging software is a common exemplar for this discussion, being a specific clinical responsibility that requires an individual to infer 3D structure from an often 2D stimulus (Pedersen, Wilson and De Ribaupierre, 2013). Increasingly complex modern applications of this technology further exacerbate this by permitting 'dynamic visualisation' of 3D structural relationships in imaging software (Bétrancourt, Bauer-Morrison and Tversky, 2000). While this seemingly enables additional geometric dimensions to be visualised without interpretation, new layers of complexity are added in trying to relate this information with alternate material provided, as well as considering progression over time (Schnotz and Lowe, 2003). As psychological models describe (outlined in section 1.5.1), previous experience appears as a key predictive indicator of the ability to perform this reasoning within dynamic visualizations (Guillot *et al.*, 2007; Hoyek *et al.*, 2014). Though trained experience can somewhat compensate for shortcomings, individual variability in the aptitude for visuospatial processing is another point of consideration, with evidence suggesting the predetermined nature of spatial reasoning ability is also a present within anatomical performance (Hegarty and Waller, 2005; Höffler, 2010).

When designing educational paradigms to elevate spatial awareness within an anatomy learner, two independent primary attributes appear key to develop: (i) spatial visualisation, and (ii) spatial relation (Colom *et al.*, 2002; Höffler, 2010). Spatial visualisation (Vz) is defined as an individual's ability to comprehend spatial information, encode it within working memory, and be able to manipulate the resultant representation (Carroll, 1993a). This aspect of awareness is hypothesised to be largely passive, with an educator advised to sequentially build upon a base level of general information (e.g. lecture content) with an opportunity for focused viewing (e.g. dissection environment) (Nguyen *et al.*, 2014). By comparison, spatial relation ability (Sr) concerns the specific interchange between 2D and 3D information (Miyake *et al.*, 2001). This can be developed through incorporation of exercises that stress quick and accurate execution (e.g. structured observation), and is thought to account for a large portion of the aforementioned advances made through experience (Berney *et al.*, 2015).

An additional point of consideration in designing anatomical education paradigms that provide this spatial experience, is that advancements can be made across an entire cohort according to either the: (i) compensating hypothesis, or (ii) enhancer hypothesis (Mayer and Sims, 1994; Hegarty and Waller, 2005). The compensating hypothesis dictates that focused multi-modal learning practice can compensate for an individual's low spatial ability by more clearly defining and reinforcing the parameters of a given system - acting as a 'cognitive prosthetic' (Mayer, 2002; Hegarty and Kriz, 2008). While for individuals who already possess a high spatial ability, the enhancer hypothesis stipulates that exposure to dynamic visualisation will be better mitigated and leave more cognitive capacity to build accurate mental representations (Huk, 2006).

Translating these concepts into the classroom, students who struggle to perceive in three-dimensions (across the aforementioned components of Vz, Sr, and dynamic visualisation) have been shown to score lower on practical anatomical tests than their counterparts with high spatial ability (Rochford, 1985a; Lufler *et al.*, 2012; Nguyen, Nelson and Wilson, 2012; Tan *et al.*, 2012; Hoyek *et al.*, 2014). In order to arrive at these conclusions, a battery of common tools are used to assess the validity of one's spatial abilities, both in isolation and when specifically relevant to anatomical study. For raw spatial ability, these include the: Group Embedded Figures Task (indicative of Vz and Sr), and the Mental Rotations Test (examining spatial relation, to be further discussed in section 1.5.3) – while for anatomy specific ability these include: comparisons of medical imaging to practical models (dynamic visualisation), and specific stereoptic tasks (depth evaluation) (Keehner *et al.*, 2004; Guillot *et al.*, 2007; Luursema *et al.*, 2008; Tan *et al.*, 2012).

1.5.3 Mental Rotation Task (MRT)

Though general spatial ability is a feature of cognition that is intrinsically hard to quantify, one particular method has risen to prominence as the colloquial point of reference for both isolated academic research and practical implementation within education. This validated metric is termed the Mental Rotations Test (MRT), a written examination that tasks individuals with visualising and orienting a series of 3D objects that are provided within a 2D reference plane (observing 2D to 3D conversion) (Vandenberg and Kuse, 1978). The MRT is thought to effectively stimulate elements of cognitive psychology that govern visuospatial ability, examining the capacity of an individual to conceptualise and rotate a series of objects in both dimensions (Anastakis, Hamstra and Matsumoto, 2000a). The traditional design of the experiment, as specified in the seminal paper by Shepard and Metzler, presents an individual with a sequence of geometric 3D structures (stacked cubes) that are referred to as the: (i) baseline object (on the left), and (ii) four target objects (on the right) (Shepard and Metzler, 1971). These sets of cubes are either identical to one another, or different in some slight way – and are irrespectively presented with an angle of rotation applied such that the images will be oriented in differing directions. The task of an individual is therefore straightforward, to mentally rotate the four target objects and determine which two of them fall into alignment with both each other and the baseline object. Question sets are designed so that they contain an even number of "same" stimuli – where objects are identical, and "different" stimuli – where they do not coincide. Spatial ability is assessed by comparing the number of objects that were correctly distinguished (accuracy), as well as how rapidly this was performed (response time). Later, and more sophisticated, iterations of the MRT have sought to improve upon the original design in a number of distinct categories, these include: using enhanced software to render 3D objects, an increased number of questions, and the inclusion of distinct 'angular disparities' to more accurately track the progression of an individual's spatial abilities (i.e. 0, 50, 100 and 150 degrees) (Ganis and Kievit, 2015).

In the time following its creation, the MRT has been used to examine the impact that a variety of factors have upon spatial ability. Of the connections drawn, a prominent correlation with gender has received considerable attention. In short, when examining large group cohorts, males have continually been shown to outperform their female counterparts on the MRT (Vandenberg and Kuse, 1978; Voyer, Voyer and Bryden, 1995; Peters and Battista, 2008). This has been attributed to a higher innate visuospatial ability in males - though conflicting items of literature report that this may only be present for isolated geometric tasks, and that that in practical application the discrepancies between genders is diminished (Bouchard and McGee, 1977; Lufler *et al.*, 2012). Other factors that have partial correlation, and hence require consideration when interpreting MRT data, include: age, handedness, and prior exposure to the task (Peters, 2005; Peters, Manning and Reimers, 2007).

1.6 Neuroanatomical basis of learning

Progressing from the broader discussion of cognitive elements that facilitate 2D-3D interchange, consideration must now be paid to the precise neurophysiological apparatus that govern visuospatial comprehension and encode for subsequent recall. While there are a diverse number of anatomical features that contribute to this process (each firing selectively to provide a given function), recognition must be awarded to the presence of innate cognitive pathways that connect these structures, allowing the resultant conceptualisation to draw from each component in designing a refined output. By first exploring the general principles of how information is interpreted and stored within the brain, this section will explore the particular deviations that occur when the subject explicitly contains anatomical, artistic, or spatial content – as determined through both a diffuse array of neuroscientific investigations and specific imaging studies.

1.6.1 Principles of neuroscience that govern memory through learning

Within the context of learning any principle, whether it be through passive means or more focused instruction, consolidation of information to memory can be discussed in a variety of ways. Most notably this occurs in the classification of information being held in either short-term memory (also referred to as WM) or stored within long-term memory (LTM) (Baddeley and Hitch, 1974; Miyashita, 2004). While short-term memory is often discussed as a transient neuropsychological process of varying anatomical origin (see section 1.5 for further detail), it serves a non-separable ‘episodic buffer’ that acts as a precursor to encoding within

LTM (Baddeley, 2000). In this latter domain, encoding can be classified in adherence to whether information has been obtained through declarative means or not – where declarative is defined as being the intentional, conscious awareness of a prior experience (Kolb and Whishaw, 2003). Regardless of the category, LTM processing can be separated into three distinct phases: (i) initial acquisition, (ii) eventual consolidation, and (iii) potential retrieval (Lupien and McEwen, 1997).

Declarative:

Governing two distinct components, this form of LTM can be further divided into either: (i) Semantic memory – encompassing fact based knowledge that is independent of context or personal relevance (e.g. the name of a particular bone), and (ii) Episodic memory – those features which do possess an association with the individual (e.g. recalling a dissection) (Collins, 2007; Brem, Ran and Pascual-leone, 2013). Though they regard differing subconscious components, both memory types are consolidated within the hippocampus, a component of the limbic system located within the medial temporal lobe (Squire, 2004). Interestingly, when recalling information for use in WM it is found that semantic information is retrieved from the cortex itself - indicating a passive migration of information to expedite the relatively binary process, while the hippocampus itself remains as the primary store for episodic memory (Miyashita, 2004).

Nondeclarative:

Commonly referred to as implicit LTM, nondeclarative memory concerns the remembrance of procedural information as defined by whether it regards associative behavior (classical emotional conditioning) or does not (reflexes and cognitive routines) (Cohen and Squire, 1980). The aptly named procedural memory component regards sequences of learned skills (e.g. surgical dissection techniques) - and primarily utlises an output component of the basal ganglia called the striatum, as well as other subcortical motor centers (Klein, 2004). Particularly involved components of the striatum include the putamen, caudate and ventral striatum (inclusive of the nucleus accumbens) (Ferbinteanu, 2016; Valdés Hernández *et al.*, 2019). When considering associative memory (classical conditioning), guiding an individual's innate emotional response, neural sequencing is shifted to be mediated by another element of the limbic system (in close connection with the hippocampus) called the amygdala (Bianchin *et al.*, 1999; Yang and Wang, 2017). While for non-associative memory, concerning reflexive sensory activities (e.g. palpation and technique) encoding primarily occurs within the neocortex, an aspect of the cerebral cortex essential for decision making (Wiltgen *et al.*, 2004; Yamashita *et al.*, 2009).

Incorporating valuable components of learning into potential encoding of new knowledge within LTM is an understandably intricate task (Ghosh *et al.*, 2016). While discourse to this point has considered the sites for this uptake to occur, an equally important component is the interaction that takes places at a cellular (neuronal) level to facilitate these changes (Kolb and Whishaw, 2003). A natural starting position for this discussion is the relatively recent discovery of mirror neurons. This specialised class of neuron, located primarily within the premotor cortex (although also present in both the somatosensory and inferior parietal cortices), is integral in our ability learn new tasks (di Pellegrino *et al.*, 1992; Rizzolatti and Craighero, 2004). Specifically, activity of these neurons allows for the modulation between specific currently noticed activities and those motor acts which have previously been executed by the individual and encoded within procedural memory repositories (Kilner and

Lemon, 2013; Ferrari and Rizzolatti, 2014). As their name might suggest, mirror neurons were so named for their adaptive ability to recognise patterns in behavior, passively transferring understanding of an array of reflexive behaviors and emotional skills (e.g. empathy) (Iacoboni *et al.*, 2005; Baird, Scheffer and Wilson, 2011).

Considering the intrinsic biology of this encoding, a diverse number of neurophysiological phenomena have been attributed to the learning process. It's believed that these cellular changes are adaptive in nature, manipulating neuronal components to facilitate the conversion of short-term (WM) into LTM (Silva *et al.*, 1998; Miyashita, 2004). These adjustments can relate to the expression of already produced compounds, or possess further reaching capabilities in manipulating gene sequencing and subsequent protein synthesis. A chief orchestrator of this process appears to be a transcription factor that mediates the intracellular second messenger cyclic adenosine monophosphate (cAMP) called cAMP-response element binding protein (CREB) (Silva *et al.*, 1998; Josselyn *et al.*, 2001). Ubiquitous activation of this protein, coinciding with its overexpression within the aforementioned brain centers, is thought mediate LTM conversion (Wang *et al.*, 2018). While deficits in CREB expression have been attributed to poor information retention capacity, the implementation of extended and repetitive training sessions have been shown to counteract this insufficiency (Brightwell *et al.*, 2007; Kim *et al.*, 2013). This finding presents a hypothesis for human variability in recollection and ability to override this with additional focus.

An alternate compound, protein phosphatase 1 (PP1), possesses an inverse relationship with learning, with its expression acting as a constraint upon memory retention (Genoux *et al.*, 2002). This is thought to occur due to PP1 directly inactivating CREB protein molecules

(Silva *et al.*, 1998; Mauna *et al.*, 2011). Owing to residual components of synaptic transmission, higher circulating intracellular concentrations of calcium ions are present within active neurons (Muri and Knöpfel, 1994). These levels of this ion appear to inform PP1 activation, with higher volume inhibiting PP1 activation and inducing long-term memory potentiation (LTP) (Klein, 2004). Similar to those findings for the CREB protein, repetition of an exercise that is interspersed with active rest periods has been demonstrated to upregulate PP1 inhibition and induce greater LTP (Genoux *et al.*, 2002). When viewed together, LTP represents the improved synaptic efficiency of groups of neurons (Hodgson *et al.*, 2005). When a monosynaptic pathway is frequently stimulated, its response magnitude is increased and the delay in transmission reduced (Doyle and Andresen, 2001). Anatomically, this enhancement results in an individual neuron possessing a longer and denser dendrite – a cell component used to gather surrounding stimuli (Kolb and Whishaw, 2003). These structural changes occur not only in response to high stimulation frequency, but also possess a long-term pattern recognition ability – adapting to interspersed but common occurrences (Kasai *et al.*, 2010).

1.6.2 Specific processing of artistic/anatomical/visuospatial information

Shifting perspective to highlight the neural integration of a particular cognitive process, both the performance of non-specific visual arts activities and direct visuospatial processing have been shown to possess overlapping pathways in their capability for encode for deep neural integration (Tyler and Likova, 2012a). This sequence of consolidation accounts for previously discernible enhanced behavioural effects that accompany the implementation of these methods into a learning routine, including: heightened stimulation of visual cues, activating prior knowledge, improved academic grades, conversion of metacognition into prompt tacit (implied) intelligence, and the bolstering of overall knowledge retention (Nayak and Kodimajalu, 2010; Azer, 2011; Naug, Colson and Donner, 2011; Lyon *et al.*, 2013; Balemans *et al.*, 2016). This aids explanation of why certain facets of artistic methodology (e.g. observational drawing – as described in section 1.3) show a strong link with memory and motor control (Chamberlain *et al.*, 2014).

In correlating performance in drawing with functional sites of the brain, several areas have been identified for their diverging or over expressed activation as compared with general didactic forms of learning (Makuuchi, Kaminaga and Sugishita, 2003; Ferber *et al.*, 2007; Miall, Gowen and Tchalenko, 2009; Schlegel *et al.*, 2015). These differences can generally be compartmentalised into their occurrence within the respective lobes of the brain and accessory regions – broadly implicating: the frontal lobe for task processing, parietal cortex for visuospatial attention, occipital lobe for visual localisation, temporal lobe for spatial memory, and the cerebellum for motor memory and coordination (Eichenbaum *et al.*, 2016; Xia and He, 2017).

Parietal Cortex:

Through the use of various reconstruction techniques, research has implicated the parietal lobe of the brain as possessing an essential role in processing visuospatial information - simplifying a variety of multimodal inputs into a cohesive signalling pathway. Within this region, studies have highlighted activation peaks within both the superior parietal lobe (SPL) and intraparietal sulcus (IPS) when an individual is utilising this spatial ability (Gauthier *et al.*, 2002; Jordan *et al.*, 2002; Wu *et al.*, 2016). Specifically, within the IPS, this activation has been found to increase linearly when presented with an affording object or situation pertaining greater angular disparity (processing demand) (Tagaris *et al.*, 1996; Carpenter *et al.*, 1999). These sites are also implicated as centres for 3D mental rotation and conceptual transformations (Jäncke and Jordan, 2007). When this manipulation concerns the explicit motor operation of an individual (e.g. grasping an object), it is the anterior IPS which shows increased prominence (Binkofski *et al.*, 1999; Jäncke *et al.*, 2001). However, if the task is of a conceptual nature, this responsibility is handled by the posterior IPS, regulating operations such as: movement trajectories, cross-modal task matching, and internal body mapping (Bonda *et al.*, 1995; Seitz *et al.*, 1997; Banati *et al.*, 2000). Together, these anatomical regions are of vital importance in planning an individual's engagement with the surrounding environment (whether explicitly or implicitly), determining the mechanisms of potential manipulation (Jäncke and Jordan, 2007).

Frontal Cortex:

Though expressed in almost equal prominence to the parietal lobe for its involvement in spatial processing, the frontal lobe appears to be less consistent in the way it accomplishes this task. While the premotor areas of the cortex are unquestionable the epicentre for frontal involvement, distinct studies have implicated different subareas. For instance, some demonstrate bilateral activation within the ventral regions of the cortex, while others have noted this unilateral arousal in those more dorsal regions (Richter *et al.*, 1997; Thomsen *et al.*, 2000; Jordan *et al.*, 2001; Suchan *et al.*, 2006). Elements of the more centrally located supplementary motor cortex, namely the mesial premotor area, have similarly been noted for their importance in this processing (Gauthier *et al.*, 2002). Understandably, physical output relating to spatial orientation is conducted under the governance of the primary motor cortex - though the extent to which this is considered spatial planning, as opposed to simple motor execution, is contested (Georgopoulos, 2000).

Occipital Cortex:

In a similar vein to the frontal cortex, the occipital lobe is a crucial component of spatial processing that has considerable variation in the precise location and nature of how it facilitates this. Principally, voxel-based analytic methods have demonstrated increased activation of the extrastriate cortex is found to accompany physical rotation (Podzebenko, Egan and Watson, 2002; Vingerhoets *et al.*, 2002). This activation chiefly occurring within either the superior or inferior sub-categories of the extrastriate, with evidence also implicating the connecting occipital pole between them (Koshino *et al.*, 2005; Vorstenbosch *et al.*, 2013). Coinciding with previous discussion of the primary motor cortex, uptake in extrastriate regions has yet been conclusively linked to conceptual mental rotation (Jäncke and Jordan, 2007). Instead, it has been suggested that this action more directly concerns visuospatial attention demands, offering little input to conceptualisation (Seurinck *et al.*, 2004).

Temporal Cortex:

Though few in number as compared to other lobes of the brain, several studies have explored the potential for temporal activation throughout spatial planning. Featured most prominently in these findings, the inferior temporal gyrus has had both bilateral and unilateral activation attributed towards it during spatial reasoning tasks (Koshino *et al.*, 2005, 2005). In addition to this, imaging studies have isolated increased activity within the nearby inferior temporal cortex when task performance requires mental computation and rotation (Kanwisher, McDermott and Chun, 1997). This area is theorised to work in association with the IPS, with its activation increasing linearly in proportion to the extent of visuospatial processing required – this being determined through the progressive elimination of descriptive information in the presented stimulus (pictures) (Diwadkar, Carpenter and Just, 2000).

Work published in the popular 'Drawing on the Right Side of the Brain' paper that has entered mainstream popular culture stipulates that by switching into 'R-mode' (engaging with tasks associated with the right side of your brain) may quicken the process to mastery of a given style of drawing or other such creative outlet (Edwards, 1989). Though this work by Edwards was highly influential, the lack of underpinning in neuropsychological evidence in favour of subject derived metaphorical understanding discredits this claim from having a true basis in scientific reasoning. Subsequent neurological research, largely derived from clinical presentations of patients suffering disparate right and left-brain injuries, provided validity to this claim by outlining that the right hemisphere of the brain (particularly the right parietal cortex) is instrumental in facilitating spatial control (Voyer and Bryden, 1990; Chatterjee, 2004). As a substantial component of this system, it follows logically that mental rotation has similarly been localised to neural networks in the right hemisphere of the brain, though this process has shown to revert to the parietal lobe (anterior IPS) of the left side for mental rotation regarding the contortion of one's own body (Bonda *et al.*, 1995; Creem *et al.*, 2001; Cook and Smith, 2006).

As it directly relates to observational drawing, voxel-based morphological analysis has revealed an increase in grey matter density of the left anterior cerebellum, right frontal gyrus, and right precuneus to coincide with individuals possessing high aptitude or experience in drawing technique (Chamberlain *et al.*, 2014). At the opposite end of the spectrum, untrained beginners who underwent a structured drawing regime across multiple session were found to have a sustained increase in both right cerebellum activation and inferior regions of the right frontal lobe (Schlegel *et al.*, 2012). Thus, it appears that changes are not limited to the duration of the task performance, with structural neural changes resulting from long term artistic training over time. While this account for differences in behavioural motor output and higher order thinking throughout drawing, the extent to which this process is modified throughout an observational learning process, especially when incorporating greater elements of touch and haptics, has yet been elucidated.

1.6.3 Prior imaging studies

While discussion to this point has drawn correlation between anatomical sites of interest and their role in facilitating spatial processing, an important consideration is the instruments of neuroimaging technology that have allowed this information to be gathered. This modern technology, assessing an array of biophysical signals within the nervous system, provides us a window into the body that was only previously accessible through post-mortem dissection. By exploring neural pathways, a picture of functioning brain networks can be deduced through estimating the integration of signals between different regions of the brain at both a macroscopic and microscopic level. The combination of this information contributes towards further understanding of the ‘functional connectome’ (Sporns, Tononi and Kötter, 2005; Biswal *et al.*, 2010; Kelly *et al.*, 2012). Recent evidence has implicated the functional connectome as possessing specific organisational traits that either integrate or segregate systems of the body, including the re-shaping of cognitive ability in response to various disease states (Bullmore and Sporns, 2009; Petersen and Sporns, 2015; Cao *et al.*, 2016). Though a spectrum of technology exists, common apparatuses that dominate both clinical application and wider academic exploration include: functional magnetic resonance imaging (fMRI), positron emission tomography (PET) scans, and electroencephalography (EEG) (to be more comprehensively discussed in section 1.7).

Functional Magnetic Resonance Imaging (fMRI):

Following its initial development in 1990, fMRI technology has featured heavily in modern examination of neurophysiology - monitoring blood flow through neural spaces to establish the regional changes that occur in brain metabolism over a given timespan (Ogawa *et al.*, 1990; Kwong *et al.*, 1992; Zacks, 2008). This imaging technique works on the principle of nuclear magnetic resonance, generating a magnetic field to assess how the blood oxygen level dependency (BOLD) signal fluctuates in response to a given task, inferring activation and suppression of differing neural regions as a consequence (Lauterbur, 1989; Glover and Law, 2001). Providing increased temporal resolution, fMRI imaging is able to delve into the microscopic functional connectivity of the neural signalling pathways that exists between inter-regional levels of the brain at low frequency levels (i.e. 0.2-0.3 Hz) (Liao *et al.*, 2013).

A broad consensus of these imaging studies ratifies aforementioned information that the parietal lobe is particularly essential in spatial processing – with individual cells within the aforementioned anterior and posterior components of the IPS showing increased activity (Billingsley *et al.*, 2004; Kaufmann *et al.*, 2008). An example of method involves tasking participants with considering the spatial orientation of human facial features as opposed to geometric patterns – examining neural signals during initial conceptualisation, memory, and subsequent drawing when presented with a stimulus (Solso, 2001; Makuuchi, Kaminaga and Sugishita, 2003; Miall, Gowen and Tchalenko, 2009; Schaer, Jahn and Lotze, 2012).

Positron Emission Tomography (PET):

Emerging in parallel with fMRI, PET scanning possesses a wide array of applications that lend themselves to both primary healthcare investigations, and as a valuable tool in preclinical academic neurophysiology experimentation (Vaquero and Kinahan, 2015). The initial step in this technique is the injection of a biological tracing compound within the bloodstream (commonly a radioactive sugar called fleurodeoxyglucose). This compound contains the active short half-life radioactive isotope of a varying number of elements (e.g. oxygen). A scanning device located around the individual, specifically called a 'scintillator', then detects the positrons that are emitted from the radioisotope as it decays within the bloodstream (beta decay) (Hoffman *et al.*, 1981; Hooper *et al.*, 1996). Images are then commonly reconstructed using analytic techniques like computed tomography (CT) to provide an excellent time-locked representation of which areas of the body (e.g. neuroanatomy) are being selectively used in a given process (Lange and Carson, 1984; Kapoor, McCook and Torok, 2004).

This technology has been instrumental in understanding the progression of spatial processing, with a number of PET experiments being responsible for uncovering those elevations in motor areas within the frontal lobe of the brain (e.g. precentral gyrus) that coincide with performance of mental rotation tasks (Kosslyn *et al.*, 1998; Zacks, 2008). An instance of this includes the evaluation of neural responses that occurred follow participants being tasked with rotating objects that were either: (i) known to the individual through training exercises, or (ii) abstract and foreign (Kosslyn *et al.*, 2001; Wraga *et al.*, 2003).

Offering an additional point of reference to those established methods of evaluation, non-invasive brain stimulation (NIBS) is a piece of modern technology used to assess neural relationships. This machinery is able to activate synaptic plasticity within the cortex through pathways analogous to long-term potentiation and depression (Cooke and Bliss, 2006; Ridding and Rothwell, 2007; Huang *et al.*, 2017). Of the various forms of NIBS that exist, transcranial direct current stimulation (tDCS) has been shown to best represent changes in resting state functional connectivity (López-Alonso *et al.*, 2014; Hordacre *et al.*, 2017). One way to examine detrimental attention deficits following an insult to a particular region of the brain is through application of a 'virtual lesion' to participants of normal health using NIBS. This mechanism provides a means to inspect neural mechanisms that govern attention, through silencing neurons by adding external signalling 'noise' (Siebner *et al.*, 2009; Chamberlain *et al.*, 2014).

While data from fMRI and PET scanning techniques has the ability to be fast-sampled and allow the spatial localisation of any short or longer-duration fluctuations in cognitive architecture that might occur in response to a given stimulus, they provide little information about the nature of this behaviour (Hutchison *et al.*, 2013; Zalesky *et al.*, 2014). In contrast, electrophysiological techniques (i.e. EEG) can provide high temporal resolution capable of discerning whether the activation in a particular anatomical region corresponds to an excitatory or inhibitory response. Thus, these imaging strategies possess complimentary attributes when analysing dynamic fluctuation of the functional connectome, making their equal consideration a crucial component of neurophysiological investigations (Kramer *et al.*, 2011; Chu *et al.*, 2012). It is surprising then that while this collaboration is effective in uncovering holistic evidence of neural sequencing, auxiliary electrophysiological imaging studies qualifying visuospatial processing feature with little prominence in comparison to their spatial counterparts.

1.7 Electrophysiological indications of visuospatial processing

Having now discussed two of the three primary instruments in medical imaging used to evaluate human neurophysiology, attention turns this third means and how it harnesses a contrasting scientific approach to aid these aforementioned technologies. Though lacking ability to determine the involvement of distinct neuroanatomical structures, EEG monitoring is a preeminent exploratory method used to substantiate the nature of cortical excitability in response to a given stimulus. After first explaining the fundamental principles of this technique, this final section will provide coverage of the: (i) inherent advantages and constraints of this technology, (ii) common behavioural phenomena that have been associated with it, and (iii) prior evidence that signalling patterns can specifically discern the neural origins of spatial processing.

1.7.1 Principles of electroencephalography (EEG)

Electroencephalography (EEG) is a diagnostic technique that has steadily become entrenched within the fields of psychology and neuroscience in the 70 years following its initial development. A German psychiatrist, Hans Berger, is credited as first examining the principles of EEG in the early 1930’s – with these ideas being progressively built upon by clinicians with understanding of electronics throughout the remainder of the 20^{th} century (Berger, 1929; Adrian and Matthews, 1934). At its core, EEG examines the electrophysiological circuits that exist within the brain. This is achieved through detection of the oscillating ionic currents expressed by neurons in their communication (Srinivasan, Nunez and Silberstein, 1998; Michel *et al.*, 2004). An element of this process called volume conduction, whereby neurons exchange ions across their membrane, is detected by a series of metal electrodes. The exact force of ion movement at a neural level then exerts a corresponding push or pull effect upon the electrons of scalp-located electrodes, resulting in a detectable change in voltage. Recording how this electric potential energy fluctuates over time provides an EEG signal (Montgomery, Montgomery and Guisado, 1993). Though described in the context of a single cell, it is only the synchronous activity of large groups of neurons (thousands or millions) possessing the same spatial orientation that will be detected (Hjorth, 1991). This implicates a particular group of cells with perpendicular dendrites called ‘pyramidal neurons’ as being key contributors – ensuring that the resultant EEG signal represents the summation of neural activity within a distinct region across a given period of time (Kirschstein and Köhling, 2009). As the ability to detect voltage diminishes drastically with distance (adhering to an inverse square law), EEG is limited in its ability to examine deeper structures of the brain, instead being predominantly used to explore currents that occur closer to the skull (cortical regions) (Binnie, 2001).

It is a non-invasive technique, with conductive gel simultaneously anchoring those individual electrodes (often bundled together by a cap) to their required place on the scalp, and reducing impedance of the received signal (Lopes da Silva, 2013). A particular international system is used to align these electrodes, taking advantage of common anatomical landmarks (e.g. the positioning of a ground electrode on the central midline of the scalp) to ensure that results: (i) correspond to known location of interest, and (ii) are consistent across laboratories (Towle *et al.*, 1993). The number of electrodes used for a given investigation can vary depending on the scope and type of analysis being conducted - with some using as little as four, and others using in excess of 256. Regardless of volume, each electrode is independently connected to a differential amplifier that heightens its voltage, comparing this value with that obtained by the ground (reference) equivalent. The signal is then filtered using both a high-pass clean (to reduce movement artefacts) and a low-pass clean (to remove high frequency artefacts) (Srinivasan, Nunez and Silberstein, 1998). Lastly, the frequency of this signal is digitally down-sampled, typically only retaining the first 256-512Hz. The resultant EEG signal can then be further processed and manipulated by an individual to accurately meet the required research or clinical scope – including the more scrutinous removal of artefacts from data using software toolbox's such as EEGLAB and FieldTrip (Delorme and Makeig, 2004; Oostenveld *et al.*, 2010).

1.7.2 Applications of EEG

In considering the intrinsic electrical conduction patterns of the brain, EEG is able to provide a unique vantage point in the assessment of operating neurophysiology. This is particularly evident in the ability to retrieve extremely accurate temporal resolution (discrete sourcing of data with respect to time) as compared to other imaging methods (Michel and Murray, 2012). However, a significant trade-off occurs in the capacity to correlate this with spatial resolution (precise location of activity), and it is here that those aforementioned technologies (e.g. fMRI and PET) are able to provide clarification (Menon and Crottaz-Herbette, 2005). When used in conjunction, clinicians and researchers possess an ensemble of imaging techniques to accurately appraise neural patterns (Mele *et al.*, 2019). Other specific advantages of EEG lie in being: (i) significantly cheaper than other imaging techniques, (ii) silent – facilitating better study of auditory stimuli, and (iii) receptive to the performance of simple experimental paradigms (e.g. trial or block-design).

The primary clinical application of EEG is the diagnosis of epilepsy, having the ability to distinguish this condition from an array of similarly presenting conditions such as: syncope (fainting), migraine variants, and psychogenic seizures (non-epileptic) (Boesebeck *et al.*, 2010). This is achieved through monitoring the voltage readout of an EEG signal for the presence of interictal epileptiform discharges, a series of characteristic spike and sharp wave disturbances in normal tracing that occur across the cortex (predominantly in the midline regions) (Binnie, 2001; Kaplan, 2006). While the extent to which this marker is solely dependable for classification, with a series attributable phenomena being linked to interpretation, the discovery of this hallmark in an individual exhibiting behavioral symptoms of epilepsy serves as a requisite implication of the pathology (Benbadis and Tatum, 2003; Smith, 2005; Chen and Koubeissi, 2019). Outside of this direct function, analysis of EEG data tends to be divided into two broad categories: (i) event-related potentials (ERP's), or (ii) spectral content.

Event-related potentials (ERP's):

This component of EEG assesses the time-locked electrophysiological response that occurs following a stimulus. They are derived through the direct comparison of how an EEG signal (typically measured in millivolt amplitude) fluctuates across a dimension of time (measured in milliseconds). The resultant ERP trace will feature a series of positive and negative deviations in voltage current, developing a characteristic waveform structure with a series of constituent components (points of interest in this recording). These underlying components are known to correlate with a series of neural patterns with corresponding physiological behaviors (Carballo-Gonzalez, Valdes-Sosa and Valdes-Sosa, 1989). How the particular stimulus of an experimental design is able to affect this baseline wavelength pattern forms the basis of ERP investigations (Light *et al.*, 2010). Components are assigned a name according to two rules: (i) their polarity (whether their occurrence accompanies a negative or positive voltage peak), and (ii) the time (latency) or order in which they typically occur post stimulus presentation. For instance, the first characteristic positive peak in voltage occurs just prior to 100 milliseconds post stimulus – therefore being named P100 (or P1). Variance in the occurrence of these components has wide-spread applications in domains such as psychology and neuroscience – where fundamental aspects of cognition can be directly monitored by ERP recordings (Sur and Sinha, 2009). An example of this includes being able to determine the latency of visual stimulus detection in the occipital lobe, useful in attentional memory or concentration analysis (Potts, 2004).

Spectral Content:

For research requiring clarification on the nature of neural response to a given stimulus, accompanying its precise location in time, spectral content analysis is able to decompose EEG into a series of meaningful rhythms known to possess cognitive significance. Through computational processing, raw power of the signal (voltage) is decoded into five constituent frequency bands, with most activity of clinical significance occurring between 0-20Hz (Dressler *et al.*, 2004). While often presented as distinct regions of interest, it is important to note that overlap occurs between subsequent bands in performing a given function. A summary of these frequency bands and their known EEG correlations is as follows…

Delta (0 – 3 Hz) – Predominantly associated with slow-wave sleep and the detection of attention. It can be found in those more posterior regions of the brain in childhood, with this shifting forward in ageing (Harmony *et al.*, 1996; Harmony, 2013).

Theta (4 – 7 Hz) – Found present in the transition from awake consciousness to being asleep, heightened theta has also been correlated to emotional processing and concentration during memory tasks (Sammler *et al.*, 2007; Sauseng *et al.*, 2010a).

Alpha (8 – 14 Hz) – The earliest discovered and most diverse band, alpha has been implicated with an array of activities across the cortex. Examples include focused task response (with relaxation), inhibitory control, and visual detection (Sauseng *et al.*, 2010a; Toscani *et al.*, 2010).

Beta (15 - 30 Hz) – Referred to as a ‘background’ frequency, beta rhythms typically exert their maximal amplitude in frontocentral regions of the brain and have been associated with features such as drowsiness (Kullmann *et al.*, 2001; Neuper and Pfurtscheller, 2001).

Gamma (> 30Hz) – Linked extensively with the somatosensory cortex (posterior area of the frontal lobe), gamma is a difficult band to distinguish against the increased prevalence of EEG noise and artefact accompanying higher frequencies (Crone, Sinai and Korzeniewska, 2006). Cross-modal processing and short-term memory recognition are two associated features of this range (Schneider *et al.*, 2011).

1.7.3 Known EEG correlates of visuospatial attention and processing

As a point of critical assessment for the anatomical sites and associated neural activities uncovered in functional imaging studies, EEG technology has similarly been utilised to explore pathways of the human cortex that facilitate visuospatial processing. Coinciding with the formative psychological theories that are thought to mediate this operation (discussed in section 1.5), EEG analysis aim to quantify not only those neural activities directly involved in spatial processing and encoding, but also capture those reactive preparatory mechanisms that occur prior to stimulus onset (Di Russo *et al.*, 2021). While this latter component has seen continued exploration within literature (discussed throughout the remainder of this section), the extent to which direct visuospatial performance has been evaluated with this technology is limited.

In assessing this pre-emptive anticipation, a particular aspect of ERP's called 'contingent negative variation' is commonly used in spatial cuing tasks to measure the latency in time that occurs between an attentional 'warning' cue and a subsequent 'imperative' stimulus requiring response (Eimer, van Velzen and Driver, 2002). Understanding that this interval time is approximately 600-700ms allows researchers to qualify the aspects of neurophysiology responsible for actioning this spatial response – with mid-parietal and occipital regions being consistently implicated (Gómez *et al.*, 2004; Flores *et al.*, 2009; Simpson *et al.*, 2011). Alternative ERP studies have explored 'lateralised readiness potentials' to qualify any hemispheric differences in initiating voluntary hand movement (Coles *et al.*, 1985; Praamstra, Boutsen and Humphreys, 2005). When assessing more common elements of an ERP signal, these posterior elements of the brain (most notably the extrastriate cortex) show asymmetric fluctuation in their N2pc component (Hopf and Mangun, 2000; Fu, Greenwood and Parasuraman, 2005). This heightened negative amplitude occurs roughly 250-350ms following the presentation of a spatial stimulus requiring imperative action, and is thought to primarily reflect visual attention (Luck and Hillyard, 1994; Im *et al.*, 2007). Difficulty in spatial discrimination and orientation tasks is known to exacerbate this principle (Mazza, Turatto and Caramazza, 2009). Other notable ERP features include increased N100 and P100 amplitudes in the contralateral occipito-temporal region that follow visuospatial fixation events governing an effector hand (Heinze *et al.*, 1994; Johannes *et al.*, 1995). By pre-emptively shifting attention across the cortex, it is thought the brain can bias the efficiency of subsequent spatial control (Johannes *et al.*, 1995).

In alternative EEG studies assessing frequency domains, attention in spatial selective tasks has been strongly correlated with amplitude suppression occurring in the alpha range (Vázquez Marrufo *et al.*, 2001; Yamagishi *et al.*, 2003). This altered signaling has been localised to contralateral parietal regions (Worden *et al.*, 2000; Sauseng *et al.*, 2005). With alpha activity commonly attributed to suppressive effects in the cortex, these frequency findings support ERP work indicating an anticipatory inhibition over the unrequired hemisphere in spatial processing and a shifting of power to the associated one (Hummel *et al.*, 2002; Roijendijk *et al.*, 2013). In contrast, the higher frequency waves of beta signaling have been shown to increase in amplitude following the fixation of an attended visuospatial stimuli (Yamagishi *et al.*, 2003). Neural stimulation studies bolster their transient counterparts, outlining the sequential bursts of beta oscillation that occur in the contralateral sensorimotor cortex approximately 500ms after exploratory finger movements are made (Salenius *et al.*, 1997; Neuper and Pfurtscheller, 2001). To confirm these results are not specific to gestural movements of the upper limb, alternative studies have similarly noted this beta synchronization occurring in mid-central brain regions following spatial re-orientation in anatomical sites such as the foot (Pfurtscheller *et al.*, 2000). While even higher oscillations within the frequency range have shown little correlation with direct visuospatial planning or execution, some evidence indicates gamma amplitude modulation in in the primary visual cortex and wider ventral stream as being correlated with spatial attention (Magazzini and Singh, 2018).

Within smaller frequency domains, synchronization of inter-regional theta oscillations has been demonstrated to elevate during WM processes (Sauseng *et al.*, 2010a). This is thought to reflect the focusing of brain attention to enable successful encoding of memory, emanating from long range frontoparietal connections (Moran *et al.*, 2010; Sauseng *et al.*, 2010b). More recent studies have isolated theta connections between the left postcentral gyrus and the right precentral gyrus as being particularly pertinent in integrating visuospatial specific WM, with low theta amplitude predictive of poor capacitance (Corbetta *et al.*, 1993; Muthukrishnan *et al.*, 2016). Though not featuring as a prominent indicator of spatial processing, delta frequency expression is known to coincide with the facilitation of mental rotation (Fernández *et al.*, 1995; Harmony, 2013). While as yet directly attributed to delta regulation, increased presence of the frequency often accompanies those cognitive processes requiring internal manipulation (Harmony *et al.*, 1996).

1.8 Summary

The capacity for visuospatial directives to elicit academic benefits and greater three-dimensional awareness when implemented into anatomical curricula has led to abundant research identifying the intrinsic components that facilitate this. In particular, the ability for these integral spatial attributes to alter neural signaling in their induction of greater attention and subsequent memory encoding poses an alluring opportunity for educators. While substantial emphasis has been placed upon exploring the neuroanatomical sites involved in mediating this process, a descriptive link with the nature of activation in these regions has yet been established. Electrophysiological recordings are able to provide this resolution, with seldom few prior studies having explored neural correlates involved in direct spatial manipulation. By first continuing to isolate whole-class advantages present in visuospatial education, experiments within this thesis aim to develop a further understanding of the cognitive pathways harnessed by an individual when employing this approach.

CHAPTER II

Visual observation and drawing in anatomy education: experimental findings resulting from its inclusion

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By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);
ii. permission is granted for the candidate in include the publication in the thesis; and
iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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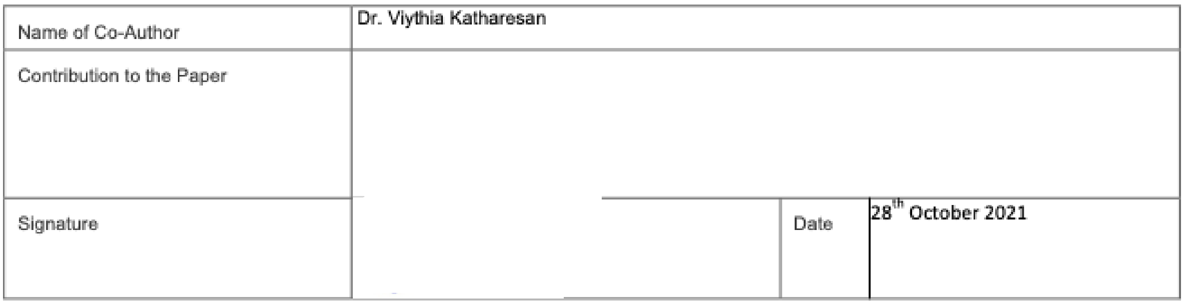

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2 Visuospatial observation and drawing in anatomy education: experimental findings resulting from its inclusion.

2.1 Abstract

Educational methods that champion visuospatial (VS) observation and drawing have been reported to enhance a variety of student outcomes. To further explore the benefits present for these approaches, we delineated the delivery of novel neuroscientific content provided within a large first-year anatomical cohort ($n = 344$). Students were assigned randomly into either of two laboratory groups featuring identical content coverage delivered in varying ways: (i) Traditional (Trad) – featuring a lecture and prosection observation, or (ii) VS – featuring a lecture with accompanying drawing instruction. Following education delivery, students were given the opportunity to demonstrate specific knowledge gained throughout the session, as well as provide written feedback regarding their perception of the method delivered. In assessing the academic components of these results, a significant increase was seen in overall performance of the VS Group (MD = 1.36, $p = < 0.0001$) - with equal gains in spatial, didactic, and extrapolation ability. In analysing this data, no evidence was found to support that a novelty effect was present, with roughly equal enthusiasm being reported for either experimental session (Trad = 4.16 ± 0.06, VS = 4.09 ± 0.05). The VS group also reported a desire for incorporation of VS methods within curriculum design (MD = 0.18, $p = 0.047$). Despite elevations in achievement, the VS Group members reported a lower amount of perceived engagement (MD = 0.25, $p = 0.002$) Taken together, these findings promote the inclusion of focused methods of VS drawing in supplementing the established approaches of anatomical curriculum design.

2.2 Introduction

Visual representations have long been utilised in informing human exploration and understanding. Our earliest recorded production of art is exhibited as collections of rock-paintings found in a multitude of locations across the world. These include renowned sites at Chauvet in France and the Pilbara region in Australia, which can be dated to have been created approximately 40,000 years ago (Blum, 2011). Complexity and style of visual representation developed steadily until the 16th century, where renaissance period artists such as Leonardo da Vinci established a catalogue of anatomical depictions that began to specifically inform medical comprehension (Calkins, Franciosi and Kolesari, 1999). Andreas Vesalius' 16th Century anatomy publication, '*De Humani Corpis Fabrica Libri Septum'*, offered an exploration of internal human anatomy that would act as a catalyst to inspire peers to document their own examination of human form (Lasky, 1990; Perloff, 2013; Ghosh, 2015). This affinity for artistic practice in anatomical education remains today, with an increasing number of methods striving to guide healthcare students from their initial anatomical understanding to direct patient care outcomes (Ione, 2009; Nayak and Kodimajalu, 2010; Naug, Colson and Donner, 2011).

Owing to this long-standing connection between the two fields, study of the exact nature and precise mechanisms that underpin this association between the visual arts and anatomical education have seen an emergence in contemporary scientific literature. A qualitative analysis found that engagement and participation within a medical student cohort was increased when additionally supported with a sketch-based artistic method in anatomy teaching (McMenamin, 2008; Bell and Evans, 2014). Supporting this, the novel inclusion of supplementary visual-arts exercises - e.g. paper drawing (Nayak and Kodimajalu, 2010), screencast drawing (Greene, 2018a), and body-painting (Jariyapong *et al.*, 2016) - have been found to successfully break repetitive aspects of anatomical course delivery, raising cohort levels of enthusiasm, enjoyment and understanding (Hake, 1998; Ward and Walker, 2008; Davis, Oliver and Byrne, 2009; Backhouse *et al.*, 2017).

Furthermore, medical students receiving supplementary artistic guidance in their learning have been correlated to display enhanced skills in observation and interpretation of character expression (Bardes, Gillers and Herman, 2001; Shapiro, Rucker and Beck, 2006; Schaff, Isken and Tager, 2011). It could be argued that these learning techniques also foster the professional skills development such as empathy within clinical settings. It is hypothesised that the adaptive learning process gained through guided artistic approaches is based on principles of metacognitive, cognitivist, and experiential education theory (Kolb, 1984; Catterall, 2005; Ausubel, 2012). This entails students' reflection on their initial creation, followed by further reflection through interpersonal collaboration. It is this incorporation of self-directed activities within prescribed education modalities that appears crucial in developing robust foundational knowledge that remains vital/crucial/relevant to long-term practice (Rodenhauser, Strickland and Gambala, 2004; Catterall, 2005; Eagleton, 2015; Choi-Lundberg *et al.*, 2016). In the case of artistic practice, this self-directed component can be derived from a variety of sources including e-learning platforms (Ruiz, Mintzer and Leipzig, 2006), drawing (L. Shapiro *et al.*, 2020), and sketching (Choules, 2007).

In examining the implementation and utilisation of visual arts methods within tertiary anatomical education, it is important to compare the distinct methods by which this information is delivered. Though this can vary greatly between institutions, common curriculum items include: lectures, laboratory visits and dissection of human cadaveric material. When considering the most course-specific of these methods *viz*. dissection, the array of benefits become apparent. By facilitating a transparent interface between medical educators and their students, practical knowledge is able to be delivered through viewing and interacting with the human form (Dyer and Thorndike, 2000; Biasutto, Ignacio Caussa and Esteban Criado del Río, 2006; Keenan and Ben Awadh, 2019). This method is however accompanied by some significant shortcomings, namely: demands on faculty time (McLachlan and Patten, 2006), the requirement for specialised facilities to teach with preserved specimens safely (Aziz *et al.*, 2002; Boulware *et al.*, 2004), and the negotiating of ethical limitations surrounding body-donation (Richardson and Hurwitz, 1995; Naug, Colson and Donner, 2011).This culminates in contrasting student perception of the use of dissection within gross-anatomical education. While heightened enthusiasm is commonly found to accompany the method, students also acknowledge that coinciding time-constraints can reduce overall enjoyment and diminish knowledge absorption (Lempp, 2005; Davis, Oliver and Byrne, 2009). With this duality in mind, supplementing dissection with a visual arts directive may potentially balance overall student enthusiasm with a more time-effective means of delivering anatomical content (de la Croix *et al.*, 2011).

In optimising a succinct method by which tertiary anatomical education can be developed, it has been suggested that we examine methods currently used across curricula and aim to carefully and appropriately pair: (i) traditional forms (e.g. lecture/cadaveric-teaching), and (ii) modern technology (e.g. imaging capabilities, interactive multimedia) (Sugand, Abrahams and Khurana, 2010; Keenan and Ben Awadh, 2019). It is in bridging these two distinct modalities that artistic methods are thought to be of most benefit, specifically a targeted design strategy titled ‘visuospatial (VS) observation’ (Miyake *et al.*, 2001; S. Reid, Shapiro and Louw, 2019; L. Shapiro *et al.*, 2020). Of the artistic methods proposed to enhance anatomy teaching, VS observation and drawing has been advocated most prominently within academic literature (Pandey and Zimitat, 2007; Nayak and Kodimajalu, 2010; Naug, Colson and Donner, 2011; Jasani and Saks, 2013; Balemans *et al.*, 2016; L. Shapiro *et al.*, 2020). This method has shown ability to foster tangential understanding - channelling initial conceptualisation into long-term memory and application (Collett and McLachlan, 2005; Ainsworth, Prain and Tytler, 2011; Moore *et al.*, 2011; Naug, Colson and Donner, 2011; Balemans *et al.*, 2016; Langlois *et al.*, 2020). The primary advantage of VS observation appears to be in upregulating the interchange between two-dimensional (2D) observation and three-dimensional (3D) understanding; an essential skill in the interpretation medical imaging and histological examination, but also more broadly in relating the mostly 2D information presented within textbooks into clinical practice (Keenan and Powell, 2020; L. Shapiro *et al.*, 2020). Likewise, with increasingly sophisticated modes of anatomy presentation and education delivery (e.g. virtual and augmented reality), it is important that students are able to reverse this process and mentally convert 3D anatomy back into the 2D representations that dominate text learning. Additionally, it is important that students improve their spatial awareness so that they might extrapolate a 2D image to its specific location within the volume of anatomy. As a directive, the method is less concerned with recreating a ‘photographically accurate’ image of the human form - instead it prioritises student consideration of the 3D structure of an anatomical part through observation, and subsequent inference of its importance in human physiology (L. Shapiro *et al.*, 2020).

The current study builds on evidence outlined above indicating that improved learning outcomes and student satisfaction will follow a structured VS program featuring observational drawing. By designing two distinct workshops that cover identical anatomical content, we explored (1) whether a VS drawing directive could elicit any academic or associated engagement improvements across a large undergraduate student group, and (2) if any components within student learning preferences (styles) might predict the aforementioned performances. We hypothesise that the focussed VS directive will heighten immediate knowledge retention amongst the student cohort, and that will best relate to individuals reporting VS methods to be engaging.

2.3 Materials and Methods

2.3.1 Ethical assessment

This study was approved by The University of Adelaide ethics committee (H-2018-060). An online announcement notifying the HB students of the proposed practical class intervention included a hyperlink to a detailed supplementary information sheet and encouraged students to raise any concerns or questions via email or telephone contact. On the day of the experiment, students were reminded of the voluntary nature of their contribution, and that resultant submission would constitute their (1) written consent of participation and (2) permission to evaluate task performance. To ensure anonymity, no qualifying questions of identity were present in the material. Students were not alternatively advantaged or disadvantaged for having been placed in either experimental group, with all material being placed online following the study date, and relevant examinable content being covered in proceeding course lectures.

2.3.2 Participants

The Bachelor of Health and Medical Sciences (BHMS) degree offered at The University of Adelaide is a three-year undergraduate degree aimed at equipping graduates with a fundamental understanding of human anatomy and public health. A compulsory first-year course within this degree is Human Biology (HB), which spans the entire academic year as either first-semester Human Biology 1A (HB1A) or second-semester Human Biology 1B

(HB1B). The course is structured to allow for all BHMS students to undertake HB, as well as some who are studying for a variety of alternative bachelor’s degrees (e.g. psychology) that ultimately wish to complete a major in a health discipline (e.g. neuroscience). The majority of students enrolled are school-leavers aged 17-19 years of age, with approximately 5% of the cohort being aged above 25 years of age, and the cohort possesses a roughly equal gender distribution.

HB is comprised of several distinct modules that aim to provide students with an introduction to the anatomical structures and physiological functions of the human body. More specifically, HB1A’s curriculum includes an introduction to the musculoskeletal, bone, nervous, reproductive and endocrine systems. Education is delivered through lectures, tutorials and fortnightly practical (laboratory) sessions over the semester. These practical sessions aim to apply theoretical knowledge to its practical environment. Practical sessions are held in a large dissection laboratory at The University of Adelaide, and run for an hour. Students can enrol in one of five sessions held throughout the day, with a maximum allowance of 100 students in each. By dividing students into smaller working groups, they are able to visit a series of stations in turn, each of which highlighting an aspect of anatomical material from the previous fortnights teaching module. These stations are led by experienced demonstrators who promote interactive learning using a variety of resources, including: whole-body cadaveric material, prosections, 3D anatomical models and histological images.

2.3.3 Study design

Students were notified of the studies implementation within the HB1A course two weeks ahead of time, and made aware that it was on a purely voluntary and anonymous basis (see ‘Ethical Assessment’ section below). In accordance with HB1A curriculum rules, students were required to attend their designated laboratory session. On this occasion, the session was comprised of two components, the first being a mandatory revision of material from the current course module, followed by the optional latter part (study conduction).

In accordance with the educational programme they would receive, students were separated into two experimental groups: (1) Traditional (Trad), or (2) Visuospatial (VS). This was accomplished in accordance with the following rule: if a student's unique university identification number was odd, they were placed in the VS Group, and if it were even they entered the Trad Group. This identification number is randomly assigned by the university upon the student's initial enrolment, and for our purposes, ensured that each experimental group was made up of a diverse cohort when comparing factors such as entrance scores, age, gender, etc.

Following the completion of the mandatory HAPIA component of the laboratory session, students were reminded of the nature of the study and provided with the opportunity to leave. Students who elected to stay were divided into those two aforementioned groups, each of which departing to a different but identical nearby laboratory to complete the experiment. Each individual was then provided an anonymous eight-page handout, comprising: three blank-pages (for drawing/note-taking), a three-page question set, and a two-page questionnaire document. The study then commenced, observing the following delineations in task design (Figure 1).

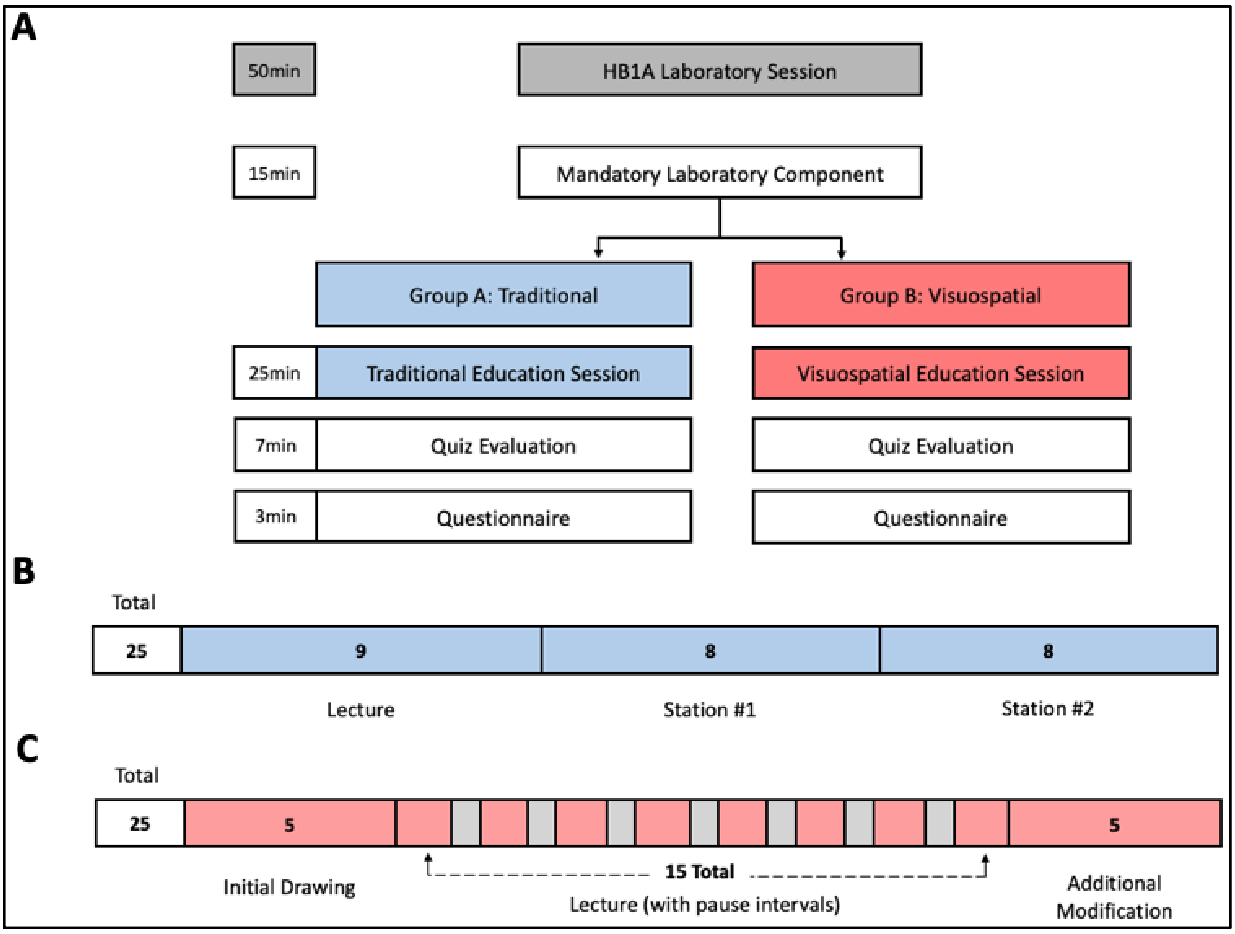


Figure 1: *Schematic overview of experimental design. (A) Flowchart outlining the core components and corresponding time allocated for each laboratory session. (B) Timeline outlining the specific breakdown of activities performed by the Trad Group. (C) Timeline outlining the specific breakdown of activities performed by the VS Group. Numbers within timelines (B) and (C) indicate the time allowed.*

Traditional (Trad):

To begin the session, a video lecture outlining relevant neurological content was played. Students were then separated randomly into two sub-groups and positioned around either of two corresponding workstations. Station #1 contained a series of brain and spinal cord prosections, accompanied by a demonstrator who guided students through the material and only clarified information contained within the prior video. Station #2 featured an array of anatomical models that could be constructed or dismantled to emphasise the three-dimensional forms of their relevant neuroanatomy. Students were allowed several minutes at their initial workstation, before the sub-groups switched to allow equal viewing. Throughout each phase of the session, students were instructed to develop notes and build-upon them throughout the ensuing activities. To conclude, students were seated apart from one another and completed the quiz and questionnaire documents.

Visuospatial (VS):

To begin, these students were instructed to view, physically interact with, and ultimately draw/sketch a representation of what they saw from a variety of relevant neurological (brain and upper spinal column) models that had been placed amongst the laboratory at a 1:2 model to student ratio (encouraging sharing). This introduction was devoid of content delivery, or the need to annotate the drawings being generated, and existed simply as a chance to observe the form of these structures. Following this, as with the traditional group, students viewed an introductory video lecture covering an introduction to the nervous system. This video contained identical content to the aforementioned group, however with the addition of short-breaks between the delivered material.

Students were instructed to use these breaks to: (1) add to, (2) alter and (3) label their drawings in light of the specific anatomical content being delivered on-screen as well as the relevant models being continually viewed. Following this lecture, students were given several minutes to make final considerations to their creations, before they were seated apart from one another in order to complete the quiz and questionnaire documents.

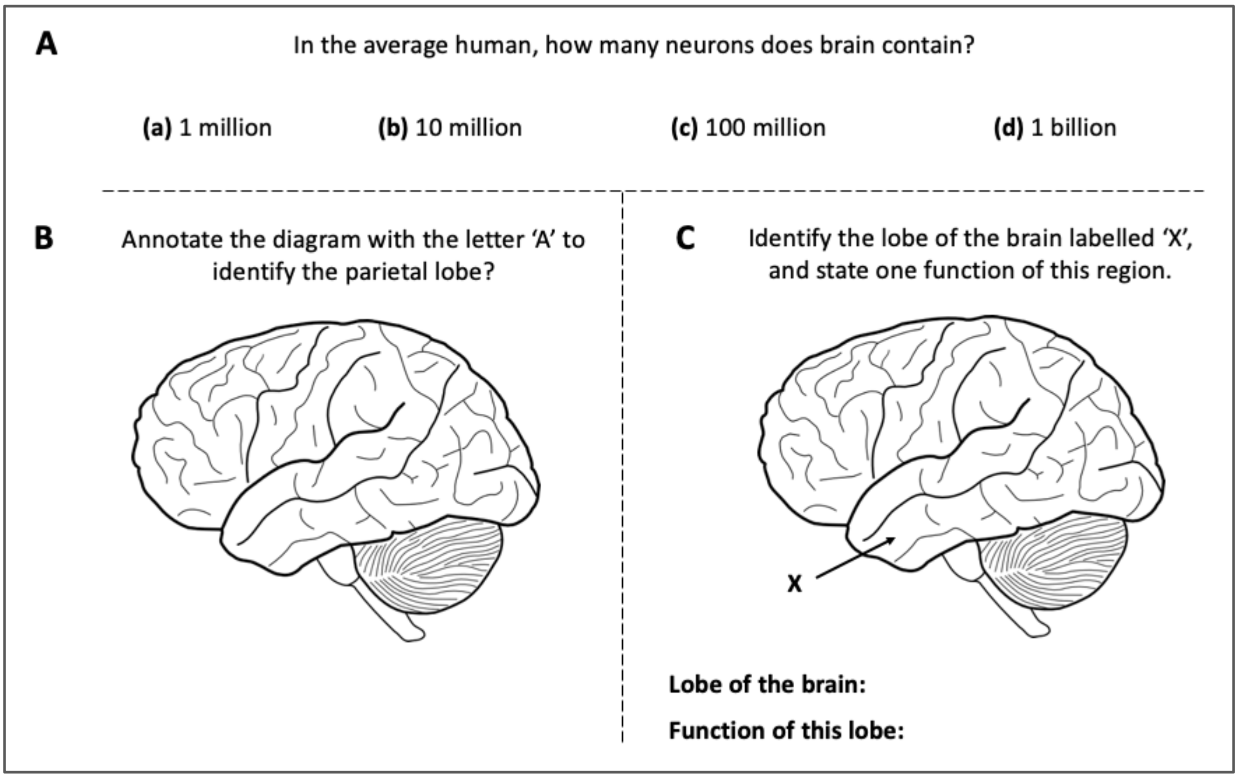
Five HB1A laboratory sessions were run across the same day at varying times. The experimental design was implemented within each of these sessions, thereby accessing the entire cohort of students. Average attendance for each session was 70 students, providing a group of approximately 35 participants in each group per session. The total duration of each session was 50 minutes.

2.3.4 Assessment material

To ensure that assessment materials represented a balanced and consistent platform that allowed for appropriate comparison, researchers were assisted by an Education Specialist Assoc Prof. Edward Palmer in the design process. This content was formulated and workshopped according to pedagogy, before being finalised in a small-group ‘face- and construct- validity’ pilot.

Quiz Evaluation:

The academic evaluation comprised twenty-marks and was administered identically between groups. It was comprised of three different components, each aiming to evaluate a specific element of anatomical understanding from material presented throughout the session (Figure 2). In the first component, students were asked to recall a series of *didactic* facts that had been delivered throughout the lecture (Fig 2A). The second section aimed at examining knowledge regarding those 3D *spatial* aspects of the material (Fig 2B). Lastly, the third component assessed understanding of material that had been *extrapolated* from provided content without explicit explanation (Fig 2C).



A In the average human, how many neurons does brain contain?

(a) 1 million **(b)** 10 million **(c)** 100 million **(d)** 1 billion

B Annotate the diagram with the letter 'A' to identify the parietal lobe?

C Identify the lobe of the brain labelled 'X', and state one function of this region.

Lobe of the brain:

Function of this lobe:

Figure 2: *Example of the different components assessed within the quiz evaluation. (A) Recollection of didactic facts. (B) Requiring additional spatial manipulation. (C) Ability to extrapolate information.*

Questionnaire:

The eight-point questionnaire provided students with an opportunity to reflect on and share their insight into their own learning styles, teaching modalities in general, and the experiment overall.

Response to the initial five points was provided through a five-point Likert style format (with options ranging from ‘strongly agree’ to ‘strongly disagree’), with an opportunity to provide additional comments.

(1) Overall, the session was informative and well structured.
(2) In addition to lectures and tutorials, supplementary learning resources (e.g. academic papers, YouTube video links, quizzes etc.) should be made available to students studying Human Biology.
(3) Visuospatial methods of learning (e.g. drawing/sketching/clay modelling) are engaging.
(4) Visuospatial methods of learning should be included in the HB1A curriculum.
(5) I enthusiastically participated in the learning activities during today’s laboratory session.

The next question was provided with a list of suggested options, allowing space for alternative responses below.

(6) Which of the following resources (select all that apply) have you used as part of your study routine throughout HB1A?

With the options available: lecture recordings, lecture handouts, laboratory and tutorial handouts, recommended (or equivalent anatomy and physiology) textbooks, Supplementary reading materials (e.g. journal papers, other textbooks), Specimens from the anatomy museum, Videos (including YouTube), Engaging in a focused drawing regime other than copying figures/diagrams, Audio recordings (including podcasts), Peer Assisted Student Support (PASS) program, any other resource (please list).

The last two questions allowed an open response.

(7) Which feature of today's laboratory session improved your understanding of the topic the most?

(8) Which feature of today's laboratory session improved your understanding of the topic the least?

2.3.5 Video production

To ensure that the same information, direction and cues were provided to students within each experimental group, a pre-recorded video of lecture quality was made. A regular demonstrator in the HB1A curriculum (who was independent to the study group) was commissioned to provide the voiceover for this video and best simulate a routine laboratory scenario. Care was taken to ensure that vocal tone, voice inflection and overall enthusiasm was consistent with authentic material presented within the HB1A curriculum. The video was divided into two components: (i) an introduction outlining the tasks to be completed and (ii) a lecture covering content from a yet to be taught module of the HB1A curriculum, 'Introduction to Neuroscience'. Though both groups received the same lecture with identical content delivery, the VS Group's version differed at two points. First, there were intermittent pauses throughout, with text prompting students to add gained knowledge to their drawings – (see 'Study Design' above). Additionally, the VS Group received an introductory slide that highlighted preferred drawing practises.

2.3.6 Data analysis

Statistical analyses were performed using *GraphPad Prism* version 9 software. Unless otherwise stated, calculated values are indicative of the mean and accompanying standard error (SEM). Significance was likewise conventionally reported as $^{a}p < 0.001$***, $^{b}p < 0.01$**, $^{c}p < 0.05$*. Each element of quantitative statistical analysis was first guided by classifying relevant data groups for their adherence to either parametric or non-Gaussian distribution through performing Shapiro-Wilk tests and viewing histogram plots. To compare between-group differences in academic performance both overall and within each constituent sub-category, we employed the separate use of either: (i) a Mann-Whitney U-test for non-parametric behaviour, or (ii) an unpaired (student's) t-test for parametric. These analyses were conducted and presented separately, so as to negate positive inflation error.

To gauge questionnaire response, the five potential Likert-scale options were converted to numerical values as follows: "Strongly Agree = 5", "Agree = 4". "Neutral = 3", "Disagree = 2", "Strongly Disagree = 1". As with academic scores, normality was determined for each data set before group response was compared using the correct unpaired analysis. For the specific questionnaire item, 'enthusiasm', we elected to separate students into their appropriate overall academic performance band (Below 10, 10-12, 12-14, 14-16, 16-18, 18-20). To establish if a linear trend was present between 'enthusiasm' response and grade achieved for either group, a set of simple linear regressions were employed.

A series of 2x2 chi-square (χ^2) analyses then compared prevalence of learning strategies reported to be used amongst students within each group. For each strategy listed, this binary test divided participant responses into two categories – 'number of students reporting use' and 'number of students not reporting use'. To mitigate any issues associated with low expected count frequency, resultant χ^2 analyses were performed using Yate's continuity correction. Prevalent favourability themes were identified by categorising student open responses into a variety of classifications related to experimental design. Within each group, the top three ‘favourite’ and ‘least favourite’ results were then qualitatively ranked according to their occurrence.

2.4 Results

2.4.1 Academic performance

To investigate differences in performance across the administrated academic test, an analysis compared overall marks obtained (Figure 3).

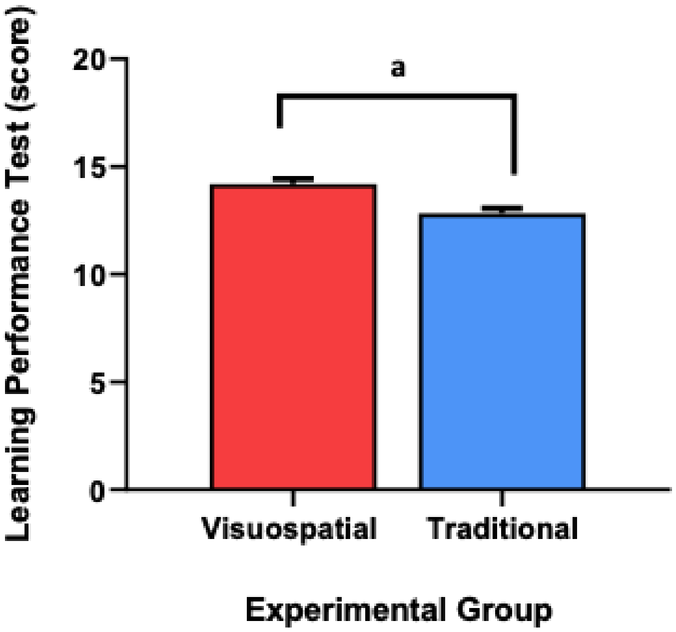


Figure 3. *Mean group score difference between performance on the academic test.* $^{a}p < 0.001$****.*

Analysis outlined a significantly higher mean score achieved by students in the VS Group (MD = 1.36, u = 11495, n_1 = 176, n_2 = 168, p = 0.0004). To understand if this increase coincided with a particular sub-category of the academic test, secondary investigations qualified scores in the underlying question styles: (i) Didactic, (ii) Spatial, and (iii) Extrapolated (Figure 4). Significant elevations in VS Group performance were observed in each of these subcategories: didactic (MD = 0.32, u = 13112, n_1 = 176, n_2 = 168, p = 0.02) (Fig 4A), spatial (MD = 0.66, u = 12820, n_1 = 176, n_2 = 168, p = 0.005) (Fig 4B) and extrapolation (MD = 0.39, u = 12642, n_1 = 176, n_2 = 168, p = 0.003) (Fig 4C).

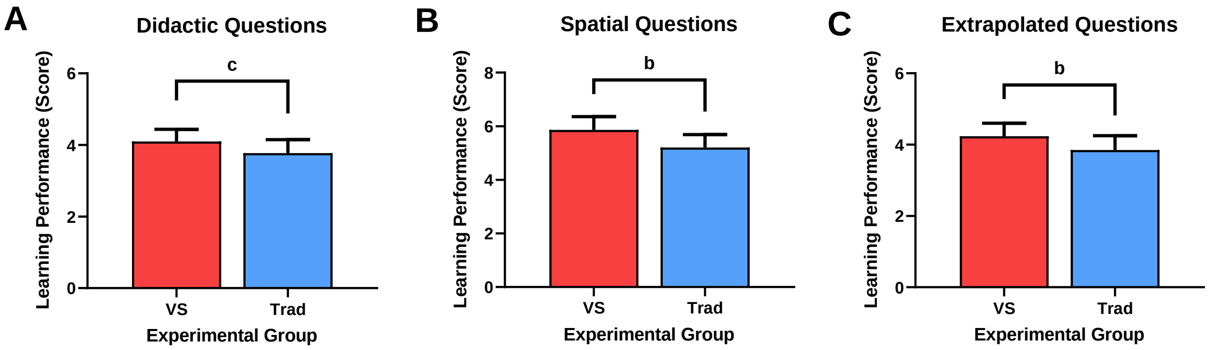


Figure 4. *Mean group score difference between performance on the different components of the academic test. (A) Didactic questions. (B) Spatial questions. (C) Extrapolated questions.* $^{b}p < 0.01^{**}$, $^{c}p < 0.05^{*}$.

2.4.2 Questionnaire response

To examine if any differences were present across questionnaire items, a collection of analyses were used to compare group response to each of the five questionnaire items (Table 1). These results are also described graphically in Figure 5.

	Traditional		**Visuospatial**		
Question	M	SEM	M	SEM	Statistics
Informative – Overall, the session was informative and well structured.	4.05	0.06	4.04	0.05	df = 342 t = 0.12 p = 0.10

Supplementary – In addition to current material, further learning resources should be made available in HB1A.	4.53	0.05	4.58	0.05	MD = 0.05 $u = 13839$ $p = 0.27$
Engagement – Visuospatial methods of learning (e.g. drawing/sketching/clay modelling) are engaging.	4.36	0.06	4.11	0.05	$df = 342$ $t = 3.17$ $p = 0.002$
Visuospatial – Visuospatial methods of learning should be included in the HB1A curriculum.	4.09	0.07	3.91	0.06	$df = 342$ $t = 1.99$ $p = 0.047$
Enthusiasm – I enthusiastically participated in the learning activities throughout the laboratory session.	4.16	0.06	4.09	0.05	MD = 0.07 $u = 14045$ $p = 0.39$

Table 1. *Mean differences between groups in response to questionnaire items. Likert score range where 'strongly disagree' corresponds to a value of 1, and 'strongly agree' to a value of 5.*

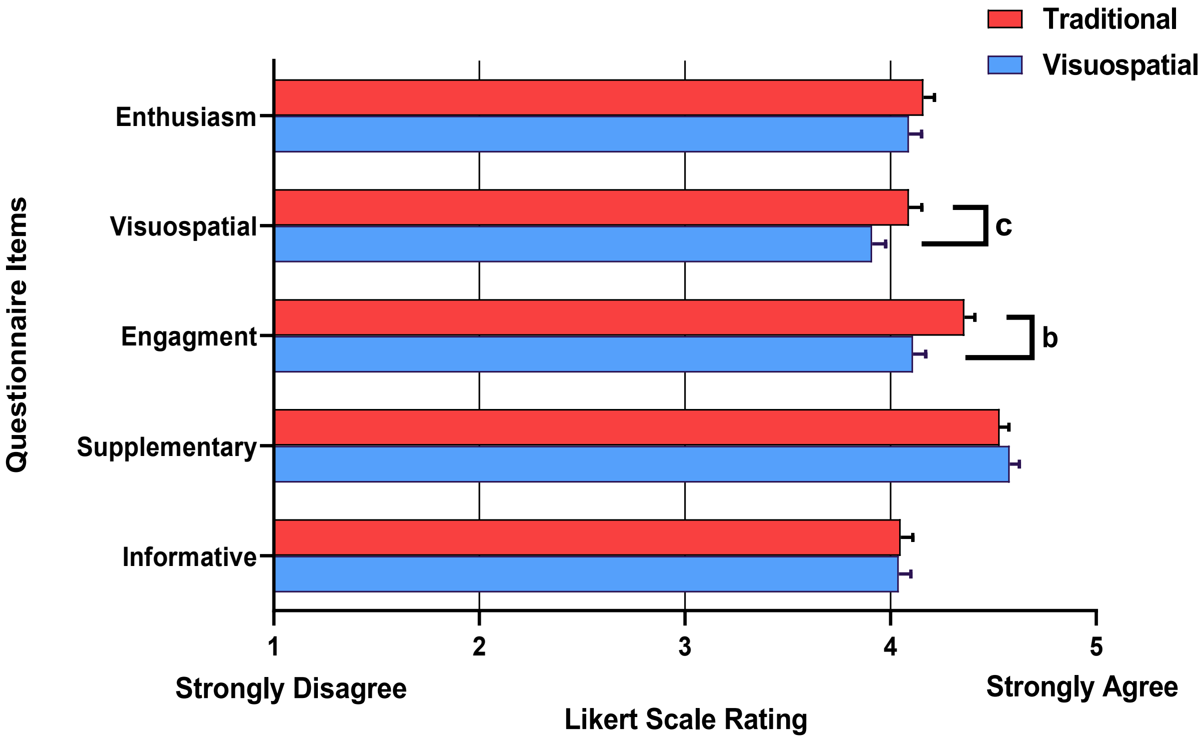


Figure 5. *Mean difference between groups in response to questionnaire items. Titles are abbreviations from those questions expressed in full within Table 1. Likert score range where 'strongly disagree' corresponds to a value of 1, and 'strongly agree' to a value of 5.* $^{b}p < 0.01$***,* $^{c}p < 0.05$**.*

Two questions yielded significantly different responses between the groups. In both cases, it was the Trad Group reporting stronger agreement than their VS counterparts – to questions assessing (i) the perceived engagement of VS methods (MD = 0.25, *df* = 342, *t* = 3.17, *p* = 0.002), (ii) whether VS methods should be included within anatomy curricula (MD = 0.18, *df* = 342, *t* = 1.99, *p* = 0.047). Remaining comparisons between question items showed no significant difference between groups in regard to the: session being informative (*p* = 0.10), addition of supplementary material (*p* = 0.27), and enthusiasm of session participation (*p* = 0.39).

2.4.3 Correlation between enthusiasm and outcome

To examine whether those academic benefits associated with the introduction of the novel VS design were clouded by corresponding increases in enthusiasm, we utilised a linear model and accompanying analyses to explore differences between groups (Figure 6).

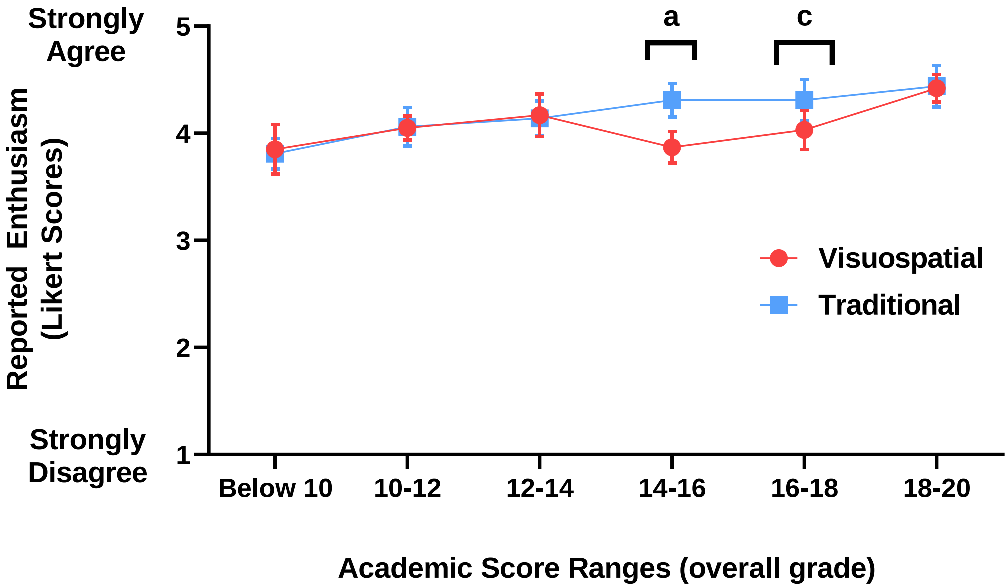


Figure 6. *Linear model exploring the correlation between an individual's response to questionnaire item 'Enthusiasm' and academic grade achieved.* $^{a}p < 0.001$***, $^{c}p < 0.05$*.

Overall, there was a strong observable overlap between groups in the reported degree of enthusiasm within each corresponding academic band. This trend indicated that as student academic performance increases, a higher level of perceived enthusiasm is reported throughout the experimental session. This is particularly evident in the Trad Group, where a moderate positive linear correlation was noted (F(1, 1054) = 64.64, $r^2 = 0.66$). Discernible differences between groups lay only in the significantly lower enthusiasm reported by the VS Group within mid-range academic scores 14-16 (MD = 0.44, *df* = 342, *t* = 6.42, *p* = < 0.001) and 16-18 (MD = 0.28, *u* = 688.5, $n_1 = 46$, $n_2 = 37$, p = 0.03). This difference suggests that academic performance in the VS Group is not attributable to heightened enthusiasm to the task design.

2.4.4 Learning methods

To explore group differences between in learning methods reported to be utilised, a series of chi-squared analyses were performed (Figure 7).

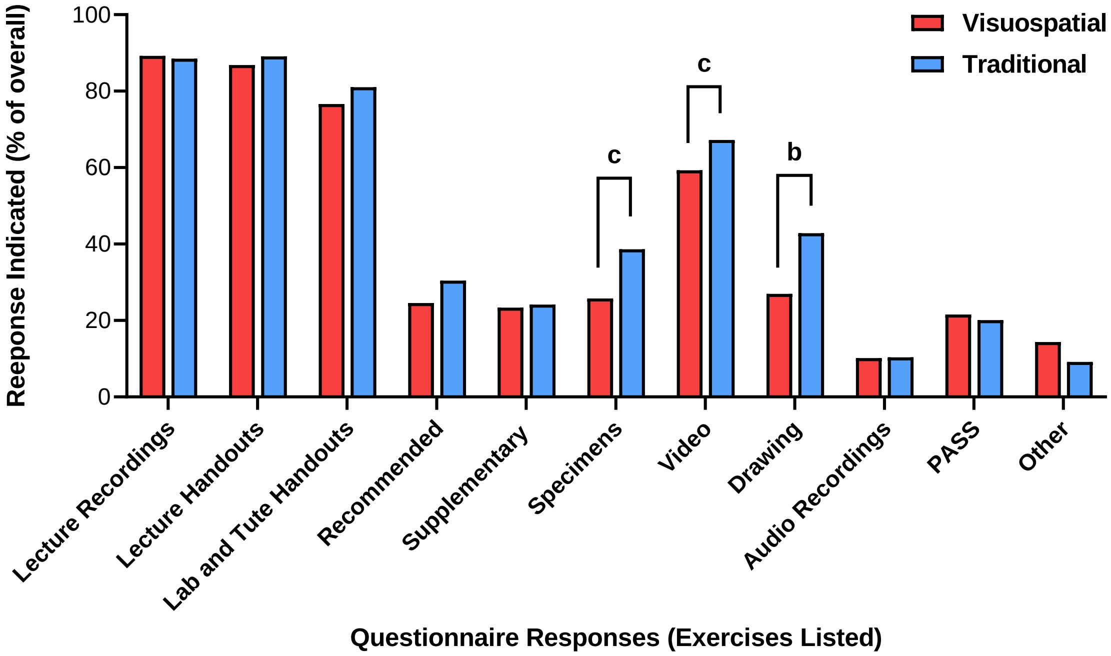


Figure 7. *Differences in mean percentage between groups for each of the learning styles outlined within the questionnaire.* $^{b}p < 0.01$**, $^{c}p < 0.05$*.

Chi-squared analyses revealed that students within the Trad Group reported a significantly higher prevalence of utilising the following learning items: (i) Specimens - χ^2 (1, N = 341) = 3.91, p = 0.048, (ii) Video - χ^2 (1, N = 341) = 4.33, p = 0.04, and (iii) Drawing - χ^2 (1, N = 341) = 7.29, p = 0.0069. To further explore potential underlying reasons for the academic benefits outlined in Figure 3., learning preferences of high-performing VS Group students were compared against the overall cohort (Figure 8).

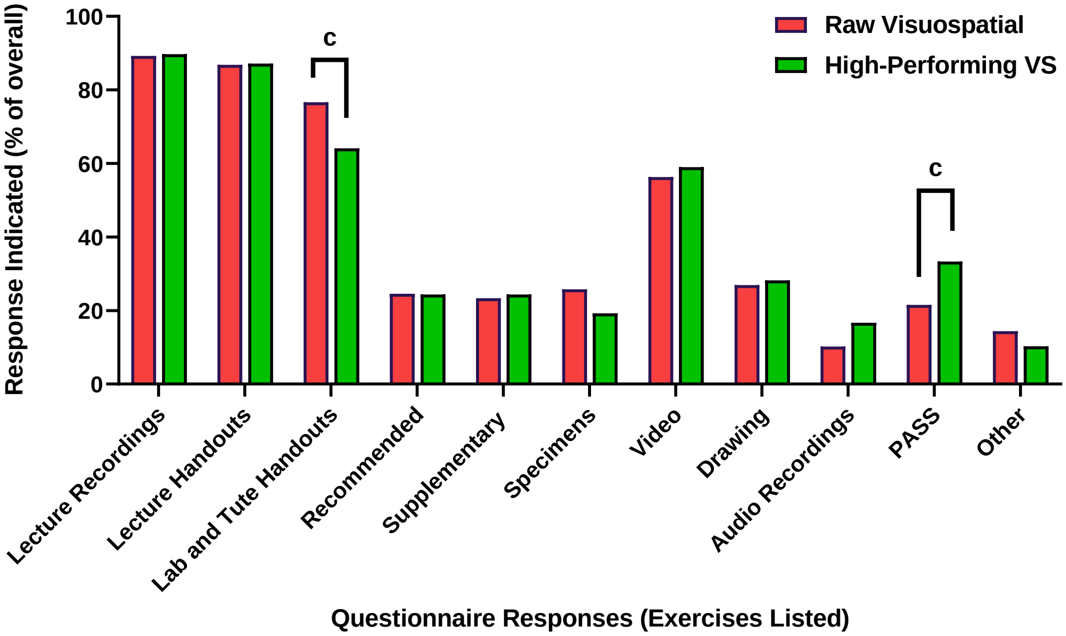


Figure 8. *Difference in mean percentage and standard error of reported learning resources utilised within the VS Group as compared to high-performing constituents.* $^{c}p < 0.05$***.

When comparing these categories, chi-squared analyses highlighted a significant elevation in peer assisted study session (PASS) attendance, χ^2 (1, N = 245) = 4.35, *p* = 0.04, amongst high VS performers and a significant decrease in the use of Laboratory and Tutorial handouts, χ^2 (1, N = 245) = 4.21, *p* = 0.04, in this sub-group. Overall, results in Figures 7 and 8 demonstrate a high level of similarity between experimental group learning preferences.

2.4.5 Prevalent themes

To identify the components of experimental design that had the greatest impact on student understanding (both favourably and unfavourably), an open response was provided to both groups. Results were collated into broad categories, and those receiving above five individual responses were ranked in order of prevalence below (Table 2).

	Favourite	**Least Favourite**
Visuospatial Group		
1.	Diagrams	Quick
2.	Drawing	Test/Questions
3.	Session Overall	Drawing
Traditional Group		
1.	Station #2	Station #1
2.	Station #1	Station #2
3.	Session Overall	Video Quick

Table 2. *Qualitative analysis of prevalent themes ranked for their emergence within group response to experimental tasks.*

Qualitative observations found both groups indicated a strong degree of enjoyment towards the experimental session. In the VS Group, it was noted that the display of diagrams and ensuing drawing received a favourable response rate, while the Trad Group found a consensus in preferring Station #2 (anatomical models) over Station #1 (prosections).

Components such as the brevity of the laboratory session (study length) and the assessment conditions were commonly expressed as unfavourable across groups.

2.5 Discussion

In this study, we explored ways in which academic and behavioural responses differed when comparing two distinct means of large-cohort anatomical education delivery – one utilising a predominately traditional method, and the other incorporating focused VS drawing. A significantly higher academic performance was observed in the VS Group, with this increase being derived equally from components assessing student didactic, spatial, and extrapolation abilities gained throughout the education session. In conflict with these findings, students in the Trad Group reported an increase in both their perception that VS methods are engaging, and a willingness for its inclusion into their current curriculum. Results were likely not confounded by the inclusion of a novel task design since linear analyses outlined little separation between academic performance and reported enthusiasm amongst groups. When exploring the reported learning methods utilised by members of each group, significance was found only in elevated usage of Specimen, Drawing, and Audio Recording material amongst the Trad Group. However, in exploring discernible traits that may predict successful VS comprehension, it was found that (as compared to their peers) high-performing VS Group students relied less on Laboratory/Tutorial hand-outs and instead recorded higher attendance at non-compulsory peer assistance (PASS) groups.

2.5.1 Academic differences

Our hypothesis that utilising a VS drawing intervention to introduce novel neuroscientific concepts would heighten the academic performance of a student undergraduate anatomy cohort, is supported. These findings align directly with reported qualities of visual arts guidance in elevating student comprehension of new material (Lyon *et al.*, 2013; Pujol *et al.*, 2016) - and also supplementary qualities such as the: recruitment of visual cues, promotion of tacit (nuanced) intelligence and secondary activation of gained knowledge (Nayak and Kodimajalu, 2010; Azer, 2011; Chamberlain *et al.*, 2014; Balemans *et al.*, 2016). Specifically, our findings complement literature supporting VS observation and drawing in enhancing anatomical learning outcomes (Naug, Colson and Donner, 2011; Noorafshan *et al.*, 2014; Markant *et al.*, 2016; Pickering, 2017; Greene, 2018a; S. Reid, Shapiro and Louw, 2019; L. Shapiro *et al.*, 2020).

Interestingly, when comparing the individual components that comprised assessment material, significant elevations were seen for each of the three question types. While increased performance in spatial and extrapolation questions had been anticipated, owing to increased 3D memorisation and understanding associated with graphical representations of anatomy (Stenning and Oberlander, 1995; Stern *et al.*, 2003a), it was surprising to observe similar trends amongst didactic content. This could be attributable to not only allowing the modification of drawings while material was presented, but also the opportunity to attach information through labelling. This integration of metacognitive and feedback mechanisms would have encouraged the constant re-evaluation of material that is thought to iteratively build not only comprehension but also active recall – cognitive load theory (Augustin, 2014; Taylor, Olofson and Novak, 2017; Anderson *et al.*, 2018). This theory dictates that dual input necessitates increasingly successful conversion of working memory into long-term memory through reduction of overall cognitive capacity, consequently improving information processing capabilities (Mayer and Moreno, 2003). Further to this, emerging evidence within the field of educational neuroscience suggests a causative link between VS education strategies and heightened neural integration (Schlegel *et al.*, 2012; Tyler and

Likova, 2012a). Specifically, it is thought that structured drawing regimes can modulate cognitive pathways so as to achieve sustained activation in those brain centers responsible for higher order thinking. (Ferber *et al.*, 2007; Miall, Gowen and Tchalenko, 2009).

Providing an interesting point of novelty, this study examined results originating from the inclusion of an isolated task design within existing curriculum. Owing to conflicting evidence, academic consensus appears divided on whether such short-term VS interventions are able to evoke deeper understanding (Backhouse *et al.*, 2017), or are substantial enough as a metric to evaluate learning on a scale that might accurately predict holistic knowledge transference. Two alternative time-scales are commonly assessed within the field, each possessing comparative advantages and drawbacks: (i) Longitudinal (providing analysis of long-term behaviour) (Balemans *et al.*, 2016), and (ii) Repeated Measures (offering course specific development) (Alsaid and Bertrand, 2016; S. Reid, Shapiro and Louw, 2019). By comparing evidence obtained from both approaches, and isolating specific directives that appear to predict success, we can best optimise how VS interventions are delivered.

2.5.2 Behavioural findings

Encouragingly, we found no evidence to suggest that in-class dynamics differed as a result of implementing either experimental design, with equally high reports that the session was informative and that students participated enthusiastically. This provided practical evidence that subsequent academic and behavioural data had been sourced from equally composed groups, without systematic experimental error. Surprisingly, the Trad Group and not the VS group indicated that VS methods were engaging and should be included within HB1A curriculum. We suggest two potential explanations for these results: (i) residual confusion surrounding the nature of VS learning within the Trad Group, or (ii) a disliking for the specific VS methods presented to the VS Group. Regarding these justifications, the term ‘visuospatial methods’ has been found to colloquially infer that a highly involved multi-disciplinary approach will be utilised within education design (Samarakoon, Fernando and Rodrigo, 2013; Backhouse *et al.*, 2017). While this possesses some merit, the traditional group may have been more receptive to the ‘theoretical idea’ of VS learning than their counterparts, having not experienced its practical implementation. Conversely, students in the VS Group encountering a version of this specific task-design, finding it was less ambiguous in its delivery of information than had been anticipated (L. Shapiro *et al.*, 2020; Lufler, Lazarus and Stefanik, 2020).

Both groups reported a high desire for additional supplementary materials to be made available within HB1A. This is consistent with similar reports that have outlined broad support amongst both general medical students and specific anatomy learners for multi-modal and auxiliary learning strategies to be incorporated within curriculum design (Samarakoon, Fernando and Rodrigo, 2013; Moro, Smith and Stromberga, 2019). These findings could be indicative of the declining rate of total course time being devoted to secondary anatomy education techniques (Drake *et al.*, 2009), or perhaps have resulted from student awareness of the rise and tangential benefits recorded for the use of online and modern technology within curricula (Cook *et al.*, 2011; Feilchenfeld *et al.*, 2017; Zargaran *et al.*, 2020). Though these digital techniques should not be used in a binary exchange for experience with traditional cadaveric materials (Davis *et al.*, 2014), it provides an opportunity for educators to fill the need for supplementary materials, as appropriate, which can additionally enhance VS observation. An extensive variety of medical imaging hardware and accompanying software that encourage 3D observation and exploration are now available, e.g. iPad, and imaging tables (SECTRA and Anatomage) (Patel and Burke-

Gaffney, 2018; Ward, Wertz and Mickelsen, 2018; Darras *et al.*, 2019), with the underlying benefits being attributed to heightened accessibility and overall enthusiasm that students associate with these devices (Khan *et al.*, 2009).

2.5.3 Enthusiasm and academic outcome

Significant evidence outlines the strong increase in student enthusiasm that accompany the introduction of non-reinforced novel task delivery (Mather, 2013; Miller, McNear and Metz, 2013; Harackiewicz, Smith and Priniski, 2016; Ramirez Butavand *et al.*, 2020). These events, essentially existing as a once-off occurrence, have additionally culminated in an ability to enhance academic scores in anatomy (Estevez, Lindgren and Bergethon, 2010; Kumar, Manning and Ostry, 2019). Issues arise in establishing whether these learning enhancements are representative of the method being utilised, or occur instead as a by-product of excitement resulting from this novel inclusion (Gravetter and Forzano, 2015). In designing this investigation, it was essential that components were included that would permit the exploration of this phenomenon, which if present might have undermined accurate comparison between experimental groups. Ultimately, our study found no evidence to support a ‘novelty effect’ resulting from the task design, with a roughly linear correlation observed between groups in a heightened expression of enthusiasm accompanied by increasingly higher academic performance. Interestingly, significant difference was noted within the mid-range academic performers, where students in the Trad Group reported more enthusiasm than their VS educated counterparts. While conventional wisdom suggests that strong academic performers flourish under most circumstances and that there is the potential for data from low-performing students to be tainted with the effects of ill attention, it is moderate performing students (often comprising the majority of a given tertiary cohort), who may provide the clearest insight into the impact of an educational design intervention. In this instance, it would be prudent to be cautious in adopting VS methods as a *primary* teaching method, but at the same time support their role in supplementing established core curriculum components (Azer, 2011; Berney *et al.*, 2015; Backhouse *et al.*, 2017; Garcia *et al.*, 2018).

2.5.4 Learning predispositions

When comparing the learning methods reported to be utilised amongst students of each experimental group, we noted only a few minor points of difference. As the groups were randomly distributed with respect to student identification number, this lack of observed differences is unsurprising. Of interest, the elevated prevalence of specimen and drawing use amongst the Trad Group presents an interesting question.

If the same logic is applied from behavioural findings (in 4.2), we might have expected a similarly measured response to those features highlighted within a group's experimental design (i.e. specimen viewing in the Trad Group). However, findings suggest that the inverse was in fact present. With seemingly little correlation able to be drawn across groups, we decided instead to focus on the VS Group specifically, highlighting any learning preferences that may have accompanied high academic performance. Interestingly, we noted a diminished use of lecture and tutorial hand-out material amongst these high-performers – perhaps inferring that those students were more likely to engage with material and educators within the class-time allotted, as opposed to relying on the notes provided to inform their learning at a later date. This would align with the literature which demonstrates a correlation between student self-efficacy and academic performance in both general leaning environments (Andrew, 1998; Artino, 2012; Olivier *et al.*, 2019; Wu *et al.*, 2020) and anatomy classrooms (Burgoon, Meece and Granger, 2012; Hayat *et al.*, 2020). It was also observed that an increased distribution of high-performing students reported attending the voluntary peer-assisted learning support sessions (PASS) offered within HB1A to compliment content delivery. Benefits of this educational intervention in primary and allied healthcare tuition have been outlined at length, with strong evidence that the additional preparedness and confidence gained by students is translated into immediate academic success and overall ability to reach course graduate outcomes (Han, Chung and Nam, 2015; Williams, Olaussen and Peterson, 2015; Agius and Stabile, 2018; Larkin and Hitch, 2019).

2.5.5 Limitations and future directions

A number of constraints impacted the design of this study. Firstly, the inclusion of a standardised entrance test prior to study commencement would have enabled valuable multiple comparisons analyses of the knowledge base possessed by each individual student. This would have provided a more accurate picture of the specific information gained throughout the experimental session. As students were in the first year of their undergraduate degree, and relevant content had been shielded from their course notes until this study date, it was decided that only a minimal chance existed for students to colloquially have gained this knowledge prior to entering this study. Another issue lay in the sequential delivery of this experiment across the course of a calendar day, providing the opportunity for students to communicate the learning objectives and potentially share information regarding assessment content. As this content was completely formative, we believe the likelihood of students engaging in this behaviour is minimal - however to mitigate against any possibility of this occurrence, we could have selected assessment material with differing questions between each laboratory session (Kurtz *et al.*, 2019). Lastly, the timing of this experiment was dictated by the constraints of the surrounding HB1A laboratory session. Ideally, we would have utilised an entire HB1A laboratory session to provide students with both additional materials representative of their given education method, as well as including more time to interact with them.

An initial intention of study design had been to track long-term effects across the teaching semester, culminating in an analysis of the relevant neuroscience section of students' final exam grade. If combined with the suggestion of a pre-test, this would have facilitated an interesting progressive evaluation, tracking: (1) baseline knowledge, (2) immediate consolidation, and (3) long-term critical recall. Due to issues in our ability to control overlapping content delivery throughout the remaining semester, it was decided this longer evaluation be removed – with it remaining as an opportunity to potentially explore tangential learning properties present for VS learning in a future study.

2.5.6 Conclusion

Results from this study support the utilisation of focused VS teaching methods to supplement established tertiary anatomical curriculum design when introducing a novel concept. Specifically, we observed elevated academic performance in a student cohort receiving VS observation and instruction within a laboratory session, in contrast with their experimental counterparts who were delivered the same content using traditional educational means. Further to these findings, there appears to be a discrepancy between student expectation of VS learning design and the realities of administering it - with differences in enthusiasm for the method being expressed between groups. Future research could continue to assess the longitudinal benefits present for observational methods of anatomy instruction, as well as explore individual characteristics that might predict 3D comprehension ability and subsequent aptitude for VS learning.

CHAPTER III

Visuospatial comprehension in anatomy: cognitive predictors of spatial problem-solving ability within a student cohort

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Name of Principal Author (Candidate)	Toby Branson		
Contribution to the Paper	Experimental design, data collection, analysis and interpretation, wrote manuscript.		
Overall percentage (%)	80%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	30th October 2021

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);
ii. permission is granted for the candidate in include the publication in the thesis; and
iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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3 Visuospatial comprehension in anatomy: cognitive predictors of spatial problem-solving ability within a student cohort.

3.1 Abstract

Accurate consideration of three-dimensional spatial relationships appears crucial in understanding the complexities of anatomical science. Specifically, it requires considered skill in visuospatial (VS) observation - of which a particular subcomponent ‘visualisation (Vz)’ shows particular importance. Though a variety of tests have assessed how this variable and an accompanying set of demographic factors (e.g. binary gender, age, prior tertiary experience) affect competence in isolated spatial awareness, scant prior evidence has explicitly linked this to subsequent anatomical performance. To explore this, fifty-three anatomy students were enlisted as participants. After initially providing their characteristic information, these individuals completed three primary exercises: (i) mental rotations task (MRT), (ii) spatial anatomy task (SAT) and (iii) academic anatomy test. Following this, participants self-evaluated their VS competency in a concluding questionnaire. When analysing demographic factors, present spatial advantages for males in spatial aptitude (MD = 8.50, p = 0.0001) were found to diminish in practical anatomy scores (MD = 1.35, p = 0.38) - while age (MD = 4.07, p = 0.0038) and prior tertiary experience proved reliable indicators of success (MD = 3.40, p = 0.02). Participants were poor adjudicators of their VS competency, failing to associate nominated aptitude with actual results ($\chi^2(1, 28) = < 1.61$). However, individual performance correlations outlined a clear trend between assessment items, with Vz ability being the clearest indicator of translating high spatial intelligence into practice ($\chi^2(1, 28) = 4.52$, $p = 0.001$). Findings further promote that Vz is crucial in developing sophisticated understanding of spatial relationships, and consequently anatomical relationships.

3.2 Introduction

A commonly overlooked yet fundamental quality required for the effective provision of healthcare is the accurate consideration of spatial relationships. Whilst immediately relevant to the effective planning and execution of procedural care, this skill has pertinent applications across all clinical techniques requiring appraisal of concealed patient biology (Hegarty *et al.*, 2007; Nguyen *et al.*, 2014). Providing this information in a transparent way, advances in diagnostic imaging have seemingly reduced practitioner reliance upon these skills while working within central medical systems (Smith-Bindman, Miglioretti and Larson, 2008; Geethanath and Vaughan, 2019). However, even in this instance where technology portrays a descriptive synopsis of the situation, it is an individual’s spatial competence that allows accurate orientation and interpretation of resultant images. To ensure these empirical skills are developed, both in relation to isolated human physiology and its representation in imaging, content exposing three-dimensional (3D) structural arrangement has received emphasis across relevant training programs (Pujol *et al.*, 2016; Clifton *et al.*, 2020). Most pertinently, tertiary study of anatomical sciences is responsible for delivering this, providing both didactic coverage of required information and encouraging subsequent 3D conceptualisation during dissection or viewing opportunities. Understandably, assessment is tied to these concepts, with achievement predictive of the ability to manipulate 3D aspects of anatomy that are presented within a diverse spectrum of reference planes (Fernandez, Dror and Smith, 2011). It stands to reason then that an individual’s success in anatomy may be closely related to their spatial ability (Garg, Norman and Sperotable, 2001; Guillot *et al.*, 2009; Lufler *et al.*, 2012).

Specifically, this format of education demands reasoning within a particular aspect of spatial attention referred to as visuospatial (VS) skill – a combination of visual consideration and innate spatial ability that provides an individual with a malleable ‘internal mental representation’ of structural information (Carroll, 1993b; Miyake *et al.*, 2001). A feature shared by VS methods is their attempt to facilitate the interchange between two-dimensional (2D) and 3D information. This possesses specific relevance within anatomical practice for not only the interpretation of medical imaging, but also relating the mostly 2D information of textbooks to real life application (Keenan and Powell, 2020; L. Shapiro *et al.*, 2020). Likewise, with increasingly sophisticated modes of anatomical delivery (e.g. virtual and augmented reality), it is necessary that students have the capacity to reverse this process and integrate 3D information with the 2D depictions they have seen in text. Though a series of sub-categories have been isolated within VS ability, particular emphasis is placed upon the contribution of aptitude in: initial visualisation (Vz), alignment within spatial relationships, closure speed (uniting disparate information), and closure flexibility (pattern detection) (Carroll, 1993b). Of these, Vz has been demonstrated to possess particular importance within anatomy learning, being strongly correlated with the rate at which novel spatial information can be processed (Garg *et al.*, 2002; Nguyen *et al.*, 2014). Theoretically, findings suggest that individuals with high Vz and associated VS aptitude expend less working memory in processing spatial information (Salthouse, 1996; Cohen, 2005), allowing additional capacity to problem solve and retain information about these novel stimuli.

To accurately track spatial ability, a number of validated tools have been developed – each aiming to appraise an individual’s capacity for 3D reasoning. Of these, the Mental Rotations Test (MRT) has become the preeminent model utilised within academic literature (Vandenberg and Kuse, 1978), tasking individuals with interpreting 3D objects that are presented within a 2D plane. The traditional design of the experiment, as specified in the seminal paper (Shepard and Metzler, 1971), presents an individual with a sequence of geometric structures (stacked cubes) referred to as the: (i) baseline object, and (ii) target objects. The task of an individual is then to determine whether these sets of cubes are identical or different to one another. In querying this, the MRT effectively quantifies aspects of cognition required in ‘rotation and translation of visual-imagery’ – indicative of Vz ability (Anastakis, Hamstra and Matsumoto, 2000b). Following its creation, MRT scores have identified a myriad of demographic factors influencing spatial ability. Of these, a correlation with gender has received considerable attention, establishing mixed consensus around the ability for male participants to outperform their female counterparts in large group cohort analyses (Vandenberg and Kuse, 1978; Voyer, Voyer and Bryden, 1995; Peters and Battista, 2008). Alternative factors identified as influencing MRT data interpretation, include: age, handedness, and prior task exposure (Peters, 2005; Peters, Manning and Reimers, 2007). Performance on the MRT has additionally been explored within anatomical education literature, finding that strong spatial ability demonstrated on the test is strongly indicative of academic performance in the field (Guillot *et al.*, 2007; Lufler *et al.*, 2012; Vorstenbosch *et al.*, 2013).

While isolated spatial aptitude can seemingly be correlated with academic success in anatomy, how it relates to solving specific spatial awareness problems is less well understood. Estimations report that individual differences in VS components may be of particular interest, especially Vz, suggesting that overlapping cognitive mechanisms may enable these practices (Guillot *et al.*, 2007; Hegarty *et al.*, 2007; Lufler *et al.*, 2012). Elevated Vz predicts not only performance in practical anatomy exams, but tangential proficiency in the objective fields it services such as surgery and radiology (Wanzel *et al.*, 2002; Luursema and Verwey, 2011). To appraise this understanding of complex spatial anatomical relationships, a novel task designed on applied MRT principles called the Spatial Anatomy Task (SAT) was developed by Nguyen and colleagues (Nguyen, Nelson and Wilson, 2012). This multi-faceted evaluation assesses distinct spatial intelligence in: (1) sectioning – seeing beyond the presented object, (2) rotation – retaining structural position in space, and (3) translation – extrapolation of a 3D structure (Rochford, 1985b; Nguyen, Nelson and Wilson, 2012). Ensuing studies have correlated strong performance in SAT domains with MRT scores (Nguyen, Nelson and Wilson, 2012; Nguyen *et al.*, 2014), indicating common overlap for Vz abilities in anatomical problem solving. However, studies have only postulated that these correlations extend to enhanced academic achievement in anatomy assessment.

While until this point various reports have disparately explored individual associations between: (i) raw spatial aptitude, (ii) its applicability to anatomy-specific reasoning, and (iii) overall correlation with academic performance, there has yet to be a comprehensive analysis sequentially linking these components. By first building upon the complexity of established metrics used to estimate these interactions, this study will survey an array of individual differences for their relevance in predicting anatomy success. Specifically, the proposed study aims to (1) determine how translatable isolated spatial aptitude is to both practical and academic anatomy performance, and (2) whether any individual demographic factors or learning preferences influence this. We hypothesise that heightened Vz ability will be the strongest indicator of achievement in spatial anatomy tasks, but that overall academic success will not be attributable to any one characteristic.

3.3 Materials and Methods

3.3.1 Ethical assessment

This study was approved by The University of Adelaide's low-risk ethical committee (H-2020-188). Responding to a variety of physical or online advertisements, potential participants making contact with investigators via email were provided with a detailed study information sheet. Informed written consent was obtained on the day of the experiment, with individuals agreeing to have the (1) performance of their tasks evaluated, and (2) demographic and questionnaire responses correlated. In order to maintain strict anonymity, each aspect of participant data was de-identified.

3.3.2 Participants

Fifty-three adults, each aged 18-36 and either currently studying for a relevant university degree involving anatomical understanding, or whom had recently finished their studies, were recruited to participate in the study. Three participants were excluded from final analysis, owing to either non-compliance or insufficient engagement with experimental tasks, leaving a total of fifty eligible individuals. All individuals were without cognitive impairment, receiving an ACE-III score > 82 (Mioshi *et al.*, 2006). Group dynamics were such that there was an average age of 23.5, comprised of a roughly equal gender spread (M = 23, F = 27). A moderate amount of average prior tertiary experience (2.7 years) was recorded, with participants being equally aligned within a spectrum of degrees - featuring the Bachelor of Medicine and Bachelor of Surgery, Bachelor of Dental Surgery, Bachelor of Psychological Science, and Bachelor of Health and Medical Science. Eligibility criteria prohibited enrolment for those individuals with: a prior neurological/psychological affliction, current prescription for medication affecting the central nervous system, history of drug or substance abuse, or uncorrected hearing or visual impairments. In exchange for their time, participants were compensated AUD $30 in the form of a retail outlet voucher.

3.3.3 Study design

The design of this experiment was such that each person completed the same task-design - with no delineation of activities requiring separate group comparisons. Participants were tested individually, each being seated at a desk with a pre-positioned laptop computer. The investigator addressed any queries, before informed consent and surrounding demographic information were obtained. This was followed by an initial psychological battery test ‘Addenbrooke’s cognitive examination’ (ACE-III). Implemented as a screening tool, this task was used to assess whether any language, attention, or visuospatial impairments were present that would exclude an individual from taking part in the study. Once cleared, program *PsychoPy* (Peirce, 2007a) governed the remainder of the experiment, automating the presentation of both the required tasks and surrounding instruction. Software also recorded participant responses in an accompanying spreadsheet, streamlining data analysis and retrieval.

Investigations began with an initial assessment of spatial ability in the Mental Rotation Task (MRT). Once completed, a pre-recorded lecture guided students through a particular series of anatomical concepts - acting as a didactic-loading phase. Participants were then presented with an anatomy-specific variant of the MRT, titled the spatial anatomy task (SAT), qualifying their ability to apply spatial reasoning within a biological setting. Concluding *PsychoPy* mediation, retention of information gained throughout the didactic-loading phase was then appraised in a multiple-choice quiz. A written questionnaire, exploring participant learning dynamics and involvement in spatial activities, then concluded the experiment

(Figure 1a and b). Though dependant on individual speed, the total duration of the session lasted no longer than 90 minutes, with an hour being the average completion time.

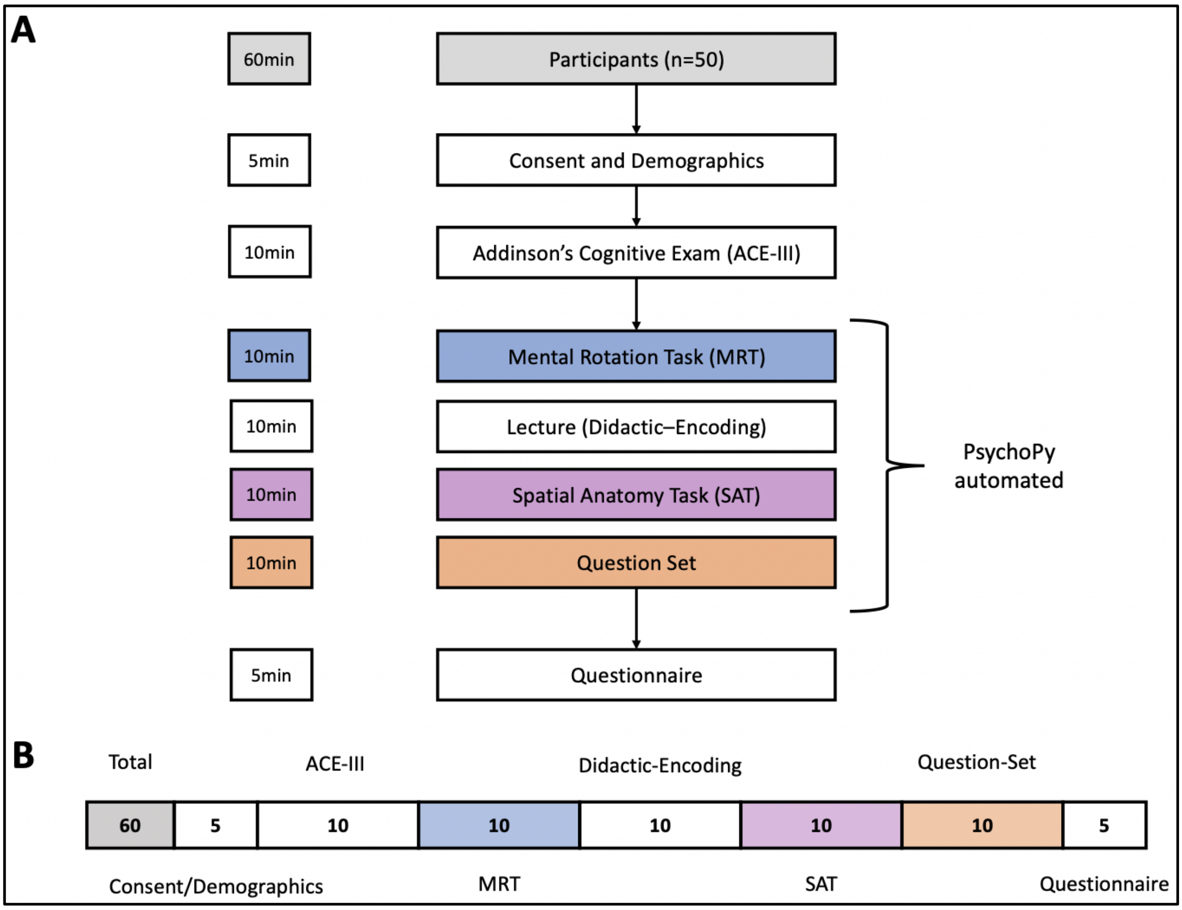


Figure 1: *Schematic overview of experimental design. (A) Flowchart outlining participant progression through each core task. (B) Breakdown of the duration for each task – with numbers representing the time in minutes. Note that times listed in (A) and (B) are indicative of the average completion time, with no time limits being imposed upon the participant.*

3.3.4 Didactic encoding

Providing participants with a series of anatomical details that were similar in nature to their prior tertiary experiences, a pre-recorded academic lecture was sequentially cued to students in between the two distinct rotation tasks (MRT and SAT). This element of experimental design elicited a didactic-encoding load upon the individual, with recall being subsequently examined in the latter multiple-choice question set. Information within this video encompassed a broad spectrum of physiological content, with content designed to the depth of a first-year undergraduate syllabus, so as to avoid providing an unfair advantage to individuals that were more progressed in their degree. Specifically, subject matter concerned: nervous system innervation, anatomy of the facial bones and skull, osteological foundations, and mechanics of the knee joint. Participants were allowed to take notes throughout with use of provided pen and paper, these being removed from sight by the investigator at the conclusion of the lecture.

3.3.5 Mental Rotation Test (MRT)

Raw visuospatial capability was assessed using the Mental Rotation Test (MRT), a validated tool that estimates the ability of an individual to mentally rotate a series of 3D objects presented in 2D. Though originally designed by Vandenberg and Kuse in 1978, we utilised a comprehensive modern variant of the task adapted by Ganis and Kievit (Vandenberg and Kuse, 1978; Ganis and Kievit, 2015). This version provides additional complexity to the seminal assessment piece, offering a more diverse profile of spatial abilities. The MRT was administered according to guidelines, presenting the participant with two near-identical neighbouring geometric structures comprised of 8-10 evenly sized cubes (positioned such that 3D form could be elucidated). Each participant’s task was to ascertain whether these two structures could be rotated in congruence with one another – consequently verifying if they were identical or different. In total, 64 questions were asked - divided equally into four even groups that indicated the angle at which the objects were rotated from each other (angular disparity). These groups were interspersed randomly throughout the total set, and specifically concerned 0, 50, 100 and 150 degrees - with higher disparity indicating the increased spatial manipulation required (Figure 2 a and b). Conducted using *PsychoPy* software, participants were presented with an initial information screen providing instructions to answer the questions as quickly possible, by selecting either of two corresponding keyboard buttons (Y or N). Ensuring that participants were fully cognisant of their responsibilities, 10 practice questions with accurate feedback were then provided. The experimental task then began, capturing correct responses and recall time across each angular disparity.

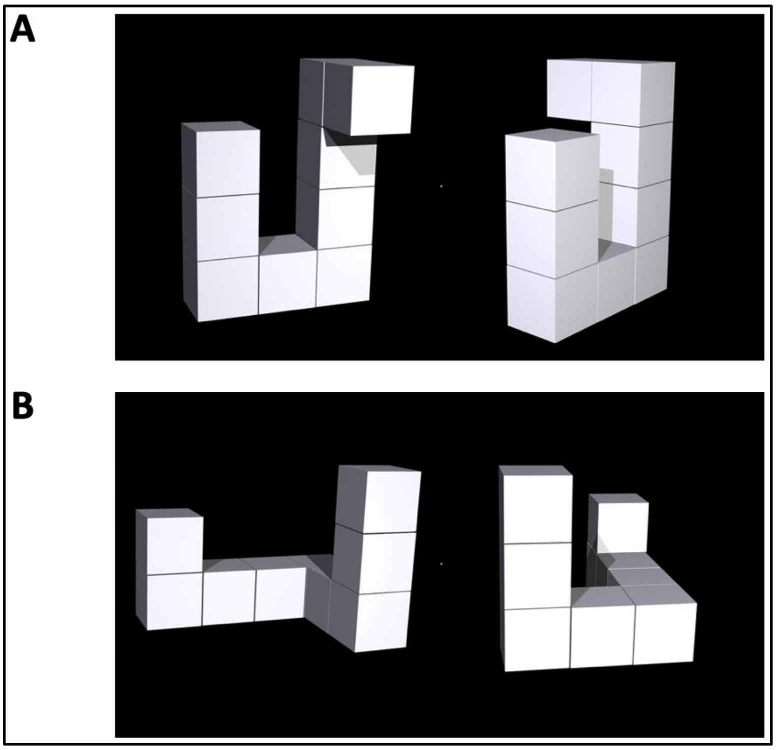


Figure 2: *Example of the geometric structures presented to participants in the MRT. (A) An incorrect rotation with 150-degree angular disparity. (B) A correct rotation with 100-degree angular disparity.*

3.3.6 Spatial Anatomy Task (SAT)

To assess how readily visuospatial ability could be applied within anatomical reasoning, we utilised isolated concepts of the MRT format in designing a Spatial Anatomy Task (SAT).

This approach, adapted from the original version created by Nyugen et al. in 2012, tasked participants with manipulation and subsequent recognition of a series of tubular anatomical structures (e.g. blood vessels) (Nguyen, Nelson and Wilson, 2012). These models were generated using computer software *Complete Anatomy (3D4M)*, with subsequent *Adobe* suite editing.

Comprised of 30 total questions, this task was divided into 10 scenarios, each of which promoting the consideration of a unique anatomical feature in three distinct approaches (Figure 3). Designed to evoke differing aspects of visualisation and mental rotation ability, these components concerned the following primary attributes: (i) static mental rotation (Fig 3A), (ii) identification (Fig 3B), and (iii) localisation (Fig 3C). Initial static rotation consisted of a target structure accompanied by four seemingly rotated copies – with participants deciding which of these copies was the untranslatable 'flipped' option. To analyse identification abilities, the next question presented the same target structure with a superimposed horizontal line and indicating arrow – tasking participants to assume the viewpoint of this arrow in deciding which of the four possible images corresponded to the accurate cross-sectional image that would be seen at the level of the horizontal line. Lastly, this process was completed in reverse – with a cross sectional image being provided to participants alongside the target image featuring the possible match of four corresponding superimposed horizontal lines. Establishment of which option correlated to the aforementioned cross-sectional image assessed localisation ability.

As with the MRT, software *PsychoPy* controlled the sequential delivery of this task, providing introductory instructions of the task and method to answer questions by selecting a corresponding keyboard button – a, b, c or d (Fig 3). Each question was evenly weighted, with the percentage of correct answers and time taken being recorded for each of the three components.

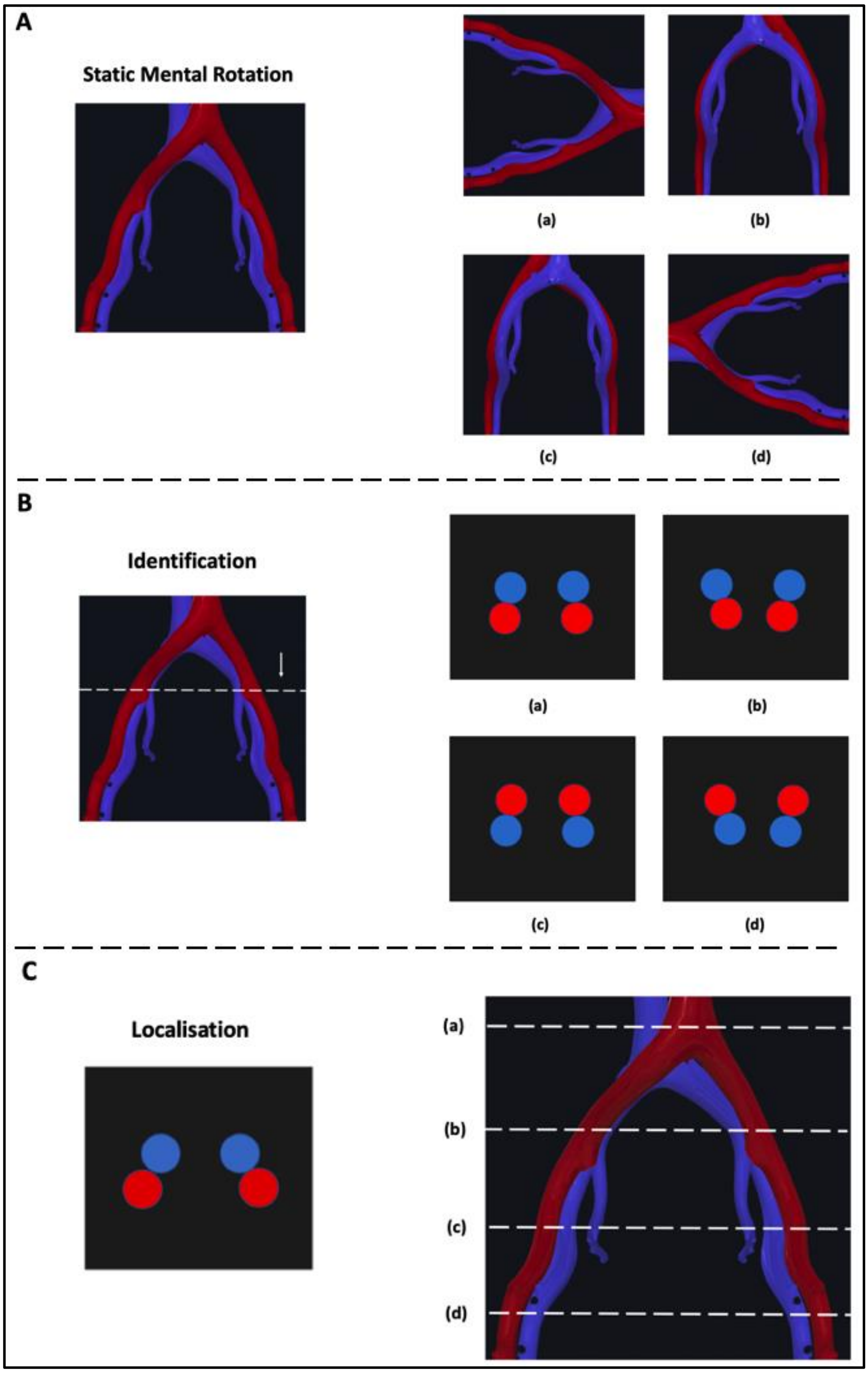
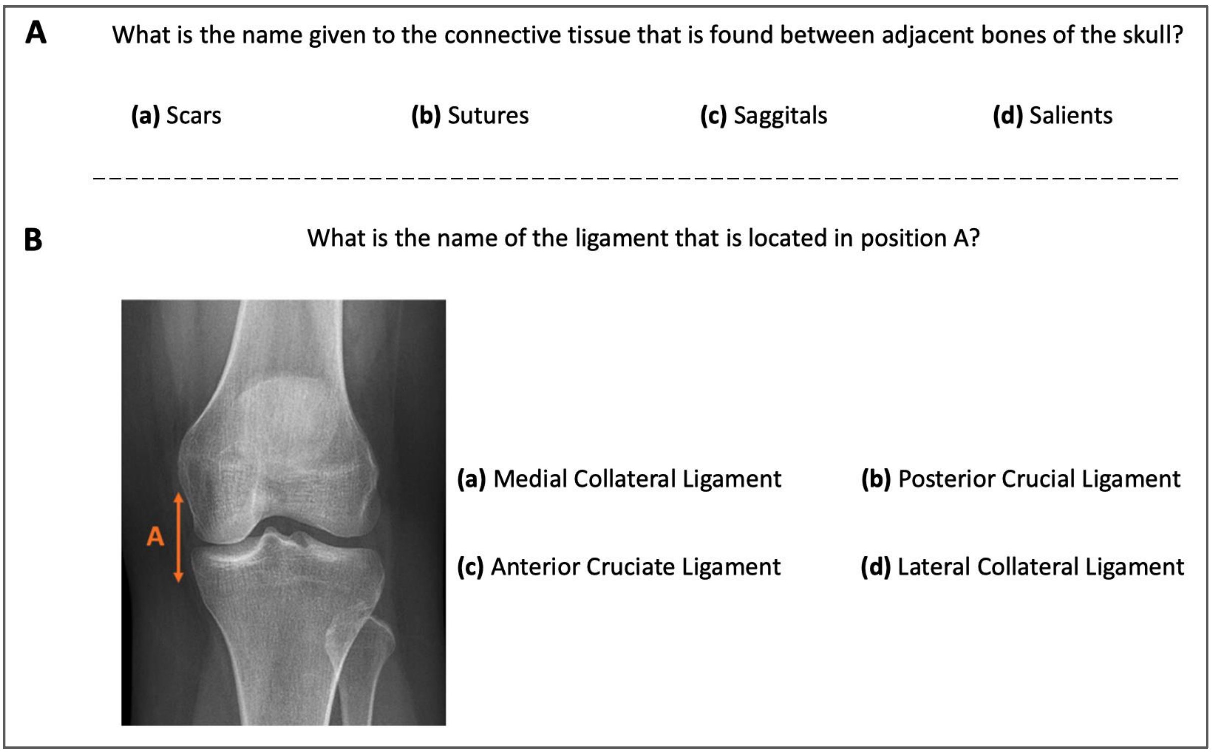


Figure 3: *Example of the different assessment types contained within the SAT. No time limit was applied in answering each question. Labels describe visualisation problems (A) Static mental rotation, (B) Identification, (C) Localisation.*

3.3.7 Question-set

To evaluate how accurately a participant could recall information provided within the didactic-encoding period, a 30-question multiple choice test was administered to conclude the quantitative portion of experimental design. Again, *PsychoPy* controlled this process, sequentially delivering questions and recording the responses provided. Each question was asked in isolation, with the participant selecting one of four possible presented options through pressing a corresponding keyboard button. The test was divided into two distinct components of equal weighting, with the first 15 questions assessing didactic recall (Academic Trad), and the latter requiring considered spatial manipulation of the presented anatomical stimuli (Academic V/S) (Figure 4).



A What is the name given to the connective tissue that is found between adjacent bones of the skull?

(a) Scars **(b)** Sutures **(c)** Saggitals **(d)** Salients

B What is the name of the ligament that is located in position A?

(a) Medial Collateral Ligament **(b)** Posterior Crucial Ligament

(c) Anterior Cruciate Ligament **(d)** Lateral Collateral Ligament

Figure 4: *Example of the different question types presented within the academic anatomical test. (A) Assessing didactic-encoding recollection. (B) Requiring spatial manipulation.*

3.3.8 Questionnaire

To assess student impression of experimental task design, views on visuospatial learning, and readiness to engage in spatial tasks, questionnaire items were administered. Specifically, six questions were asked, each accompanying a five-point Likert scale – with response options ranging from strongly disagree → strongly agree. Additional space was provided for an extended response to the sixth component, with participants providing a brief description of pertinent activities.

(1) I concentrated and actively participated in today's experiment.
(2) The material covered in today's session was similar in style, not content, to what I have seen in tertiary education previously.
(3) I would describe myself as a visuospatial learner.
(4) I find it easy to learn a new concept through visual means alone.
(5) I am someone who regularly employs drawing as part of their learning or revision (e.g. drawing figures from lecture notes and attaching notes).
(6) I am someone who regularly participates in activities that require, and potentially train, visuospatial attention or performance.

3.3.9 Data analyses

Statistical analyses were performed using *GraphPad Prism* version 9 software. Unless otherwise stated, calculated values are indicative of the mean and accompanying standard error (SEM). Significance was likewise conventionally reported as $^{a}p < 0.001$***, $^{b}p < 0.01$**, $^{c}p < 0.05$*. Each element of quantitative statistical analysis was first guided by classifying relevant data groups for their adherence to either parametric or non-Gaussian distribution through performing Shapiro-Wilk tests and viewing histogram plots. Validity of MRT data was confirmed by comparing the percentage error rate and response times of the participant cohort to reported values in source literature. Each set displayed normal distribution, and a series of Bonferroni corrected repeated measures one-way ANOVA's with accompanying linear regression were used to establish significant trends and equations of best fit. In assessing descriptive statistical differences in MRT, SAT and academic test score data, normality in relevant data sets informed the separate use of either: (i) a Mann-Whitney U-test for non-parametric behaviour, or (ii) an unpaired (student's) t-test for parametric. Demographic categories were implicitly derived from participant information sheets, with the latter component of VS activity determined by broad agreement with Q5 of the questionnaire document. Individual Spearman correlation analyses were selected to examine interactions between scores achieved on those three primary points of assessment found in the study (MRT, SAT, academic), as well as those distinct sub-components that comprise the latter two. Significance values in this analysis were corrected for multiple comparisons.

To obtain estimations of underlying Vz ability for the final analysis, participants were grouped into three categories of MRT performance [High (n = 16), Intermediate (n = 18) and Low (n = 16)]. To distinguish only those trends associated with upper and lower bounds, the intermediate group was excluded from analysis. A series of 2x2 chi-square (χ^2) analyses then compared Vz ability to student response on a series of self-reflective Likert-scale questionnaire items regarding prior incorporation and aptitude for visuospatial learning (Question 3, 4, and 5 from Questionnaire). This binary test was accomplished by dividing participant responses into two broad categories – 'indicating support ↑' or 'not indicating support ↓'. There were five potential options presented "Strongly Disagree", "Disagree", "Neutral", "Agree", "Strongly Agree". The entries reporting either form of agreement were considered representative of the former group, while those indicating disagreement or neutrality were grouped into the latter category. Academic test scores, whether above or below the overall mean cohort value, were collated in the same manner. To mitigate any issues associated with low expected count frequency, resultant χ^2 analyses were performed using Yate's continuity correction. Independent t-tests were then used to compare the normally distributed SAT performance within each of these Vz and response groups.

3.4 Results

3.4.1 MRT validation

To establish if the stratified MRT results achieved by our participant cohort were accurately representative of spatial performance, experimental values were assembled and matched against those validated scores outlined by seminal work (Table 1 and Figure 5) (Ganis and Kievit, 2015).

	% Error Rate		**Response Times**	
Angular Disparity	M	SEM	M	SEM
0	7	1.42	2.55	0.14
50	12.50	2.44	3.34	0.23
100	18	2.39	4.19	0.29
150	23.37	2.14	4.62	0.39

Table 1. *Results obtained in the MRT. Mean of incorrect responses (% error rate) and time taken (in seconds) reported alongside corresponding standard error (SEM) for each level of angular disparity (cube rotation) (n = 50).*

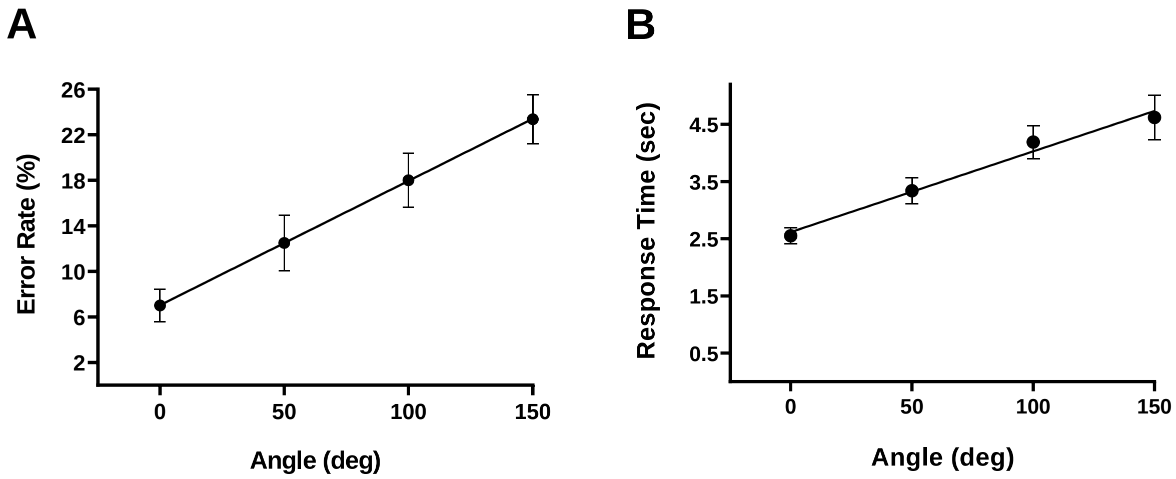


Figure 5. *Visual depiction of MRT validation results. (A) Percentage mean error rate, and (B) the accompanying mean response rate recorded in seconds for the set of 64 presented questions.*

Each angle of rotation (0, 50, 100 and 150 degrees) was assessed in relation to successful response rate, finding that higher error values coincided with those presenting objects of greater angular disparity [F(3, 134) = 34.12, p<0.001)]. This effect was also indicative of a strong linear correlation [F(1, 198) = 291.10, r^2 = 0.98, p<0.001] (Fig 5A). A corresponding analysis then compared the impact of rotation angle against trial response time, finding a similar increase in latency accompanying greater angular disparity [F(3, 134) = 193.43, p<0.001], with near analogously positive linearity [F(1, 198) = 291.10, r^2 = 0.96, p<0.001]

(Fig 5B). When comparing the equation of best-fit regression for each of these components, we note equations of (i) error rates ($y = 0.106x + 5.30$), and (ii) reaction times ($y = 0.819x + 2.42$).

3.4.2 Descriptive statistics

To determine the influence that any demographic factors might have possessed upon resultant experimental success, we compared a set of individual qualities with accompanying outcomes in each of the three primary experimental metrics (Figure 6).

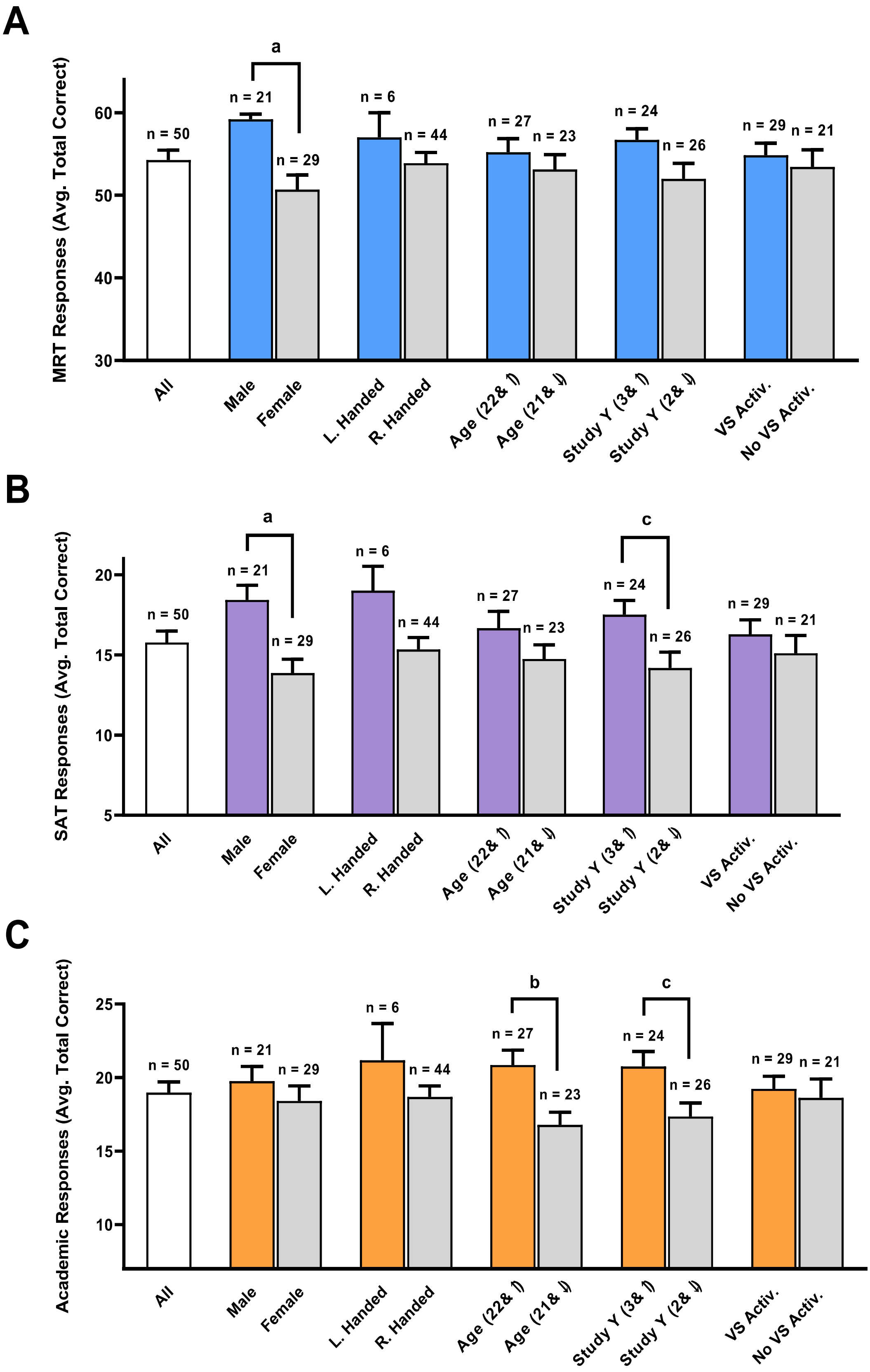


Figure 6. *Descriptive statistical results for each of the primary experimental tasks. (A) Mental Rotations Task (MRT). (B) Spatial Anatomy Task (SAT). (C) Academic question-set.*

Values indicate the mean ± SEM for overall performance in each demographic category, with (n) representing the constituent population size. $^{a}p < 0.001$***, $^{b}p < 0.01$**, $^{c}p < 0.05$*.

For each of the primary experimental metrics, overall group analysis demonstrated that for the (i) MRT – there was an average score of 54.26 ± 1.21, (ii) SAT – an average score of 15.78 ± 0.70, and (iii) Academic – an average score of 18.98 ± 0.72. Specific gender analyses revealed that males significantly outperformed their female counterparts on both the MRT (MD = 8.50, $u = 118$, $n_1 = 21$, $n_2 = 29$, p = 0.0001) and SAT ($p = 0.0008$, $t = 3.593$, $df = 48$) (Fig 6A and B) – though this trend did not extend to wider Academic results (MD = 1.35, $u = 259$, p = 0.38) (Fig 6C). Inversely, age analyses found significance only in determining that older participants obtained higher academic results than their younger equivalents (MD = 4.07, $u = 164.5$, $n_1 = 27$, $n_2 = 23$, p = 0.0038) (Fig 6C). Lastly, additional prior years of study were found to be significantly indicative of greater success on the SAT ($p = 0.02$, $t = 2.48$, $df = 48$) and Academic test ($p = 0.02$, $t = 2.45$, $df = 48$) (Fig 6B and C), without influencing MRT outcome (MD = 4.71, $u = 214.5$, $n_1 = 24$, $n_2 = 26$, p = 0.0001) (Fig 6A).

No significant differences were found across factors of handedness or prior exposure to visuospatial (VS) activities. Alternate metrics of ‘engagement’ and ‘similarity with prior material’ were omitted from analysis owing to lack of population variability in addressing those questionnaire items.

3.4.3 Component correlations

To examine correlations between individual performance on the Mental Rotations Task (MRT), Spatial Anatomy Task (SAT) and academic evaluation, we compared overall score obtained from each task as well as achievement within sub-categories that comprise the latter two (Table 2).

	MRT	SAT (O)	SAT P1	SAT P2	SAT P3	Acad (O)	Acad (Trad)	Acad (VS)
MRT	1							
SAT (Overall)	0.65^a	1						
SAT Part 1	0.44^b	0.76^a	1					
SAT Part 2	0.52^a	0.81^a	0.38^b	1				
SAT Part 3	0.60^a	0.82^a	0.47^a	0.56^a	1			
Academic (Overall)	0.41^b	0.47^a	0.38^b	0.28^c	0.38^b	1		
Academic (Trad)	0.53^a	0.47^a	0.37^b	0.30^c	0.38^b	0.84^a	1	
Academic (VS)	0.24	0.39^b	0.33^c	0.22	0.32^c	0.92^a	0.57^a	1

Table 2. *Correlation between individual performances on the three primary experimental measures. Specific components that comprise the SAT (SAT Part 1, 2, 3) and academic test (Trad and VS) are similarly listed.* $^a p < 0.001$****,* $^b p < 0.01$***,* $^c p < 0.05$**.*

Analyses revealed significant positive correlations existing between the overall scores achieved in each study measure: (i) MRT and SAT - $r(50) = 0.65$, $p = < 0.001$, (ii) MRT and academic Test ($r(50) = 0.41$, $p = 0.003$), and (iii) SAT and academic Test ($r(50) = 0.47$, $p = < 0.001$).

Though each was significant, Table 2 outlines that high MRT performance is better correlated with SAT scores than the academic test. Additionally, results in this category are nondescriptly tied to each subcomponent except VS oriented academic test questions ($r(50) = 0.24$, $p = 0.10$). Featuring similarly resounding significance within each of the alternate metrics, SAT performance is also more soundly associated to MRT performance than academic scores ($r(50) = 0.24$, $p = 0.10$). In comparison to components of static mental rotation (SAT Part 1) and identification (SAT Part 2), localisation ability demonstrated in SAT Part 3 appears to most strongly predict overall score on the SAT ($r(50) = 0.83$, $p < 0.001$) - with this component being indicative of MRT reasoning also ($r(50) = 0.61$, $p < 0.001$). Though once again significantly correlated to other results, overall academic test scores find noticeably less overlap with individual components of other primary metrics. This is particularly in respect to performance in SAT Part 2 questions – exemplified by a lacking interrelatedness between those identification questions and VS academic questions ($r(50) = 0.30$, $p = 0.08$).

3.4.4 Visualisation association

To assess the extent by which individual visualisation capacity could be correlated to both performance on ensuing experimental tasks and participant-identified traits of visuospatial competency, we compared results on the SAT within each of these categories (Figure 7).

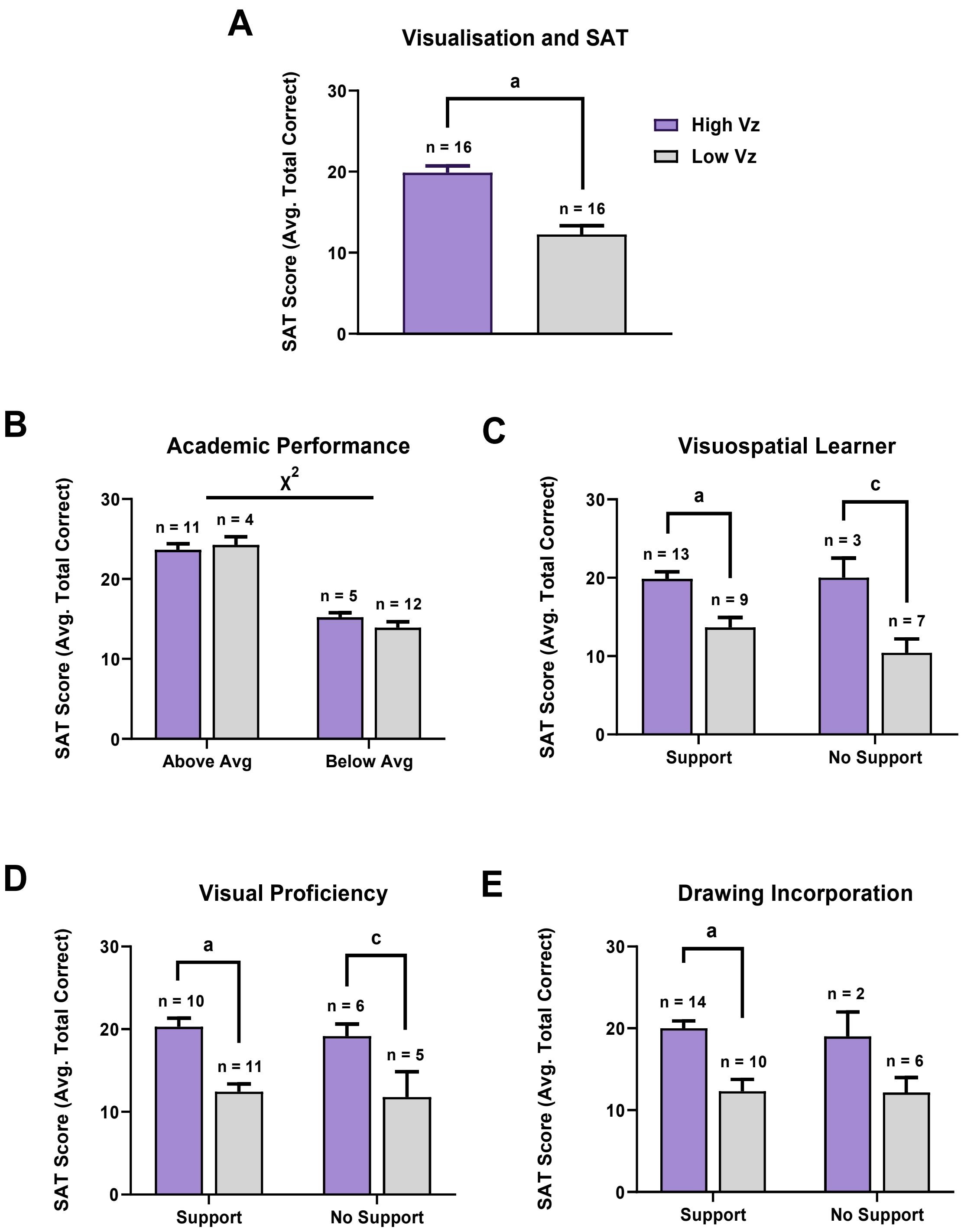


Figure 7. *Relationship between Visualisation (Vz) ability and relative performance on the SAT, as categorised by a variety of associated achievement or questionnaire response groups. (A) Isolated comparison between Vz and SAT score. (B) Association with academic performance. (C) Influence of being a visuospatial learner. (D) Influence of possessing*

*visual proficiency. (E) Influence of having previously incorporated drawing within learning. Values indicate the mean ± SEM for overall performance in each demographic category, with (n) representing the constituent population size and (χ^2) denoting significance between groups, $^a p < 0.001$***, $^c p < 0.05$*.*

Derived from relevant individual score on the MRT, participants were split into one of three performance groups indicative of their underlying visualisation (Vz) ability. These were referred to as the High Vz group (61.13 ± 0.45, $n = 16$), Intermediate Vz group (56.28 ± 1.12, $n = 18$), and Low Vz group (44.00 ± 1.93, $n = 16$). With subsequent score on the SAT serving as a performance metric, a number of differing responses between High and Low Vz individuals were noted for academic strength and response to questionnaire items (see 'data analysis' section for indexing detail). Overall, a significant correlation was found between heightened visualisation ability and performance on the SAT (MD = 7.63, $t(30) = 8.65$, $p < 0.0001$) (Fig 7A). This trend did not continue to wider academic results, where only statistically insignificant differences were found for Vz ability in relation to either above average (MD = 0.61, $t(13) = 0.36$, $p = 0.72$) and below average (MD = 1.28, $t(15) = 1.07$, $p = 0.30$) outcome on this test (Fig 7B). However, providing further validation of results in Table 2, analyses found that academic performance and Vz ability were related ($\chi^2(1, 28) = 4.52$, $p < 0.001$) (Fig 7B).

Individual perception of visuospatial learning proved a poor indicator of accompanying visualisation ability ($\chi^2(1, 28) = 1.31$, $p = 0.25$) - though SAT correlation outlined that individuals with higher Vz outperformed their counterparts across both supportive (MD = 6.18, $t(20) = 4.10$, $p = 0.0006$) and non-supportive (MD = 9.57, $t(8) = 3.03$, $p = 0.0163$) aspects of this domain (Fig 7C). Likewise, connection between Vz ability and self-identification of visual learning proficiency was scant ($\chi^2(1, 28) = 0.14$, $p = 0.71$), though SAT results continued to unveil a strong connection with Vz ability in both supportive (MD = 7.85, $t(19) = 5.64$, $p < 0.0001$) and non-supportive (MD = 7.37, $t(29) = 2.30$, $p = 0.0469$) individuals (Fig 7D). Finally, there was similarly no correlation between participants self-reporting prior incorporation of drawing within their learning and demonstrated Vz ability ($\chi^2(1, 28) = 1.50$, $p = 0.22$) (Fig 7E). Results favoured a positive answer to this questionnaire item, allowing a subsequent positive correlation between SAT and support to again be drawn (MD = 7.70, $t(22) = 4.79$, $p < 0.0001$), but lacking sample size prohibited comparison with opposing support (Fig 7E). No significant difference in performance was seen for the effect of gender when comparing attribute identification (Figure 7C, D and E).

3.5 Discussion

Throughout this study, we aimed to assess how performance on a spectrum of assessment modalities (ranging from isolated spatial performance to applied anatomical understanding) could (i) be correlated with one another, and (ii) fluctuate with respect to various demographic and classification features. Significant disparity in gender performance was observed; with males demonstrating higher aptitude in both isolated and applied spatial understanding than their female counterparts. By contrast, older age proved a strong indicator of heightened academic performance in anatomy – and homogenous prior tertiary experience coupling this with anatomical spatial performance. Between individuals, strong correlations in performance were achieved across each primary metric and the majority of their encompassed subcategories – with inherent Vz ability appearing as the best indicator of success. However, participants proved poor adjudicators of their proficiency in this domain, with individual response to questionnaire items showing little relation to actual Vz ability.

3.5.1 Demographic associations

Findings of Figure 5 indicate that MRT results obtained in this study are consistent with values outlined as effective by original task creators - validating the success of our chosen MRT task in assessing spatial aptitude and evoking Vz ability (Ganis and Kievit, 2015). Subsequent analysis of whole cohort MRT data revealed a significant sex difference between the spatial reasoning abilities of men and women. This finding showed that males exhibited higher isolated spatial comprehension and this was consistent amongst expansive literature recorded for iterations of the MRT and associated qualifiers (Vandenberg and Kuse, 1978; Linn and Petersen, 1985; Peters *et al.*, 1995; Langlois *et al.*, 2013). This discrepancy was similarly pronounced for anatomy-specific spatial reasoning ability adjudicated by the SAT, supporting the findings of original task creators (Nguyen *et al.*, 2014). Intriguingly, this trend ended when comparing gender performance on the overall academic test. To extrapolate, while men demonstrated superior spatial ability in rotation tasks, holistic anatomy study and performance was not associated with gender. Our findings sit well within nuanced prior academic literature of the field – suggesting the higher innate VS ability of males is more pronounced in geometric tasks, with gender discrepancies being diminished in practical application (Bouchard and McGee, 1977; Lufler *et al.*, 2012). Anatomy success is, in all likelihood, more dependent upon individual intellect, material engagement, and desire to perform.

Inversely, increased age appears to anticipate anatomical academic performance but not raw spatial aptitude. This conflicting result appears common, with prior studies reporting sporadic applicability for age to predict spatial aptitude on the MRT (Geiser, Lehmann and Eid, 2008; Jansen and Heil, 2010). With each participant being a young-adult (18-34), potential interrelatedness between performance and cognitive decline was negated. Perhaps overlapping with age, prior experience proved significant in determining both anatomy specific spatial aptitude on the SAT and overall academic performance. As this metric is contingent upon progression within an anatomy related tertiary program, this result is unsurprising. However, it does suggest that image interpretation skills are gained passively throughout these education programs. We hypothesise that age and experience results are more likely circumstantially associated to individual familiarity with assessment question styles.

While literature has implicated left-handedness and prior VS task exposure as indicating greater spatial ability – our results show little to support this (Peters, 2005; Peters, Manning and Reimers, 2007). Investigation of handedness may have originated from colloquial understanding that motor interactions regarding left-handed functions are under right-brain hemisphere control – with the cortex of this lobe being recognised as possessing human spatial reasoning centres (Corballis, 2003; Bartolomeo, Thiebaut de Schotten and Chica, 2012). While this is somewhat accurate, proximity and potential interconnectedness of these neuronal pathways appears to have little practical effect upon performance. Although not supported statistically, prior exposure to VS tasks found common reporting of video-games, sporting activities and general puzzle solving, each of which having been tangentially shown to strengthen VS awareness (Chueh *et al.*, 2017; Fissler *et al.*, 2018; Milani, Grumi and Di Blasio, 2019).

3.5.2 Individual correlations

Experimental results show strong correlations between individual performances on each of the three-primary metrics utilised – implying that aptitude on isolated and practical spatial reasoning tasks is highly tied to subsequent anatomical performance. This finding is unsurprising given the reliance upon which spatial information is transformed when surveying anatomical relationships, with individual ability to conduct this having been linked to greater conceptual understanding of material (Keenan and Powell, 2020; L. Shapiro *et al.*, 2020; Pedersen, Wilson and De Ribaupierre, 2013). Although trained experience is though to foster intrinsic spatial ability, the extent to which this can be altered with practice is questioned (Hegarty and Waller, 2005; Höffler, 2010). Wider evidence has however outlined principle course outcome improvements following inclusion of VS methods within anatomy curricula (Nayak and Kodimajalu, 2010; Ainsworth, Prain and Tytler, 2011; Balemans *et al.*, 2016). With SAT scores having done so, it was surprising to note the lack of correlation between MRT scores and visuospatially oriented academic question - adding an interesting caveat to our hypothesis that isolated spatial abilities are transferrable to anatomical success.

Though each component of the SAT possessed significant correlation with MRT and academic scores, localisation skills identified in Part 3 were shown to possess the strongest of these interactions – reiterating findings of original task designers (Nguyen *et al.*, 2014). Though there may be some ability to discern which specific ability examined by the SAT is most applicable to academic performance, it appears global spatial aptitude presents an adequate indication of success. When extrapolating MRT results to underlying subcomponents of spatial conceptualisation – individual differentiation in high and low Vz ability becomes more pronounced in SAT and academic results. This established Vz as the prevailing predictive characteristic of individual anatomical success outlined by this experiment. It should be acknowledged that this is consistent finding amongst an assortment of isolated and practical classroom results, with students lacking 3D conceptualisation ability commonly: (i) demonstrating lower isolated and dynamic Vz aptitude, and (ii) scoring lower on practical anatomy tests (Rochford, 1985a; Lufler *et al.*, 2012; Nguyen, Nelson and Wilson, 2012; Hoyek *et al.*, 2014). Thus, when designing educational paradigms to promote spatial awareness within an anatomy learner, consideration of Vz appears necessary (Colom *et al.*, 2002; Höffler, 2010).

3.5.3 Attribute identification

When aligning response to questionnaire items with categorical experimental results, little correlation was found amongst the participant cohort. This allowed us to infer that there exists a discrepancy between an individual's self-described command of VS learning and veritable aptitude. With the present study aimed at determining indicators and overlapping features of spatial ability, those more objective measures (especially Vz) appear exceedingly more reliable than student identification. When addressing the first of these responses, being a VS learner, lacking reliability could be attributed to misguided colloquial understanding of what this style entails. Perhaps owing to visual similarity between tests such as the MRT, acumen within the domain of VS learning can often be mistakenly associated to broader mathematical performance (e.g. representing skills such as arithmetic) (Lufler *et al.,* 2012; Allen, Higgins and Adams, 2019; Fanari, Meloni and Massidda, 2019). An item for future research might compare the differing responses observed from a participant cohort who are better aware of what this method exemplifies.

The lack of accuracy in identifying a visual learner might lie in the modern comprehension of there being distinct learning approaches. Having entered public consciousness, these patterns of learning typically state that dominant attributes of an individual align with accompanying methods that best suits their learning (Curry, 1981; Romanelli, Cain and

Smith, 2006). Of these, the visual, auditory, read/write and kineasthetic (VARK) method continues to find most prominence within diffuse education streams (Fleming and Mills, 1992), owing perhaps to its ease of use and simplicity of ensuing analysis (Pashler *et al.*, 2008b; Scott, 2010). This method, along with counterparts, has been strongly questioned for its validity and nuance when categorising individuals (Sandmire, Vroman and Sanders, 2000; Husmann and O'Loughlin, 2019). While drawing as a technique to describe and enhance the delivery of information within anatomy is well documented, its casual use amongst a participant cohort appears a poor determinant of broader spatial ability (Contreras *et al.*, 2018). This is not to suggest drawing be omitted as a tool to convey anatomical complexity, with this means appearing extensively as an excellent intermediary step between initial observation and subsequent memory consolidation of spatial relationships (Bell and Evans, 2014; Davis *et al.*, 2014; Balemans *et al.*, 2016).

3.5.4 Limitations

Authors recognise the presence of several constraints impacting this experimental design. Firstly, with the mixed demographic participant sample utilised in this study, we could not absolutely control for the level of prior knowledge possessed by each individual. Though spatial ability scores on the MRT and SAT are relatively unaffected by this, influence of time years spent within a tertiary program could have influenced academic results (Thompson and Zamboanga, 2003; Hailikari, Katajavuori and Lindblom-Ylanne, 2008). To mitigate this, authors ensured that presented content was indicative of first-year level information, with VS questions relating to obscure anatomical features. Regarding this specific assessment item, to our knowledge this is the first study to attempt delineation between didactic information recall and image interpretation. In practical anatomy situations there are many assessment items used to estimate this, ranging from basic structure-identification tests to clinically applied exams using radiology imaging modalities (Smith and McManus, 2015; Choudhury, Gouldsborough and Shaw, 2016; Luursema, Vorstenbosch and Kooloos, 2017). Being a novel inclusion, our method may have yielded improper estimation of academic achievement in these distinct categories, perhaps accounting for the lacking correlation between spatial ability and performance on VS questions. Finally, the self-reflective questionnaire used to gauge participant demographics and experience in this session had not been substantiated. Though authors designed questions around examples in prior literature, consultation of an education specialist or preliminary pilot investigation would have ensured that the intent of these questions were accurately conveyed (Artino, 2012; Hauer *et al.*, 2020). Additional inclusion of specific examples within questions may also have increased the reliability of responses.

3.5.5 Conclusion

The present study explored interconnectedness between factors of spatial aptitude and academic anatomical performance, outlining both a number of novel trends and consolidating many established ones. Chiefly, gender disparities in spatial aptitude diminished in academic performance – with age and prior experience acting as more reliable indicators. Individual performance was tightly correlated across measures, implying that underlying isolated reasoning skills were analogous to practical implementation – while accompanying self-assessment of spatial abilities returned little pragmatic association. However, the clearest determinant of spatial translation appeared in Vz ability. Being itself a sub-component of VS ability, Vz has been implicated to represent visual working memory capacity, reflecting the rate at which new spatial information can be processed (Salthouse, 1996; Shah and Miyake, 1996; Miyake *et al.*, 2001). As these skills are heavily utilised in anatomical study, evidence also relates Vz to specific spatial aptitude and performance within this field (Guillot *et al.*, 2007; Hegarty *et al.*, 2009; Nguyen *et al.*, 2014). While prior work has attempted to bolster Vz, little is understood about the origins and processing mechanisms that govern this ability (Terlecki, Newcombe and Little, 2008; Hoyek *et al.*, 2009). Identifying these features may better pinpoint individual weaknesses in VS ability, and permit the targeted intervention of appropriate education exercise to rectify them.

CHAPTER IV

EEG and behavioural correlates of instruction mediated visuospatial education in anatomy

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Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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4 EEG and behavioural correlates of instruction mediated visuospatial education in anatomy.

4.1 Abstract

Many educational benefits have been attributed to instructional visuospatial (VS) education strategy for anatomy students as a result of heightening three-dimensional comprehension. The neural correlates of VS learning, however, are unclear. Here, we have used electroencephalography (EEG) to compare the electrical signals across the scalp during didactic and VS learning as measures of the neural activities underlying these two forms of learning. Thirty 30 healthy participants (aged 18-30 years), each of whom were enrolled in a tertiary degree with anatomical emphasis were included in the study. Participants were divided into two equal groups, each undergoing a task-design with four primary components: (i) Didactic Encoding, (ii) VS Encoding, (iii) VS Task, and (iv) Quiz Evaluation. We report that variance between groups arose only in the type of VS Encoding provided, with one group receiving mild VS direction, and the other moderate. No recall differences were observed in mean score and standard error between groups (mild VS = 12.27 ± 0.60, moderate VS = 13.27 ± 0.75) – however, a significantly higher ability to answer questions requiring VS skills was found in the moderate VS group (mean difference = 1.53 ± 0.64, p = 0.02). No between-group differences in EEG power were observed during either the Didactic Encoding or VS Task phase. Further, although resting EEG power increased across multiple frequency bands after both Didactic Encoding and VS Task periods, these changes did not differ between groups. We conclude that the benefits of VS teaching are not associated with changes in EEG activity using our experimental approach.

4.2 Introduction

A history of utilising arts-based approaches in the teaching of anatomy has been well documented, with recent findings supporting its overall inclusion within a tertiary curriculum (Schlegel *et al.*, 2012; Freeman *et al.*, 2014; Keenan and Ben Awadh, 2019; S. Reid, Shapiro and Louw, 2019). The incorporation of interactive graphical or diagrammatic depictions of anatomical content, promoting geometric or topological understanding, is likely to be beneficial in initial conceptualisation, comprehension and memorisation of anatomical form (Larkin and Simon, 1987; Stenning and Oberlander, 1995; Stern *et al.*, 2003b). A particular directive of this education style is visuospatial (VS) learning, whereby haptic feedback obtained from physical manipulation of an anatomical structure, combined with visual observation, facilitates a deeper three-dimensional (3D) understanding. This comprehension aids not only in understanding the anatomical structure in isolation, but also in how it is integrated with surrounding physiology to accomplish its function (Keenan and Ben Awadh, 2019). It is this conversion of two-dimensional (2D) information into 3D spatial understanding that serves as a primary goal for VS education, having widespread applications in primary clinical care and comprehension of medical imagery. In particular, cohort analyses have outlined several educational benefits present for VS learning, including increased academic scores, improved consolidation of information and recall, and ability to prompt tactile intelligence (Nayak and Kodimajalu, 2010; Azer, 2011; Balemans *et al.*, 2016). In establishing the array of benefits present for VS instruction methods, we now expand on the potential physiological underpinnings in how we perceive this education delivery.

Deviations in archetypal neural signalling, found to coincide with the processing of non-specific artistic observation, indicate a potential neuroscientific basis for the learning benefits of VS learning (Tyler and Likova, 2012b). Generally speaking, the parietal lobe is known to facilitate our perception of multimodal data, i.e. the ability to simplify a variety of sources into a cohesive pathway (Gainotti, D'Erme and Diodato, 1985). This can be particularly evidenced within drawing tasks, where increased parietal activation has been observed (Solso, 2001; Makuuchi, Kaminaga and Sugishita, 2003; Miall, Gowen and Tchalenko, 2009). Specific neural regions, namely the anterior parietal cortex (Hyvärinen, 1982; Felleman and Van Essen, 1991) and precuneus, have been implicated in processing somatosensory information, through incorporating short-term retention of tactile and visual information (Jones *et al.*, 2006). Other brain regions are thought to serve auxiliary roles in processing VS stimuli, including the frontal lobe for execution of informed tactile orientation (Colombo and Gross, 1994), temporal lobe for spatial memory and identification throughout multimodal tasks (Xia and He, 2017), and the cerebellum for motor memory and drawing competency (Ferber *et al.*, 2007; Schlegel *et al.*, 2012). Discussion surrounding the underlying neurophysiology of VS learning has primarily been informed by studies utilising an array of neuroimaging methods, including functional magnetic resonance imaging (fMRI) (Solso, 2001; Kaufmann *et al.*, 2008; Schaer, Jahn and Lotze, 2012) and positron emission tomography (PET) (Corbetta *et al.*, 1993; Kosslyn *et al.*, 1998; Wraga *et al.*, 2003). While these approaches allow for sophisticated exploration of the specific sites of neural activation during task performance, they provide only an indirect measure of neural function based on regional changes in haemodynamic or metabolic activity. This greatly limits the interpretability of the monitored neurophysiological response.

A more direct approach for investigating the dynamics of neural activity in the human brain is electroencephalography (EEG). EEG is a non-invasive technique for recording electrophysiological activity of the brain, measuring voltage fluctuations at the scalp that reflect the summed electrical activity of underlying neuronal firing (Niedermeyer and Silva, 2005). These voltage fluctuations – termed ‘oscillations’ – are thought to coordinate brain regions in facilitating aspects of cognition, e.g. information flow or task planning (Siegel, Donner and Engel, 2012). Oscillations can be divided into a series of frequency bands, each corresponding to a variety of known psychological and behavioural states – the most commonly reported of which are delta (0 - 3 Hz), theta (4 -7 Hz), alpha (8 - 14 Hz), beta (15 - 30 Hz) and gamma (>30 Hz). As an example, alpha oscillatory power is reduced when attention is directed to a visual stimulus, with greater alpha suppression aiding in discriminate task recall (Bollimunta *et al.*, 2008; Vaden *et al.*, 2012). Specifically relating to VS learning, theta power has been correlated with VS working memory and increased performance during motor tasks - outlining a likely role in the maintenance of temporal knowledge (Gevins *et al.*, 1997; Jensen and Tesche, 2002; Caplan *et al.*, 2003a; Sauseng *et al.*, 2010a; Hsieh, Ekstrom and Ranganath, 2011; Perfetti *et al.*, 2011). The frontal midline of the brain, encompassing a diffuse array of medial prefrontal areas, has been implicated as a concentration point for theta oscillations (Sasaki *et al.*, 1996; Gevins *et al.*, 1997; Jensen and Tesche, 2002). Additionally, modulation within theta and gamma frequency bands have been shown to both facilitate the formation of new memories and enhance their rate of consolidation (Perfetti *et al.*, 2011; Ishii *et al.*, 2014). Low-range gamma may also be crucial in distinguishing true from false memories, and aid in developing ‘transient representations’ between multisensory modalities (e.g. visual and haptic integration) (Gray *et al.*, 1989; Sederberg *et al.*, 2003; Kaiser, Bühler and Lutzenberger, 2004; Senkowski *et al.*, 2009).

While advantages have been outlined for the use of VS instruction methods in anatomy education, and neurophysiological evidence shows that VS stimuli can evoke distinct activation patterns, no study has yet explored: (i) whether there is a connection between altered learning outcomes with VS instruction and altered brain activation patterns, and (ii) the nature of this activation. Therefore, the aim of this study was to characterise EEG activity in human participants while they engaged in conventional (didactic) or VS-style learning. We hypothesised that increased guidance provided by VS instruction would result in an increased ability to comprehend 3D anatomical structures, relative to didactic learning styles, and that this would be accompanied by increased frontal midline theta and low-range gamma band activity.

4.3 Materials and Methods

4.3.1 Ethical assessment

This study was approved by The University of Adelaide's low-risk ethical committee (H-2018-233). After making initial contact via either email or phone, all participants were provided with a detailed information sheet. On the day of the session, an informed written consent document was provided to have their task performance evaluated and brain activity monitored. Each component of participant data was de-identified so as to maintain anonymity.

4.3.2 Participants

Thirty-two adults, aged 18-30 years and currently studying for a health-related university degree, were recruited to participate in the study. Two participants were excluded, owing to failure in engaging with the task, leaving 30 total participants equally pseudo-randomly divided into two groups: (i) Mild VS), and (ii) Moderate VS. No significant difference was seen in age between groups (mild VS: M = 21.4 years, SD = 1.9 years; moderate VS: M = 21.8 years, SD = 2.3 years; $t_{28} = 0.493$, $p = 0.626$), and an equal gender spread was present, with 5 male and 10 female members included for each group. Similarly, there was no significant difference in average years of tertiary education experience (mild VS: M = 2.9 years, SD = 1.8 years; moderate VS: M = 3.0 years, SD = 1.5 years; $t_{28} = 0.106$, $p = 0.916$), across an equal degree spread featuring Bachelor of Medicine and Bachelor of Surgery (MBBS), Bachelor of Dental Surgery, Bachelor of Psychological Science, and Bachelor of Health and Medical Science. Eligibility criteria prevented enrolment for those with: a previous history of neurological/psychological disease, a current prescription for central nervous system altering medication, previous drug/substance abuse issues, and uncorrected visual or hearing impairments. Participants were compensated AUD $40 for their time, in the form of a department store voucher.

4.3.3 Study design

Participants were tested one at a time, each seated at a table on which we had placed desktop and laptop computer. Cranial circumference measurements were taken, and an appropriately sized EEG cap with 64-lead electrodes was secured to the scalp of each participant using conductive gel. Study directions were issued verbally, along with advice to maximise clean EEG data (avoidance of unnecessary motor movement, touching of face, etc.). Participants were also made aware of two break periods within the study where they could relax and engage in these behaviours. Software PsychoPy (Peirce, 2007b), installed on the desktop computer, was then used to automatically queue the remaining instruction and stimuli to the participant as they progressed throughout the experiment (Figure 1A).

Each session was primarily comprised of the sequential presentation of four stages: (i) Didactic Encoding, (ii) VS Encoding, (iii) VS Task, and (iv) Quiz Evaluation. These individual components are described in detail below, with divergence in the structure of VS

Encoding acting as this difference between groups. EEG was recorded throughout each stage to assess between group differences in neural oscillatory activity. Prior placement of triggers within PsychoPy software enabled the subsequent excision of relevant EEG data occurring throughout an individual’s engagement with Didactic Encoding and VS Task. Additionally, 1 min of eyes open resting EEG was measured at three times during the session: (1) before Didactic Encoding, (3) after Didactic Encoding, and (3) after VS Task but before Quiz Evaluation. These were included to assess changes in resting oscillatory activity after each stage, and if these differed between groups. Following the conclusion of experimental tasks, EEG recording was stopped and the accompanying cap removed. Participants were then given provisions and time to remove electrode gel from their hair (e.g. fresh towel, warm water), before answering a concluding questionnaire document to gauge individual characteristics and perception of the experiment.

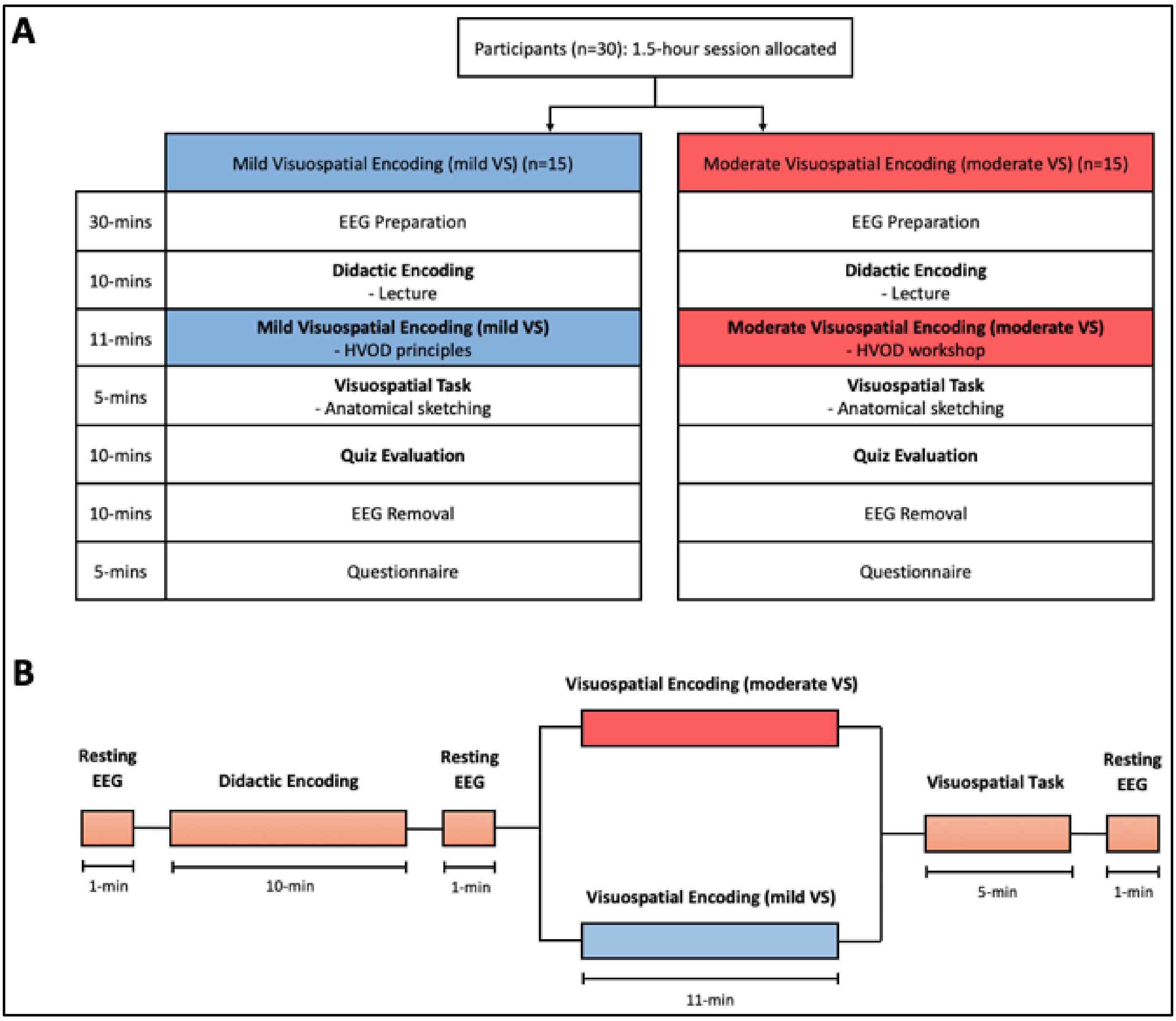


Figure 1: *Schematic overview of experimental design. (A) Flowchart detailing each of the core components within study design. The numbers within each box indicates the time (in minutes) allocated for that component. (B) Not-to-scale timeline outlining the position of EEG specific segments (highlighted using the colour orange) within study design.*

4.3.4 Didactic encoding

To evoke the style of learning typically delivered in tertiary education, a lecture featuring anatomical content was pre-recorded, edited, and shown to each participant at the appropriate time during their session. The video focused on detailing osteological content that would typically be aimed at a first-year level. Content included: distinctions of the skeleton, types of bone, specific anatomy of a long bone, bone composition and accompanying cells, knee joint anatomy and bones of the skull and face. PsychoPy queued the presentation of this video on the provided laptop computer, with the instruction to ‘press spacebar’ when they were ready to start. Use of a pencil or pen was permitted for notetaking throughout the video. These notes were then removed from sight after completion of the video.

4.3.5 Visuospatial encoding

Our selected method of VS Encoding utilised a recently developed learning technique titled the *Haptico-visual observation and drawing* (HVOD) method. This method aims to promote multisensory understanding and spatial adeptness in surveying the 3D complexity of anatomical structures (S. Reid, Shapiro and Louw, 2019). It can be divided into a three-stage process (as seen below), which is then assessed by the “Task Performance” metric immediately following (S. Reid, Shapiro and Louw, 2019).

Stage 1: Identifying and Modifying Repetitive Upper Limb Movements

Stage 1. Prepares the hand and upper limb of the observer to produce directed, purposive, spontaneous, fluid, and varied movements, in contrast to the average, typically repetitive movements.

Two exercises achieve this. The first involves the manipulation of an 80gsm A4 piece of paper and the second exercise involves the making of spontaneous, fluid, and varied marks on paper using graphite.

Stage 2: Visual and Haptic Observation

Stage 2: Haptic and visual exploration of a selected object, in this case a 200g/7oz ball-peen hammer. This exercise is performed with open and closed eyes.

Stage 3: Observation and Drawing

Stage 3: Combined haptic and visual exploration of the object (200g/7oz ball-peen hammer), while *simultaneously* drawing what is being observed.

Task Performance: Application of HVOD to an anatomical structure provided (humerus or skull).

Participants in both groups were provided with all the necessary materials: 8B solid graphite stick, 6B solid graphite stick, sharpener, several sheets of both A3 and A4 paper, and a Masonite board with a pre-placed bulldog clip to secure and stabilise the paper being worked upon.

Moderate VS: Received a filmed recording of an HVOD workshop that had been conducted at the University of Cape Town. This originally 2-hour video, largely comprised of elongated task completion due to Mr. Shapiro's interaction with students, was edited to fit the relatively shorter period of our experiment. This video was shown to participants on the experimental laptop computer. The format allowed participants to hear Shapiro’s explanation of concepts and view his demonstrating a given task, before allowing the participant to attempt that same task that had been explained and demonstrated (Figure 2).

Mild VS: Received the same instruction as Group B, with regards to task completion and examples of anticipated work, without the accompanying HVOD recording and Shapiro’s guidance. Text of the directions was similarly presented to participants on the laptop computer. Time dedicated to each stage remained consistent across groups.

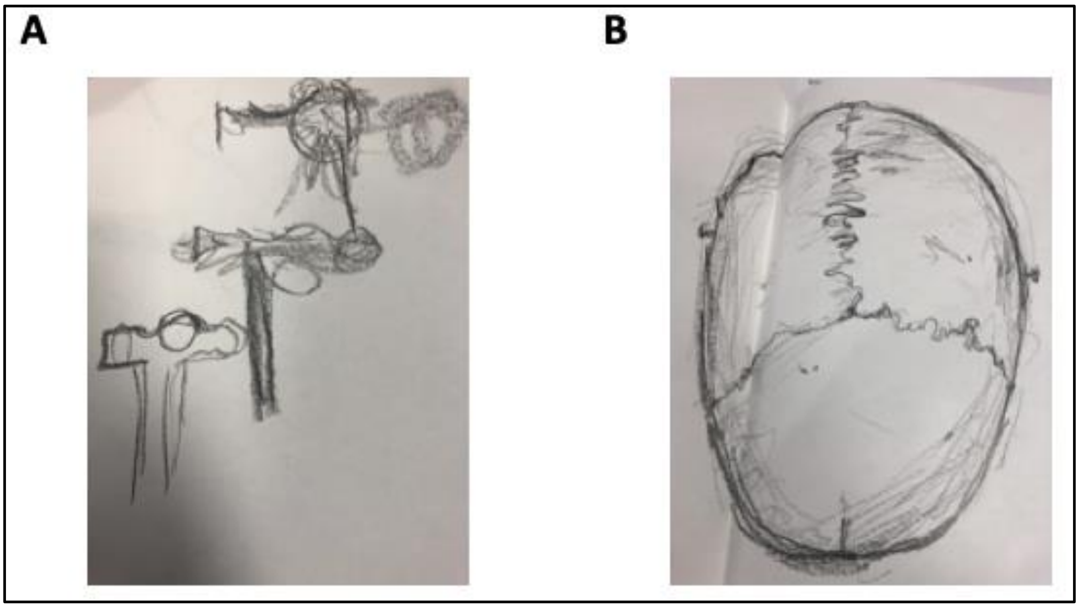
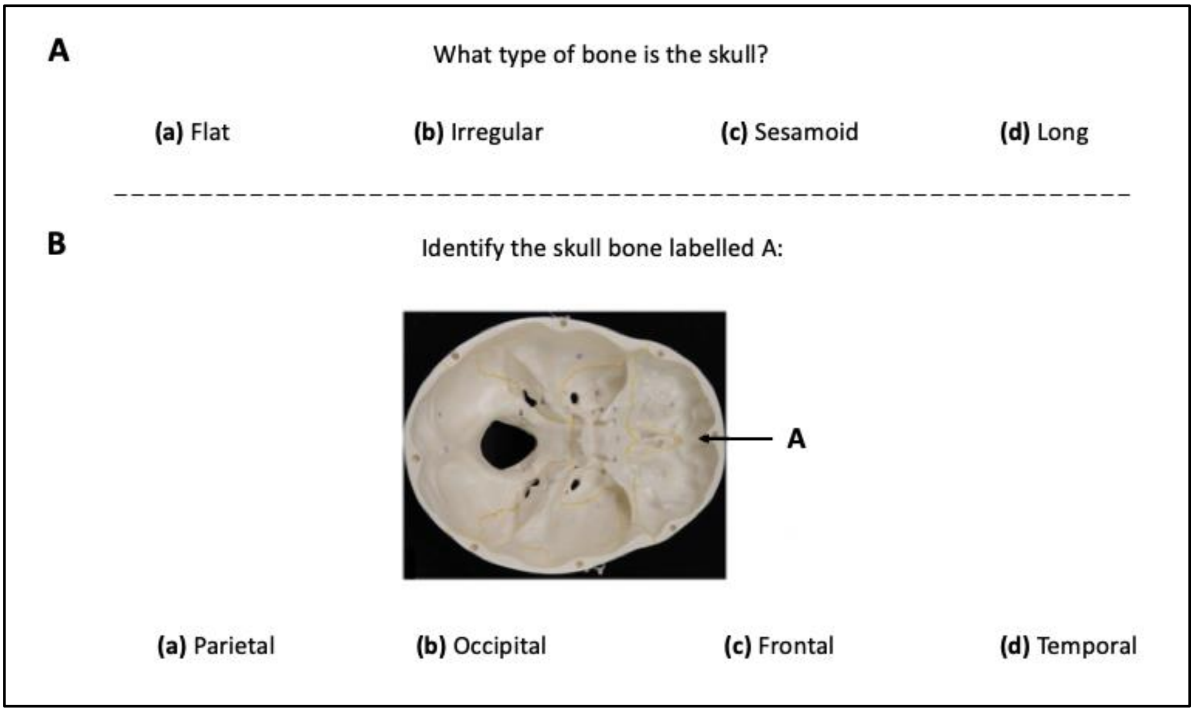


Figure 2: *Example of resultant participant drawings following HVOD instruction (A) A 200g ball-peen hammer focussed upon in Stage 4, (B) The superior aspect of the skull depicted throughout VS Task performance.*

4.3.6 Quiz evaluation

A 20-question multiple choice quiz was designed to evaluate how participants recalled information from the didactic lecture, in combination with those skills of spatial manipulation that had been gained throughout the VS Task. Participants were presented with each question singularly, along with four possible answers - corresponding to keyboard strokes. Once an answer had been lodged, the next question in sequence was queued, with each key stroke registered in PsychoPy as being a correct or incorrect response. The test consisted of two distinct 10-question sections: the first aiming to assess didactic recall of directly presented material, while the second required active spatial manipulation to rotate presented anatomical structures (Figure 3).



A What type of bone is the skull?

(a) Flat **(b)** Irregular **(c)** Sesamoid **(d)** Long

B Identify the skull bone labelled A:

(a) Parietal **(b)** Occipital **(c)** Frontal **(d)** Temporal

Figure 3: *Example of the different components assessed within the quiz evaluation. (A) Recollection of didactic facts. (B) Requiring additional spatial manipulation.*

4.3.7 Questionnaire

To evaluate student perception of experimental design, and VS learning as a whole, a short questionnaire was devised. This consisted of a five-question, five-point Likert scale ranging from strongly disagree → strongly agree.

(1) I concentrated and actively participated in today's session.
(2) I felt distracted by the EEG leads placed on my head.
(3) The material covered in today's session was similar in style, not content, to what you have seen in tertiary education previously.
(4) I would describe myself as someone who enjoys drawing, or as a visuospatial learner.
(5) I am someone who regularly employs drawing as part of their learning or revision (e.g. drawing figures from lecture notes and attaching notes).

4.3.8 Obtaining EEG data

EEG data were acquired using a Polybench TMSi EEG system system (Twente Medical Systems International B.V, Oldenzaal, The Netherlands), that featured 62 electrodes arranged in a 10-10 structure (Waveguard, ANT Neuro, Enschede, The Netherlands). The ground electrode was positioned at a central point on the crown of the scalp (AFz). Gel to conduct electrical potential was applied to each electrode using a blunt-needle syringe, ensuring an impedance of <5 kΩ. Recorded signals were online referenced to the average of all electrodes, sampled at 2048 Hz, amplified 20x and online filtered (DC-533 Hz). EEG data were recorded across the entire session, with periods of interest later extracted and analysed (see 'study design' section above).

4.3.9 Pre-processing of EEG data

Custom scripts within programming platform MATLAB (R2019a, The Mathworks, USA), employing toolbox EEGLAB (Delorme and Makeig, 2004), were used in pre-processing EEG data. Utilising pre-placed event triggers, required segments of EEG spliced from the original sequence and merged into a single array. These components of interest were the: (i) Lecture, (ii) VS Task, and (iii) the minute of eyes-open resting data proceeding and following these interactions. Poor or unused electrode channels were removed. Data were down-sampled to 256 Hz, epoched at 2-second time intervals, and both band-pass (1-100 Hz) and band-stop (48-52 Hz) filtered. An initial visual inspection removed those epochs displaying clear evidence of distortion arising from physical movement - with these extractions being roughly equal in each group and accounting for no more than 5% of each stage’s duration. An Independent component analysis (ICA), employing algorithm FastICA (Hyvärinen and Oja, 2000), was then used to remove artefacts belonging to electrode noise, scalp muscle activity, and eye-blinks. The merged data array was then separated back into its individual segments.

4.3.10 Spectral analyses

Spectral analysis of EEG data was conducted using the FieldTrip toolbox (Oostenveld *et al.*, 2011). Power spectra were computed from EEG time series data using time-frequency analysis with multi-tapers. A time window encompassing 3 cycles was selected for each frequency (in 0.5 Hz intervals), and data were multiplied with a Hanning taper. Power was calculated within each 2s epoch before averaging across trials. The resultant spectra were $\log_{10}$-transformed and averaged into canonical oscillation bands: delta (2 – 3 Hz), theta (4 – 7 Hz), alpha (8 - 14 Hz), beta (15 – 30 Hz), gamma (30 – 4 5Hz).

4.3.11 Data analyses

Statistical analyses were performed using either GraphPad Prism version 9 software or MATLAB R2019a. Unless otherwise stated, calculated behavioural data values are shown as the mean and standard error of the mean (SEM). Significance was likewise conventionally reported as $^{a}p < 0.001$***, $^{b}p < 0.01$**, $^{c}p < 0.05$*. Data were checked for normality using Shapiro-Wilk tests and histogram plots. To compare between-group differences in academic performance both overall and within each constituent sub-category, we employed the separate use of either: (i) a Mann-Whitney U-test for non-parametric behaviour, or (ii) an unpaired (student's) t-test for parametric data. These analyses were conducted and presented separately, to negate positive inflation error.

To gauge questionnaire response, the five potential Likert-scale options were converted to numerical values as follows: "Strongly Agree = 5", "Agree = 4". "Neutral = 3", "Disagree = 2", "Strongly Disagree = 1". As with academic scores, normality was determined for each data set before group response was compared using the correct unpaired analysis.

For neurophysiological data, cluster-based permutation analyses were used to compare differences between mild and moderate VS groups and resting EEG segments. These tests are able to mitigate type 1 error rate when comparing across multiple channels (Maris and Oostenveld, 2007). Clusters were defined as two or more adjacent electrodes, for which the difference in power between groups (unpaired t test) or between resting EEG segments (paired t test) had a p-value < 0.05. To determine whether a cluster was significant, a permutation distribution informed by the Monte Carlo method was employed (simulating 2000 'chance' variations). If the ensuing p-value obtained when comparing the original cluster statistic (defined as the cluster of largest value) with the resultant permutation distribution was p< 0.05 (two-tailed), significance was confirmed.

4.4 Results

4.4.1 Academic performance

To examine group differences in academic performance on the administered quiz, a series of analyses compared both overall results and results within each of the two constituent sub-categories (Figure 4).

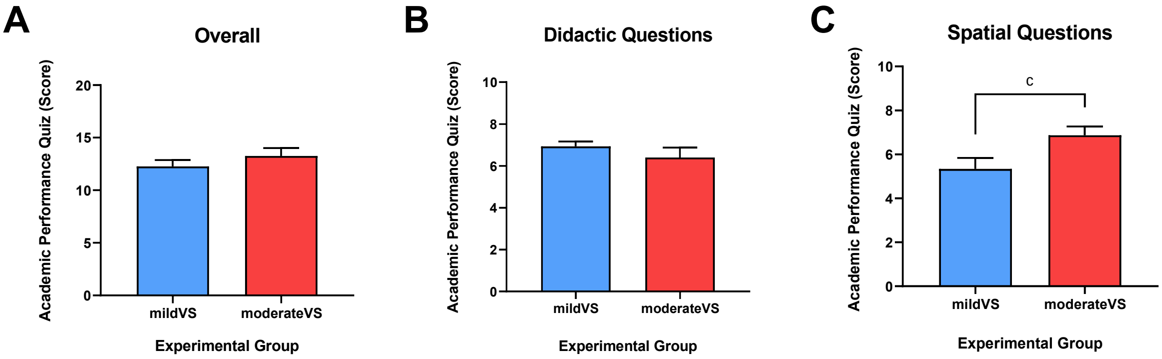


Figure 4. *Mean group score difference between performance on the different components of the academic test. (A) Overall result. (B) Performance in didactic questions. (C) Performance in spatial questions.* $^{c}p < 0.05*$.

Analyses revealed no significant difference between groups when comparing overall academic scores (MD = 1.00, *df* = 28, *t* = 1.035, *p* = 0.2) (Fig. 4A). When comparing constituent sub-categories, this trend continued for didactic questions, where no significance difference was found between groups (MD = 0.53, *df* = 28, *t* = 1.01, *p* = 0.21) (Fig. 4B). However, a significantly greater ability to address questions requiring spatial interpretation was seen in the moderate VS group (MD = 1.53, *df* = 28, *t* = 2.38, *p* = 0.02) (Fig. 4C).

4.4.2 Questionnaire response

To examine if any differences were present across questionnaire items, a collection of analyses were used to compare group response to each of the five presented questions (Table 1). These results are also described graphically in Figure 5.

	Mild VS		**Moderate VS**		
Question	M	SD	M	SD	Stat. Analyses
Q1: Concentration – I concentrated and actively participated in today's session.	4.60	0.49	4.40	0.49	MD = 0.20 *u* = 96 *p* = 0.11
Q2: Distraction – I felt distracted by the EEG leads placed on my head.	1.47	0.50	1.53	0.50	MD = 0.06 *u* = 98 *p* = 0.86
Q3: Similarity – The material covered in today's session was similar in style, not content, to what you have seen in tertiary education previously.	4.27	0.85	4.13	0.85	*df* = 28 *t* = 0.36 *p* = 0.72
Q4: Visuospatial Learner – I would describe myself as someone who enjoys	4.00	0.73	3.00	0.73	*df* = 28 *t* = 2.65 *p* = 0.008

drawing, or as a visuospatial learner.					
Q5: Drawing Interest – I am someone who regularly employs drawing as part of their learning or revision.	3.37	1.14	3.53	1.14	MD = 0.16 *u* = 111 *p* = 0.97

Table 1. *Mean differences between groups in response to questionnaire items. Likert score range where 'strongly disagree' corresponds to a value of 1, and 'strongly agree' to a value of 5. Items returning significant differences between groups are highlighted in grey.*

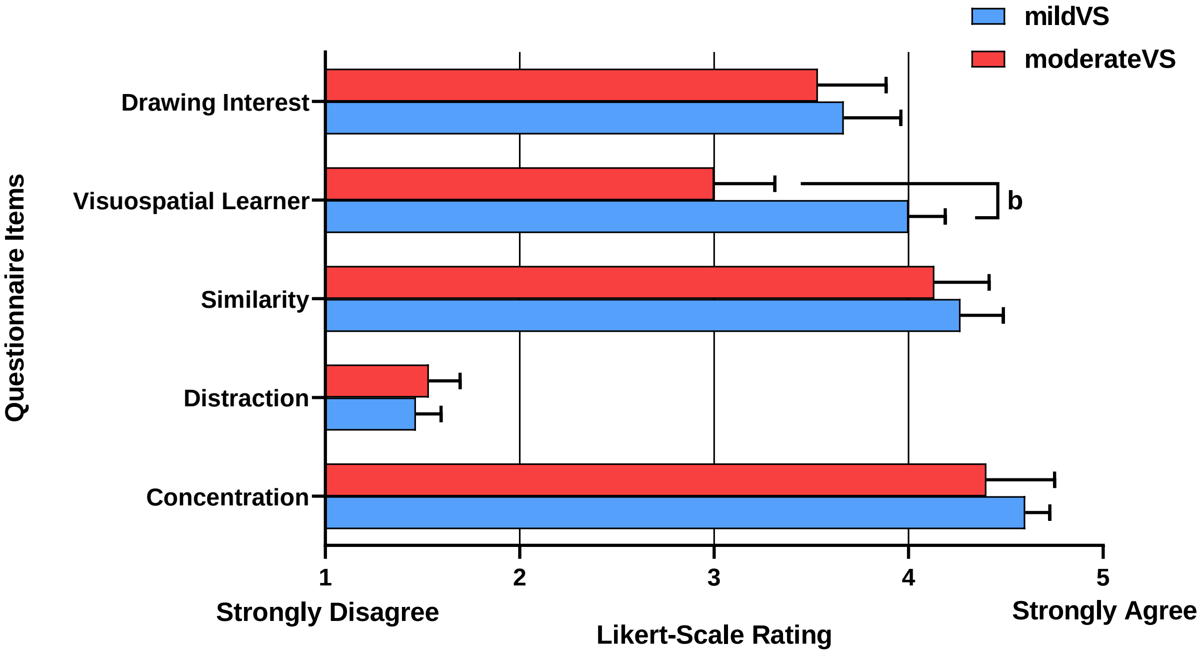


Figure 5. *Mean difference between groups in response to questionnaire items. Titles are abbreviations from those questions expressed in full within Table 1. Likert score range where 'strongly disagree' corresponds to a value of 1, and 'strongly agree' to a value of 5.* $^{b}p < 0.01^{**}$.

Of each of the five questions presented, only one item “I would describe myself as someone who enjoys drawing, or as a visuospatial learner” showed a significant difference between groups (MD = 1.00, *df* = 28, *t* = 2.65, *p* = 0.008) - with participants in the moderate VS group reporting significantly lower enjoyment in drawing or in their VS learning desire or capabilities as compared to the mild VS group. Other item comparisons showed no significant difference in ratings between groups when responding to questions surrounding participant concentration (*p* = 0.11) or distraction (*p* = 0.86) throughout experiment, similarity with prior material (*p* = 0.72), or interest/use in drawing (*p* = 0.97). These results confirmed that there were no discernible differences between groups in the way in which participants experienced the experiment, with concentration levels being reported as quite high, and distraction levels being low.

4.4.3 Between-group differences in oscillatory power during learning activities

In order to establish whether any differences existed between groups in the way in which learning activities were processed, we examined spectral power obtained throughout both the Didactic Encoding (lecture) and VS Task stages to determine whether any changes in neural oscillatory activity were present in distinct frequency bands (Figure 6).

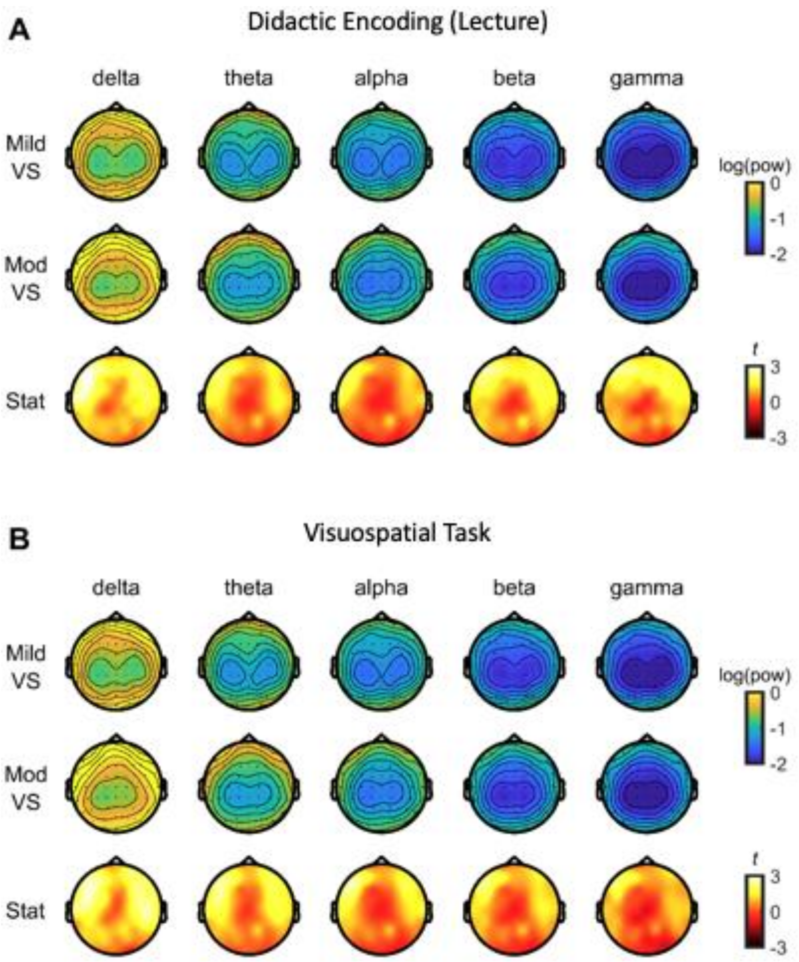


***Figure 6:** Normalised log power across indicated frequency bands throughout learning activities. (A) Lecture viewing. (B) VS task performance. Topoplots show* $\log_{10}$*-transformed power in mild VS (top row) and moderate VS (middle row) groups, and t-statistics comparing between them (bottom row). Black dots indicate non-significant clusters.*

Cluster-based permutation tests revealed no significant differences between groups during either lecture viewing (Fig 6A) or task performance (Fig 6B) in any frequency band ($p \geq 0.057$). As there were no experimental differences proceeding or throughout the lecture between groups, results for this activity are unsurprising. However, it is striking to note that the disparate VS Task approaches taken in each groups design did not elicit any significant changes. We therefore find no evidence to suggest that increased VS guidance throughout anatomical task performance impacted neural oscillatory power.

4.4.4 Changes in resting oscillatory power following learning activities

Next, we examined spectral power from eyes open resting EEG recorded either side of each learning activity to determine whether any differences could be found in resting oscillations (Figure 7).

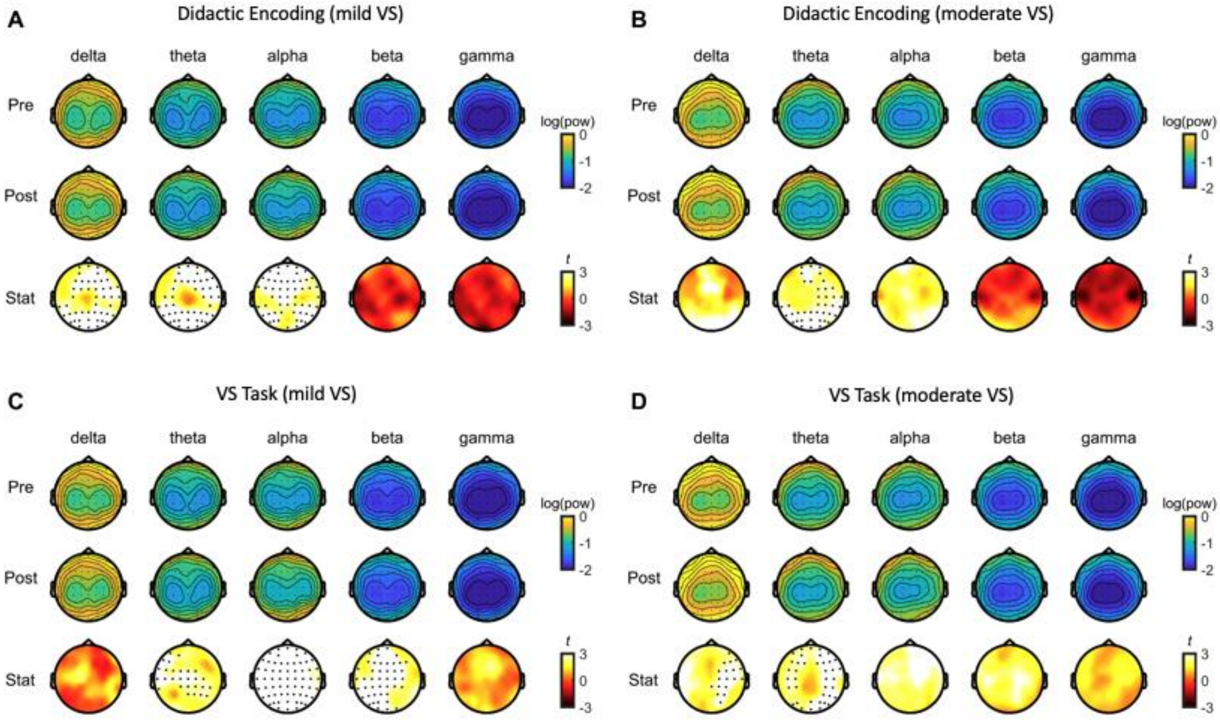


Figure 7. *Normalised log power across indicated frequency bands from "eyes-open" resting EEG before and after learning activities. (A) and (B) Lecture viewing in mild and moderate VS groups, respectively. (C) and (D) VS Task performance in mild and moderate VS groups, respectively. Topoplots show log*$_{10}$*-transformed power both pre- (top row) and post- (middle row) each learning activity within each group, and t-statistics comparing between these conditions (bottom row). White dots indicate significant clusters identified in permutations tests, while black dots represent non-significant clusters.*

Cluster-based permutation tests revealed a number of significant differences resulting from engagement with learning activities in both groups. In the mild VS group, resting oscillatory power was increased following lecture viewing in the delta ($p = 0.003$), theta ($p = 0.002$) and alpha ($p < 0.001$) frequency bands (Fig 7A), while following task performance, increases were observed in the theta ($p = 0.008$), alpha ($p = 0.001$), and beta ($p = 0.009$) bands (Fig 7C). For the moderate VS group, resting oscillatory power following lecture viewing was only increased in the theta band ($p = 0.009$) (Fig 7B) - while following task performance, increases were present in both delta ($p = 0.005$), and theta ($p = 0.005$) (Fig 7D). No clusters were observed in the gamma frequency band for either learning activity or group. Results show that irrespective of experimental conditions, increased resting oscillatory power was observed across multiple frequency bands following academic learning activities.

4.4.5 Between-group differences in altered resting oscillatory power following activities

Building upon the results in Figure 7, we aimed to determine whether the change in resting oscillatory power observed following each learning activity differed between mild and moderate VS groups.

Cluster-based permutation tests revealed no significant differences between groups when comparing changes in resting oscillatory power following either learning activity. Increased delta oscillatory power following VS Task performance tended to be larger in the moderate compared to the mild VS group, although this did not reach significance ($p = 0.053$). For changes in lecture viewing, no clusters were identified. Results suggest that there are no overt changes in neural signaling that result from increased VS guidance during education, but that non-significant associations identified in the delta frequency range warrant further exploration.

4.5 Discussion

In this study, we investigated how academic performance and neural oscillatory activity were affected by two contrasting methods of VS guidance (differing in magnitude of guidance provided), to a more didactic education counterpart. No significant differences in performance was observed in the total score achieved by those participants in the more moderate VS group (moderate VS) as compared with the mild VS group (mild VS). However, when separated into individual components, a significantly higher ability to reason through VS information was found for moderate VS (Fig. 4c). This demonstration of higher performance contradicts questionnaire responses, where the moderate VS group reported significantly lower levels of competence and enjoyment with VS material (Table 1, Q4). When exploring the EEG response, no between-group differences in oscillatory power were observed during either the Didactic Encoding or VS Task phase. Further, although resting EEG power increased across multiple frequency bands after both Didactic Encoding and VS Task periods, these changes did not differ between groups. While these findings confirm the established academic benefits of VS teaching methods, the underlying neurological mechanisms remain obscure.

4.5.1 Behavioural differences

Encouragingly, across both questionnaire items posed to participants regarding their experience of the experimental session, there was no observed difference in response between groups. High levels of concentration paired with low levels of distraction suggest the behavioural and electrophysiological data was collected consistently and reflects high levels of internal validity. Academic familiarity with anatomical material was equally high with participants in both groups. Therefore, findings support that the inclusion criteria for this study was effective in attracting students with basic anatomical knowledge, but lacking the in-depth anatomical content introduced during the experimental session. Both groups claimed to have similar levels of interest in drawing (n.s., MD = 0.16), corresponding to an indifferent position on the questionnaire scale. This aligns with current literature that highlights the polarising nature of compulsory drawing exercises within anatomical curricula (Nayak and Kodimajalu, 2010; Balemans *et al.*, 2016).

Reported identification as a VS learner was significantly lower in the group receiving the more guided VS education delivery (moderate VS). This may be attributed to previously reported components such as (1) the more structured and rigid method by which this education was delivered (Backhouse *et al.*, 2017), or (2) the amount of individual and specialised attention provided by the educator themselves (Mattheis and Jensen, 2014; Noorafshan *et al.*, 2014). Alternatively, participants in the moderate group were exposed to our categorisation of a ‘VS design’, as opposed to the mild group who answered ambiguously, thereby having unbiased freedom to create their own interpretation. This aligns with previous findings reporting student desire for the availability of multi-modal learning approaches within tertiary education, such as VS delivery (Samarakoon, Fernando and Rodrigo, 2013; Backhouse *et al.*, 2017; Moro, Smith and Stromberga, 2019).

4.5.2 Academic differences

Overall academic performance (relating to the knowledge and ability to retain specific session information) did not improve in the group receiving moderate VS education, against our hypothesis that it would. This reporting an improvement in behavioural response and academic performance in response to arts-based teaching styles (Lyon *et al.*, 2013; Pujol *et al.*, 2016; L. Shapiro *et al.*, 2020). An interesting aspect of this study lay in its cross-sectional design, compared to longitudinal studies (Ranaweera and Montplaisir, 2010; Balemans *et al.*, 2016) that have evaluated the progression of desired academic outcomes over time. Prior literature has mainly focused on repeated-measures (Alsaid and Bertrand, 2016; S. Reid, Shapiro and Louw, 2019) or longitudinal studies that evaluate long-term progression of academic outcomes (Ranaweera and Montplaisir, 2010; Balemans *et al.*, 2016).

This study provides a different perspective on VS learning methods within the field of education. The ongoing propagation of systems such as VARK (Visual, Aural, Read/Write, Kinaesthetic) which suggest the presence of distinct leaning styles, each of which being best serviced by a different pedagogical education approach (Fleming and Mills, 1992; Pashler *et al.*, 2008b; Husmann and O'Loughlin, 2019), continue to be reinforced despite being discredited for lack of academic merit. Therefore, VS methods may commonly be introduced in a random and casual manner outside of the established syllabus, to appease each suggested learning style. Consequently, such VS methods may receive minimal support from teaching staff who are under-resourced to facilitate such methods optimally - resulting in both poor academic outcomes and student perceptions of the content delivery (DeSutter and Stieff, 2017).

In line with previous evidence (Backhouse *et al.*, 2017; Wainman *et al.*, 2020), this study suggests that the introduction of a short-term VS project does not elicit any academic benefits. The extent of guidance between groups proved irrelevant when evaluating a short-term VS task. However, when the data was isolated we noted that VS performance and reasoning was increased with a corresponding level of guidance provided. This suggests VS ability could be improved in a short time span. However, benefits may be limited to personal skill acquisition in short-term investigations, while translation to wider academic outcomes may need to be elucidated in longitudinal approaches.

4.5.3 Neural differences throughout learning activities

No neural differences were observed between groups when individuals were engaged in either the: (i) Didactic Encoding (lecture) or (ii) VS Task. Being that there was an absence of experimental design differences either proceeding or throughout the lecture between groups, null findings for this activity align with our hypothesis, and further reiterate that between-group variation in baseline oscillatory power did not exist. However, lacking differences throughout the latter VS Task activity contradicted out hypothesis that divergent levels of guidance provided in VS Encoding (i.e. mild vs moderate), would result in contrasting neural signalling patterns when participants applied their strategies to novel tasks.

The VS Encoding phase tasked participants with identical performance of a variety of workshop steps (motor output), with variation in the level of attention paid to provision of this material (sensory input) being the point of difference between groups. It was anticipated that the increased guidance provided to the moderate VS group would then relate to an increased receptiveness and ability to apply VS techniques within the task period. If present, this greater VS consideration would likely have been evidenced through participant expression of heightened visual input (Kuschel *et al.*, 2010; Tyler and Likova, 2012b), tactile feedback (Tal and Amedi, 2009), and haptic exploration (Klatzky and Lederman, 2011; Loomis *et al.*, 2012). While no evidence has previously captured how neural excitability relates to these individual components throughout practical VS education, data associated with their isolated presentation provided an initial reference point for our analyses. These include: (i) increased suppression of oscillatory alpha power in pre-frontal cortex areas following engagement with a visual stimulus (Bollimunta *et al.*, 2008; Vaden *et al.*, 2012), and (ii) increased theta power across the frontal midline of the brain when utilising VS working memory (Jensen and Tesche, 2002; Caplan *et al.*, 2003a; Sauseng *et al.*, 2010a; Perfetti *et al.*, 2011). Given our results do not support our hypothesis, we find little evidence to suggest that the magnitude of VS guidance provided in the encoding-phase influences a student's ability to apply VS consideration throughout a task.

A novel element of this study involved amalgamating EEG data across the entirety of education, which allowed a comprehensive overview of oscillatory fluctuations. However, this could have alternatively resulted in masking of local effects in time-locked datasets. Previous studies have aimed to evaluate such components by utilising an alternate EEG metric, Event-Related Potentials (ERPs) to explore micro-fluctuations in electrical signals that coincide with each activated component (Brandeis and Lehmann, 1986; Nelson and McCleery, 2008).

A confounding variable could stem from the participants' declining attention spans during the educational periods, albeit these were relatively short in comparison to their real-world counterparts. Indeed, behavioural and cognitive EEG studies report how accessory considerations such as working memory, attention span and motivation have the capacity to influence experimental task data (Lorist *et al.*, 2009; Grissmann *et al.*, 2017; Ko *et al.*, 2017). A final factor of potential difference is the impersonal nature of VS information delivery and task. While on-line lectures continue to rise in prominence within tertiary education, information encompassed within a VS design has yet to be optimised for this format (Allen, Eagleson and de Ribaupierre, 2016; Green *et al.*, 2018). We therefore may not have been able to capture the essence of a true, guided VS design as we utilised pre-recorded electronic delivery, compared to a live and direct format. This transition to an online delivery of learning content has previously been shown to elicit differences in attention within EEG research (Ni, Wang and Liu, 2020).

4.5.4 Neural differences after learning activities

Marginal increases in resting oscillatory power were found within the two groups when comparing eyes-open resting EEG preceding and following learning activities. This reiterated the capacity for each learning activity to indiscriminately elevate resting oscillatory power and can likely be attributed to engaging the participants. Comparing these changes in power between groups showed no differences for either activity. The absence of significant differences in task performance between groups does not support our hypothesis that increased guidance with the moderate VS group would equip them with a heightened ability to retain 3D information, which would result in distinct neural signalling patterns.

Taken together, these results suggest VS guidance was difficult to elucidate under our experimental design. In addition to those features of oscillatory power theorised to reflect VS consideration throughout task performance, we anticipated that subsequent consolidation of VS information would evoke signalling differences. With scant prior evidence shaping how these differences may present following the practical opportunity to apply VS skills, we instead looked to the change in resting EEG data that had been isolated in stimulus-based VS tasks as a starting point. Noticeably centred around findings in mid-range frequency bands, these studies find increased: (i) beta synchronization following both motor task training and VS skill acquisition (Mima *et al.*, 2000; Serrien and Brown, 2003; Boonstra *et al.*, 2007), (ii) alpha power in mediating task performance related to perceptual learning (Payne and Sekuler, 2014; Bays *et al.*, 2015), and (iii) theta power in successful encoding and retrieval of episodic memory (Sederberg *et al.*, 2003; Hsieh, Ekstrom and Ranganath, 2011; Roberts, Hsieh and Ranganath, 2013; Rozengurt *et al.*, 2016). It has also been suggested that VS skill has a correlation with long-band oscillatory synchronization in the low-range of gamma frequency (Senkowski *et al.*, 2009; Ng *et al.*, 2011). We did not find any evidence to support this view. Paradoxically, the closest our results came to showing a difference for the effect of guidance between groups following task performance lay in a non-significant association within the delta frequency range, a component of EEG spectra that has previously shown little association with VS stimuli or processing (Harmony, 2013).

We theorise three potential reasons why our results are at odds with previously published data: (1) group differences in VS Encoding were not sufficient in altering how a participant would approach a novel task, (2) the VS Task did not effectively engage participants to apply their VS consideration, or (3) EEG was not the optimal measure to capture the changes that occurred. Concerning the latter point, mapping of voltages to brain areas is notoriously difficult through EEG alone, with standardised positioning of electrodes often failing to account for nuances the composition of an individual's cortex (Towle *et al.*, 1993; Jurcak, Tsuzuki and Dan, 2007). Future studies might look to incorporate the simultaneous use of other approaches, such as fMRI and transcranial magnetic stimulation (TMS), in conjunction with EEG to further investigate brain areas that contribute towards VS understanding.

4.5.5 Limitations

Resulting from disparities in required sample-group sizes for electrophysiological recordings and behavioural analyses, academic results within this study were not conducted on a scale that was likely to reveal significance. Specifically, we observed a trend in overall quiz performance within the moderate VS group, that may have been a more robust difference if examined in a larger sample size (Backhouse *et al.*, 2017). Another limitation lay in our delivery of guided VS instruction through the use of a pre-recorded video. While this ensured that identical information was provided to each participant, it meant our design did not fully impart the individualised experience for each student that is purported by this method. Owing to the positioning of electrodes on the scalp, EEG technology is limited in its ability to detect changes in deeper aspects of the brain such as the limbic system. It is in this system that we might have found fluctuations associated with memory storage or conversion centres throughout either learning modality (Lega, Jacobs and Kahana, 2012; Longoni *et al.*, 2015). While emerging techniques in data processing are purported to be able to transduce this subcortical information from transient EEG recordings (source localisation), these methods pale in comparison to established measures such as fMRI in being able to detect spatial location of deeper neural activity (Dumontheil and Klingberg, 2012; van Geest *et al.*, 2018). Lastly, given that task performance required the physical manipulation of objects, it was unclear to what extent corresponding temporary elevations in primary motor cortex activity (arising from this movement) would confound the ability to evaluate the underlying neural learning response. Future studies may look to omit recordings throughout task performance, and instead place more emphasis on resting EEG data either side of task delivery, where motor activity can be negated entirely.

4.5.6 Conclusion

Results from this study support the inclusion of guided VS instruction methods within tertiary anatomical education, specifically for their ability to heighten 3D conceptualisation and understanding of relevant imaging material. However, no observable electrophysiological differences account for the effect of this guidance when applied to a novel stimulus requiring spatial consideration. Future research should explore the time-locked neural responses that may be present for individual components comprising this VS education, and to discern the longitudinal behavioural benefits that are present in a more guided approach.

CHAPTER V

General Discussion

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5 General Discussion

Within recent academic literature, there has been much discussion surrounding the merits of implementing visuospatial guidance methods in fields such as anatomy education. By encouraging accurate three-dimensional consideration of a relevant target structure or system, these instructional methods excel in providing an individual with a comprehensive appreciation of anatomical relationships that can be utilised in subsequent clinical application. Although the benefits of these approaches are apparent for an individual, it remains unclear as to whether both the underlying mechanisms and these effects scale to encompass a large-group cohort. Thus, the experiments described in this thesis have investigated the: (i) results of including visuospatial exercises within a large cohort of anatomy students, (ii) role of individual spatial ability in facilitating these outcomes, and (iii) novel markers of cognition and neural signaling that may underlie VS guidance.

5.1 Visuospatial methods possess course-wide learning benefits

Reports in academic literature suggest that including VS approaches to teach anatomy to individual students and small groups are highly beneficial. However, what remains to be elucidated on is the efficacy of these methods when scaled to large-group cohorts (Backhouse *et al.*, 2017; L. Shapiro *et al.*, 2020). Therefore, in Chapter 2, I explored this question by introducing a novel VS education system within the existing curriculum of a large undergraduate anatomy course. The findings of this study support prior contentions that advantages of these approaches would extend to a wider group of students – with higher academic performance and engagement being reported in those students receiving VS (rather than didactic) education (Luursema, Vorstenbosch and Kooloos, 2017; Stephen Reid, Shapiro and Louw, 2019). This corresponds to similar results seen for the inclusion of visual arts directives, such as drawing and plasticine modelling, within large anatomy student cohorts (Naug, Colson and Donner, 2011; Balemans *et al.*, 2016).

It is worth noting that this study investigated only the immediate recollection of information that had been obtained throughout the session. As touched upon throughout various parts of this thesis, a major strength of visual arts directives (inclusive of VS methods) is not only limited to improvements in initial conceptualisation of information, but also how readily this can be retained and recalled through long-term memory (Ainsworth, Prain and Tytler, 2011; Moore *et al.*, 2011). While we had initially planned to examine this by testing students at later points throughout the semester, it was decided that the methodological approach we had selected would not adequately control for external confounding variables. Consequently, it remains unsubstantiated that the specific VS methods we used can exert long-term influence on knowledge retention when used in a large-group setting.

A secondary question addressed within both Chapter 2 and 4 was whether the inclusion of a short-term (once-off) VS intervention would be capable of transferring these educational benefits. While inconsistent results were seen for overall score, spatial consideration of anatomical material was demonstrated to be heightened in both chapters. This was an interesting finding, as other sources commonly report that such VS methods feature in formalised-guidance provided by an educator across an extended duration (Greene, 2018b; Stephen Reid, Shapiro and Louw, 2019). These are typically administered through repeated instruction with students at regular intervals throughout a learning module, or isolated longer-form workshops that incorporate an opportunity for individualised feedback. Additionally, the context of these sessions is often limited to the revision and consolidation of material (Pickering, 2015; Balemans *et al.*, 2016). Findings of this thesis suggest that VS methods may feature more diverse application than previously thought. Specifically, that these methods can be adapted to introduce new concepts to a student group, in a format not requiring manipulation of existing curriculum architecture. One might propose that VS directives may even be best implemented prior to more formalised coverage of an anatomical system in question. When first possessing three-dimensional appreciation of a novel anatomical structure, an individual is more likely able to understand its function and more easily able to annotate relevant features.

A theorised constraint of VS methods is the requisite skills and experience needed by an educator or faculty, with implementation of these methods commonly attributed to an individual with a visual arts background and most importantly, one with a sound understanding of how to tailor an arts-based practice in order to achieve a VS outcome for the student. Numerous interventions aiming to combat this perception are in progress. Such interventions highlight that provisional delivery of VS principles can be conveyed through consultation of openly-available online platforms.

In accordance with our hypotheses, Chapter's 2 and 4 of this thesis found that in the instances where students were presented with a visuospatial task, it was found that academic advantages in their spatial understanding followed. We can therefore postulate that VS methods used in these studies strengthened an individual's retention of 3D form, affording them a greater capacity to manipulate structures and apply information in practice. Didactic information recall was found to only accompany these findings in Chapter 2, allowing us to theorise that VS methods did not enhance the intake of details – but importantly, how those details translated into application. As touched upon in Chapter 3, this application possesses broad relevance in clinical scenarios requiring informed consideration of concealed patient biology - a growing component of which relates to medical imaging (Hegarty *et al.*, 2007; Nguyen *et al.*, 2014). With this in mind, broader medical curriculum is being engaged to consider whether it now services these clinical expectations (Benatar and Daneman, 2020; Elsayes *et al.*, 2021). While the experimental Chapters 2, 3, and 4 of this thesis elucidate the promise of VS techniques to bridge this connection to clinical application within the classroom, the provided Appendix Chapter demonstrates how the same principles can also be utilised in practical application (e.g. surgery) to better understand 3D form. Thus, these data suggest VS methods (as exemplified by the HVOD method selected in Chapter 4 and Appendix Chapter) pose a plausible option in providing translatable spatial skills to learners at different points of medical understanding (L. Shapiro *et al.*, 2020; Branson, Shapiro and Venter, 2021).

5.2 Visuospatial methods and competency are poorly identified

A common finding across Chapters 2, 3, and 4 was that participants perception of their innate VS skills did not correlate with their performance in VS testing. This was most apparent in Chapter 3's comparison of isolated spatial reasoning ability, but was also incorrectly recognised in relation to the learning approaches of Chapters 2 and 4. Extrapolating upon these findings, this discrepancy may have arisen on account of two factors: (i) incorrect understanding of the nature of visuospatial methods, and (ii) mistaken correlation that previous problem-solving capacity or associated learning preferences predict VS understanding.

The first of these points can be exemplified through our direct comparison of questionnaire item 'I would describe myself as a visuospatial learner' and attributable test scores in Chapter 3 and 4. Finding no existing connection between these metrics, our results align with those in prior multi-disciplinary studies purporting individuals as poor identifiers of their performance attributes (Lambe and Bristow, 2011; Sharma *et al.*, 2016). In theorising a basis for this disparity, the term 'VS understanding' can often draw relation to mathematical reasoning abilities (Mix and Cheng, 2012). This may be associated with how the latter component of the word, 'spatial' is used colloquially to denote dimensional considerations. Indeed, a consistent point of qualitative feedback heard throughout the conducting of each experimental study of this thesis, was student anticipation that presented material would be of a more arithmetic nature - akin to stimuli of the Mental Rotations Task utilised in Chapter 3.

Further ambiguity may also have arisen due to the somewhat miscellaneous definition of what is encompassed by the term 'VS education'. Students may have been afforded greater flexibility to project their assumptions that these techniques relate to a sophisticated 'all-encompassing' teaching method. Findings of Chapter 2 add reference for these concerns, with the group not receiving VS education being more receptive to the 'theoretical idea' of these methods being effective. By contrast, students who had seen a proponent of this method were better aware that it possessed constraints much like any other means of education.

Addressing point (ii) above, misconceptions surrounding learning predispositions appear to add further weight to these discrepancies. Indeed, diverse results found in each experimental chapter of this thesis provide associated support for growing scientific consensus that not only are these classification systems inaccurate, but also potentially detrimental towards students' confidence and ability to engage within a course (Pashler *et al.*, 2008b; Papanagnou *et al.*, 2016). While nuances between different learning approaches is acknowledged within several of these classifying systems, the aforementioned issues can arise in separating individuals into distinct groups and passively instilling within them a sense of the optimal methods they should look to utilise, while foregoing others (Husmann and O'Loughlin, 2019). Furthermore, such methods are inherently biased by student errors in self-identification (e.g. as either an aural or visual learner), and the corresponding surveys accept that a student is accurately aware of their learning approach (e.g. 'learning through visual means' and association with drawing expressed in Chapters 3 and 4) (Norman, 1988; Kollöffel, 2012). This is not to say that comparing individual response to questionnaire items provides little value (as performed in each experimental chapter), but instead that extrapolation of these questions to governing theories of learning approaches is inappropriate. As an alternative theory to prototypical learning approaches, sentiments expressed in wider education literature contend that it is the commitment to focussed attention in any teaching approach that best predicts overall class outcomes (Dyche and Epstein, 2011; Gottlieb, 2012). This facilitates greater student engagement and ability to retain relevant information.

5.3 Spatial ability does not appear to limit visuospatial use in anatomy

Owing to the perceived skills required, concerns have been expressed that the success of VS education design within anatomy curricula would be contingent upon overarching spatial abilities possessed by an individual (Berney *et al.*, 2015). To address these points, Chapter 3 investigated whether raw spatial ability would be associated with aptness to either apply spatial reasoning when regarding anatomical content or performance on test scores within this subject field.

Addressing the first of these relationships, a correlation was seen between raw spatial ability (as demonstrated through geometric understanding) and specific spatial reasoning when presented with anatomical content. These results support conventional wisdom and prior scientific reports that propensity for anatomical interpretation (e.g. diagnostic medical image rotation) is linked to inherent spatial ability (Langlois *et al.*, 2020). Though utilising a different approach, these findings are consistent with those reported by original authors Nyugen et al., (2012) who created and verified the Spatial Anatomy Task (SAT). They also support practical results seen in small-group cohorts of anatomy students engaged in medical education curricula (Henn *et al.*, 2018; Bogomolova *et al.*, 2020).

For the latter of these associations, findings showed that there was no association between an individual's underlying raw spatial ability and subsequent capacity to recall anatomical material resembling that presented within tertiary assessment. Though findings are limited by the brief nature of their introduction and assessment, they provide an initial support for the notion that VS education strategies would not be limited by the spatial aptitude possessed by the sole learner. As touted within wider educational literature, a vast array of external features extending beyond the scope of this thesis would likely have implicated these academic findings – including requisite passion for the content, drive to perform, and direct clinical applicability of the content being taught (Roh and Jang, 2017; Gilal *et al.*, 2019; Bond *et al.*, 2020). More pertinently, we must acknowledge that attention and motivation to perform in the experimental protocol does not exactly match that which is paid towards real curriculum items, clouding our ability to draw a more definitive connection. Nevertheless, our report was the first to attempt an understanding of whether this knowledge corresponded to greater didactic or spatial information.

Interpolating the combined context of these results, the influence of individual spatial ability appears to reduce when the individual engages in mental manipulation while at the same time attempting to integrate specific information. This is consistent with a feature termed ‘cognitive overload’ by the multimedia theory of learning (Sweller, 1988; Mayer and Morenno, 1999). When relating these results to those described in section 6.1 above, Chapter 2 provided supportive evidence that VS education was able to elevate spatial understanding within a large undergraduate group of anatomy learners. This large sample size accounts for a broad spectrum of spatial ability. Thus, we can confidently say that the varying degrees of spatial ability in students did not affect the implementation of VS methods; at least not across the short-term demonstration of these skills tested in this study.

In attempting to find a cognitive basis for these spatial results, Chapter 3 provided further context for the previously described relationship between visualisation (Vz) ability and anatomy performance (Garg, Norman and Sperotable, 2001; Nguyen, Nelson and Wilson, 2012). Interpersonal variability in Vz is thought to reflect VS working memory - the rate at which visuospatial information can be processed and stored (Carroll, 1993b; Miyake *et al.*, 2001; Cohen, 2005). This made it an excellent point of exploration for broadening the thesis, with results in Chapter 3 further rationalising its importance when considering spatial relationships in anatomical imaging. This is a point laboured in relation to practical radiological understanding, but currently features inadequate reinforcement by scientific understanding (Luursema *et al.*, 2008; Vorstenbosch *et al.*, 2013). While the attempt of prior reports had explored isolated relationships between Vz ability and (i) overall anatomy score, and (ii) performance on anatomy questions requiring spatial consideration, results in this chapter demonstrated that the apparent connection between these three variables may not be as clear as had been postulated by prior authors (Guillot *et al.*, 2007; Lufler *et al.*, 2012).

When results of Chapter 3 were further itemised to explore any underlying demographic associations, a discernible trend in superseding male performance was seen on both isolated and spatial anatomy tests. Though underpowered for any significance to be drawn, findings of Chapter 4 also provide circumstantial evidence for these claims. These findings are well-substantiated but somewhat divisive in the 21st century due to the claim that males possess higher raw spatial ability than their female counterparts (Peters and Battista, 2008; Wei, Chen and Zhou, 2016). Interestingly, results then followed that this correlation ended relating overall academic scores. Two potential explanations for this could assert that (i) other relevant attributes such as intellect are far better utilised in this assessment, or (ii) spatial ability assumes a lower importance in predicting learning than imagined. In any case, gender does not appear to predict anatomy performance in any way.

5.4 No EEG differences add to our understanding of visuospatial processing

In Chapter 4, I presented the first EEG based study to investigate the differences in neural signalling to account for the educational benefits observed in VS teaching (reported throughout both external literature and each experimental chapter of this thesis). Findings showed that no significant differences in oscillatory power evidenced that a guided VS instruction method was able to alter the way in which a participant engaged with or consolidated spatial information regarding a novel structure. Therefore, results of this thesis are unable to further advance our understanding of the compensatory neurophysiological mechanisms that are commissioned under VS learning. Nevertheless, there remains reason to believe that the effect of structured VS methods can be unveiled using advanced EEG technology, given a more considered methodological approach that would better mitigate limitations of the technology.

Prior research has outlined the presence of certain electrophysiological features that change in the presentation of stimuli requiring VS consideration. A primary point of novelty in our study design resides in comparing how these results would compare to those seen for undergoing practical VS education and an ensuing reasoning task. Though this latter point is undoubtedly closer to estimating the holistic processes that take-place throughout VS education strategies, addressing specific questions posed by this thesis, the act of measuring this accurately with EEG proved difficult. Primarily this concerned the haptic element of our selected instruction method (Haptico-visual observation and drawing) (L. Shapiro *et al.*, 2020). This is a valuable component of assessing practical VS education, particularly within the context of anatomy, as it is this physical interaction with a target structure that is commonly reported as being acutely responsible for associated learning benefits (Backhouse *et al.*, 2017; Stephen Reid, Shapiro and Louw, 2019). Unfortunately, we theorise that the null differences reported between groups arose due to a large amount of motor activity arising from this haptic exploration, clouding our ability to discern any difference that may have accompanied participants applying their VS consideration. This is to say that our results did not find any evidence that resembled prior indication of VS consideration such as (i) increased suppression of oscillatory alpha power within pre-frontal cortex areas during engagement with a visual stimulus (Bollimunta *et al.*, 2008; Vaden *et al.*, 2012), and (ii) increased theta power across the frontal midline of the brain when utilising VS working memory (Jensen and Tesche, 2002; Caplan *et al.*, 2003b; Sauseng *et al.*, 2010a; Perfetti *et al.*, 2011).

To remedy these issues, I would advise potential investigators looking to build upon this thesis, to restrict their assessment of EEG correlates surrounding VS education to time intervals where this haptic interaction is not occurring. For instance, following practical VS Encoding, experimental design may need to be delineated into two distinct assessment types to qualify as VS consideration: (1) A behavioural task requiring physical manipulation of a novel stimuli (with no EEG), and (2) A cognitive task requiring only mental manipulation of relevant material (with EEG). Indeed, the SAT utilised in Chapter 3 would be ideal for these purposes, and one may look to additionally incorporate the Mental Rotations Task (MRT) as a baseline measurement for how an individual processes spatial information before they receive VS education. It is also important to remember that guided VS instruction provided in Chapter 4 was delivered via a pre-recorded video. While this ensured an accurate level of information was provided to each student, it does not necessarily encapsulate the individual attention that is purported under guided VS education. Careful thought surrounding the best evaluation of guidance is required.

While EEG is an excellent technique for evaluating overall shifts in neural activity that take place across the scalp, correlating any observed changes to the region of the brain they correspond to is particularly difficult. Furthermore, it is only the cortex of the brain that is ever examined under this method without the use of unsubstantiated modelling methods. In trying to better elucidate the sequence of neuronal mechanisms that contribute towards VS understanding, future studies may look to use EEG in combination with those more entrenched imaging methods described in Chapter 1 such as fMRI and PET.

5.5 Concluding remarks

Education strategies featuring VS techniques are continuing to find prominence within modern classrooms, particularly in relation to fields such as anatomical sciences that necessitate the use of spatial abilities. Although an assortment of tangential evidence describes the student learning benefits that result from small-group implementation of VS instruction, little is yet known about the wider course applicability for these methods, and how effects manifest within the individual. In this thesis, I presented evidence that VS paradigms can increase short-term spatial understanding of anatomical material on both an individual and large-group scale. Furthermore, while items of cognition such as Vz appear to correlate with these results, we could not isolate any apparent electrophysiological differences that might account for these changes. Future studies may look to employ longitudinal assessment techniques in qualifying the presented educational benefits of VS education methods, as well as examining alternative EEG outputs to qualify the neural basis for these. While preliminary research presented here investigated only the impact of practical VS education upon associated spectral content, a natural extension of this work would explore whether any changes in event-related signalling mechanisms would further classify these effects.

Clear understanding of spatial relationships existing within human physiology is an essential skill for medical professionals to possess, as it relates to both medical imaging and the proper execution of clinical skills. The research of this thesis contributes to growing literature aiming to establish whether VS techniques are uniquely advantageous in encouraging this consideration in anatomy learners, and how we can optimise the delivery of this education within existing curriculum frameworks.

APPENDIX CHAPTER

Observation of patients' 3D printed anatomical features and 3D visualisation technologies improve awareness for surgical planning and in-theatre performance

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Statement of Authorship

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Principal Author

Name of Principal Author (Candidate)	Toby Branson		
Contribution to the Paper	Design of descriptive review, provided neuroscientific information, wrote the majority of the chapter (paper).		
Overall percentage (%)	50%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	30th October 2021

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Leonard Shapiro		
Contribution to the Paper	Invited by editor Paul Rea to contribute chapter to Biomedical Visualization Volume, published by Springer. Assembled authors, Toby Branson and Rudolph Venter. I authored the first draft of the anatomy education component and laid down the theoretical discussion around 3D spatial awareness as it applies to visualization and improved surgical planning. Revised edited manuscript with Toby Branson. Corresponding author.		
Signature		Date	25 October 2021

Name of Co-Author	Rudolph Venter		
Contribution to the Paper	Provided clinical context to the neuroscientific information by Toby Branson and educational component by Leonard Shapiro.. Expanded on applications in Orthopaedic surgery. Reviewed and edited with Leonard Shapiro and Toby Branson.		
Signature		Date	26 October 2021

6 Appendix Chapter: Observation of patients' 3D printed anatomical features and 3D visualisation technologies improve spatial awareness for surgical planning and in-theatre performance

Abstract

Improved spatial awareness is vital in anatomy education as well as in many areas of medical practice. Many healthcare professionals struggle with the extrapolation of 2D data to its locus within the 3D volume of the anatomy. In this chapter, we outline the use of touch as an important sensory modality in the observation of 3D forms, including anatomical parts, with the specific neuroscientific underpinnings in this regard being described. We explore how improved spatial awareness is directly linked to improved spatial skill. The reader is offered two practical exercises that lead to improved spatial awareness for application in exploring external 3D anatomy volume as well as internal 3D anatomy volume. These exercises are derived from the Haptico-visual observation and drawing (HVOD) method. The resulting cognitive improvement in spatial awareness that these exercises engender, can be of benefit to students in their study of anatomy and for application by healthcare professionals in many aspects of their medical practice. The use of autostereoscopic visualisation technology (AS3D) to view the anatomy from DICOM data, in combination with the haptic exploration of a 3D print (3Dp) of the same stereoscopic on-screen image, is recommended as a practice for improved understanding of any anatomical part or feature. We describe a surgical innovation that relies on the haptic perception of patients' 3D printed (3Dp) anatomical features from patient DICOM data, for improved surgical planning and in-theatre surgical performance. Throughout the chapter, underlying neuroscientific correlates to haptic and visual observation, memory, working memory and cognitive load are provided.

3. 3D visualisation in medical education – a foreword

An emerging field of visualisation technologies are being marketed towards education and healthcare practice. This applied science aims to hone skills in spatial awareness, improving planning and execution abilities.

Spatial awareness facilitates skill acquisition and accurate diagnosis and execution of specific tasks e.g. interpreting physiological scans and extrapolating three-dimensional (3D) correlates from the presentation of two-dimensional (2D) information.

This appreciation of 3D concepts is desirable across the vast array of primary and allied medical professions, particularly as it relates to anatomical understanding (Keenan and Ben Awadh, 2019); perhaps most directly related being the field of surgery, combining informed planning with physical recourse. Coupling a more developed spatial awareness with 3D visualisation technology allows a surgical team to i) better interpret diagnostic images, elevating their awareness of the pathology and surrounding anatomy, ii) plan and rehearse surgical procedures and iii) more accurately execute these procedures, leading to improved patient outcomes.

1.1 Haptics in observation. Drawing in observation.

Haptics is a sensory and motor perceptual system based on cutaneous and kinaesthetic receptors throughout the body (Lederman and Klatzky, 1993). The term *haptic perception* refers to the processing of inputs from multiple sensory subsystems, including those within the skin, muscles, tendons, and joints (Wolfe *et al.*, 2015). In anatomy education, the sense of touch is evoked as an observation sense, albeit passively, while dissecting the human body and exploring anatomical parts. Drawing has been employed in both historical and contemporary approaches to anatomy education. Early anatomists such as Andreas Vesalius drew as a way of recording his observations from cadaveric dissections (Saunders, JB. and O'Malley, CD., 1982; S. Reid, Shapiro and Louw, 2019). Currently, artistic practices - especially the practice of drawing - are included in contemporary medical and anatomy education and training at, for example, University of Brighton, University of Cape Town, University of Dundee, The University of Edinburgh and Newcastle University. While developing skills in observation has direct applications within a variety of professions, it has been stated that physicians "*learn to see*", and thus it is of importance for these skills to be refined (Elkins, 2007; Boudreau, Cassell and Fuks, 2008). Other fields noted for their reliance on drawing and visual skills include many scientific, engineering, and mathematical disciplines (Liben and Titus, 2012). Accompanying visual processing, touch is able to support and augment 3D comprehension through feedback (Klatzky and Lederman, 2011).Thus, touch is fundamental to our observation and understanding of the 3D physical world (Klatzky, Lederman and Matula, 1993). We need to consider providing appropriate and new skill-sets to learners, in addition to those currently provided by most educators, and by looking towards both the sciences and the visual arts, our attention turns to how, inter alia, haptic and drawing practices might be incorporated within a class design.

1.2 The HVOD method

The Haptico-visual observation and drawing (HVOD) method couples haptic and visual object exploration with the simultaneous act of *drawing* the object, such that what is being haptically explored with the one hand (the non-drawing hand), is being reflected by the other hand (the drawing hand) as marks on paper. As the non-drawing hand explores the object, sensory information informs the corresponding motor actions of the drawing hand. The application of HVOD benefits medical students in their study of human anatomy, as well as health care professionals in their various fields (e.g. the extrapolation of medical imaging sections to their position in holistic anatomy). As they specifically relate to anatomical study, the benefits of incorporating the HVOD method include i) enhanced observation of the 3D form of anatomical parts and features, ii) improved spatial orientation within anatomical volume and iii) the cognitive conceptualisation and memorisation of an anatomical forms as a ‘mental picture’. This ‘picture in the mind’ of the observer consolidates this comprehension, such that information is available after the object itself is no longer directly accessible (S. Reid, Shapiro and Louw, 2019).

Six hand and digit movements have been identified in object exploration and the gathering of specific object information (Klatzky, Lederman and Reed, 1987).These hand movements, termed ‘exploratory procedures’ (EPs), are employed both spontaneously and subconsciously (Klatzky, Lederman and Reed, 1987). However, when practicing the HVOD method, these EPs are *actively employed* to gain an understanding of the 3D form and detail of the anatomical part under observation (S. Reid, Shapiro and Louw, 2019; L. Shapiro *et al.*, 2020). When observing using HVOD, one is primarily employing the following EPs: ‘enclosure’, ‘contour following’ and ‘lateral motion’ (**Fig. 1**).

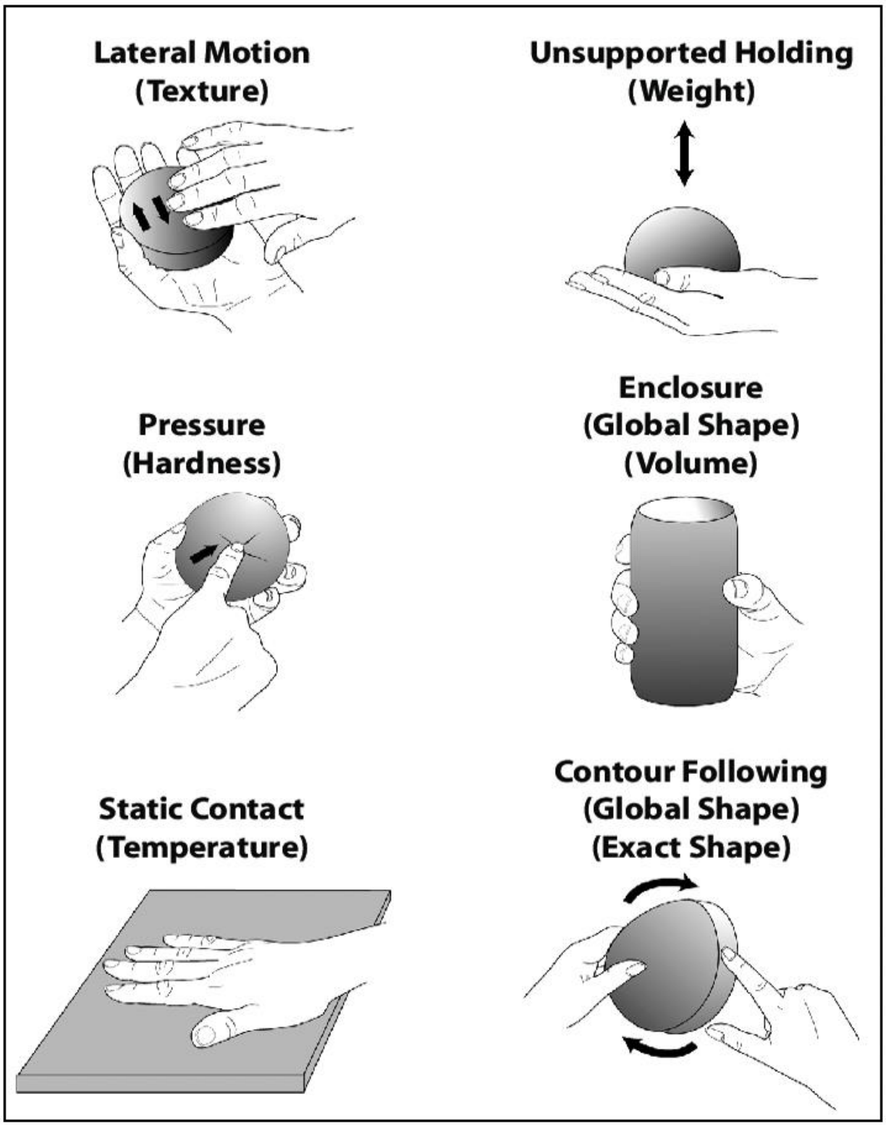

Figure 1. *Depictions of six manual exploratory procedures (EPs) and their associated object-properties (Klatzky, Lederman and Reed, 1987).*

1.3 Spatial awareness and spatial ability in anatomy

Contrary to popular belief, s*patial ability* is not solely pre-determined; it is a developed skill that is directly linked to and is preceded by improved *spatial awareness*. Spatial awareness involves a fundamental, cognitive understanding of 3D space. The HVOD method is designed to improve spatial awareness by focussing the observer on two distinct, but linked, conceptual components of 3D objects: i) 3D object *internal volume* and ii) 3D object *external form*. The ability to comprehend *both* of these 3D components of an object enables an improved spatial understanding of the object *in its entirety*.

1.4 ***Two HVOD exercises for improved spatial awareness***

Exercise 1 focuses on developing spatial awareness of the external form of an anatomical structure (e.g. a bone, outside of a heart or outside of a skull), while exercise 2 focuses on developing spatial awareness of the internal volume of an object (e.g. the spaces (fossae) within a skull, or the intertwining vasculature of the heart and lungs. Both of these exercises involve learning the HVOD method (S. Reid, Shapiro and Louw, 2019; L. Shapiro *et al.*, 2020). Exercise 1 encompasses the principles, learning and practice of the HVOD method, while Exercise 2 is an extension of the practice of the HVOD method, and specific to developing spatial awareness of internal volume.

In practicing the HVOD method, drawing is employed as a direct motor correlate to sensory input while the 'sensing hand' follows the contours of an anatomical part, the 'moving hand' simultaneously reflects the movements of the 'sensing hand', on paper with a pencil (S. Reid, Shapiro and Louw, 2019; L. Shapiro *et al.*, 2020).

Exercise 1: Observation of the *external volume of a* 3D object.

For this exercise, a 200gram (70z) ball-peen hammer is recommended. This object is light enough to hold, and importantly comprises a range of volumetric shapes. This exercise involves using the sense of touch and sense of sight - however, the emphasis of this exercise is on use of the sense of touch as an important observation modality (L. Shapiro *et al.*, 2020).

In this exercise, the sense of touch is employed to observe the external contours of the object using the aforementioned EPs: contour following, enclosure and lateral motion. These EPs in particular extract the object's external volumetric properties. Executing these procedures naturally involves hand and digit gestures, and this is coupled with the simultaneous act of reflecting the gestures made with the 'observing hand', by making *corresponding* gestural contour marks (on paper) with the 'drawing hand'. The lines comprising the drawing of the object (**Fig. 2a**) visually inform the observer of areas that they may have either not yet observed at all or only partially observed. These marks become a visual guide to areas of the object that require further haptic exploration. Both the haptic observation activity and the simultaneous and corresponding mark-making activity add to the observer's haptic and visual accumulation of observable data – the form of the object is observed through touch (and sight), and the corresponding marks made are observed through sight. The marks made on paper follow the haptically explored object contours and visually reinforce what has been observed through touch, as well as guide the observer in further haptic object exploration. In anatomy education, HVOD can be applied for the deeper observation of anatomical parts and features. (**Fig. 2b**).

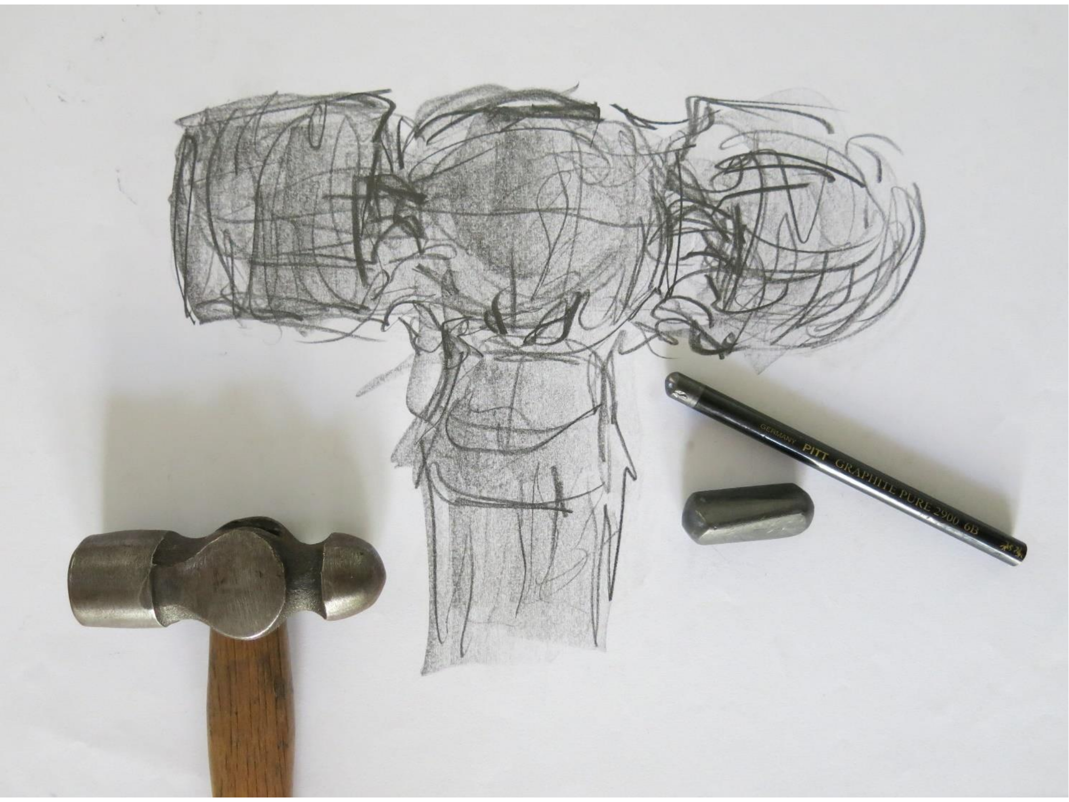

***Figure 2a** HVOD Exercise 1. Drawing made while haptically exploring the external volume of a hammer, by Graham Taschner - HVOD workshop at the University of Cape Town, 2015.*

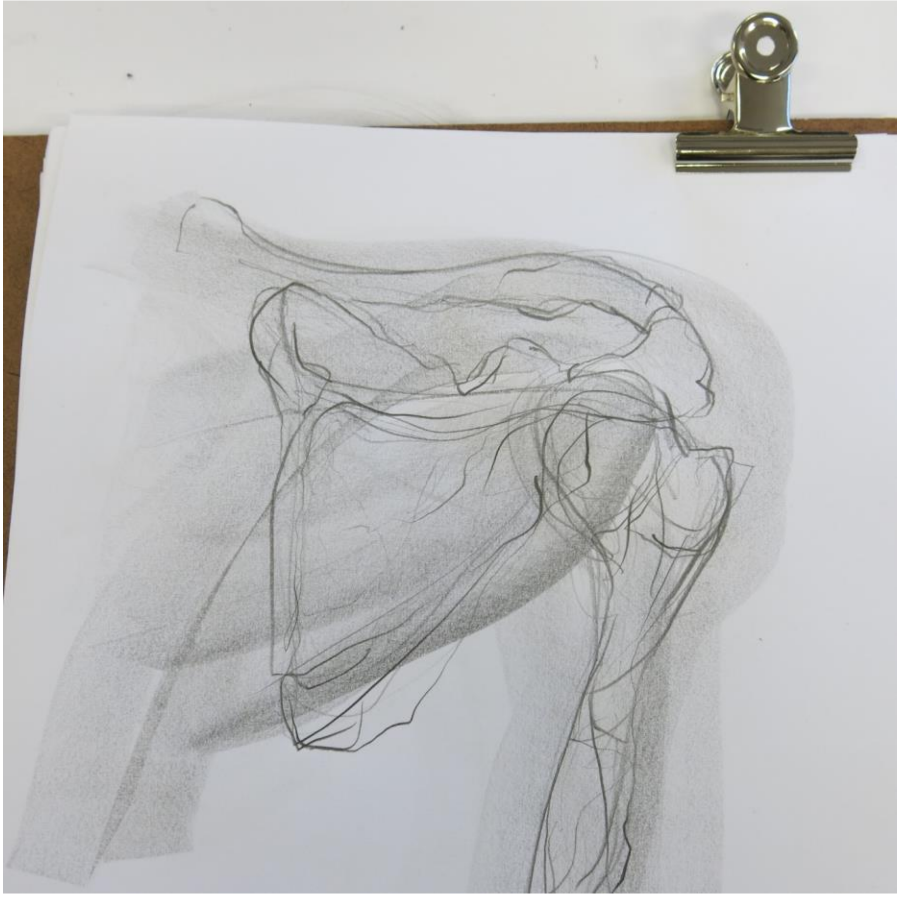

***Figure 2b** After learning to observe the hammer using HVOD, a drawing made while haptically exploring an upper-limb prosection, by Rivoningo Baloyi - HVOD workshop at the University of Cape Town, 2015.*

Exercise 2. Observation of the *internal volume of a* 3D object.

This exercise utilises a corrugated cardboard box, of a size measuring a minimum of 23cm x 15 cm x 15cm. If the box was any smaller, the average hand would not be able to move around enough within it and explore its space. The closure flaps are stuck down to the sides of the box.

Throughout this exercise, the empty space within the box is explored with one hand while simultaneous marks are made on paper, with the drawing hand. As the hand moves randomly throughout the interior space (in both linear and nonlinear directions), the marks made reflect the multitudinous planes within the box. At the same time, the drawing hand executes marks on paper that correspond to the trajectories made by the hand within the box (**Fig. 3**).

While medical imaging records the inner volume of the anatomy and represents information in essential 2D axes (X, Y, Z), human exploration and recording of the 3D space within the box records multiple increments between the planes and engenders in the observer a cognitive understanding of 3D space. By understanding a 3D space in this way, the location of a 2D medical image within the 3D anatomy volume is more easily accomplished.

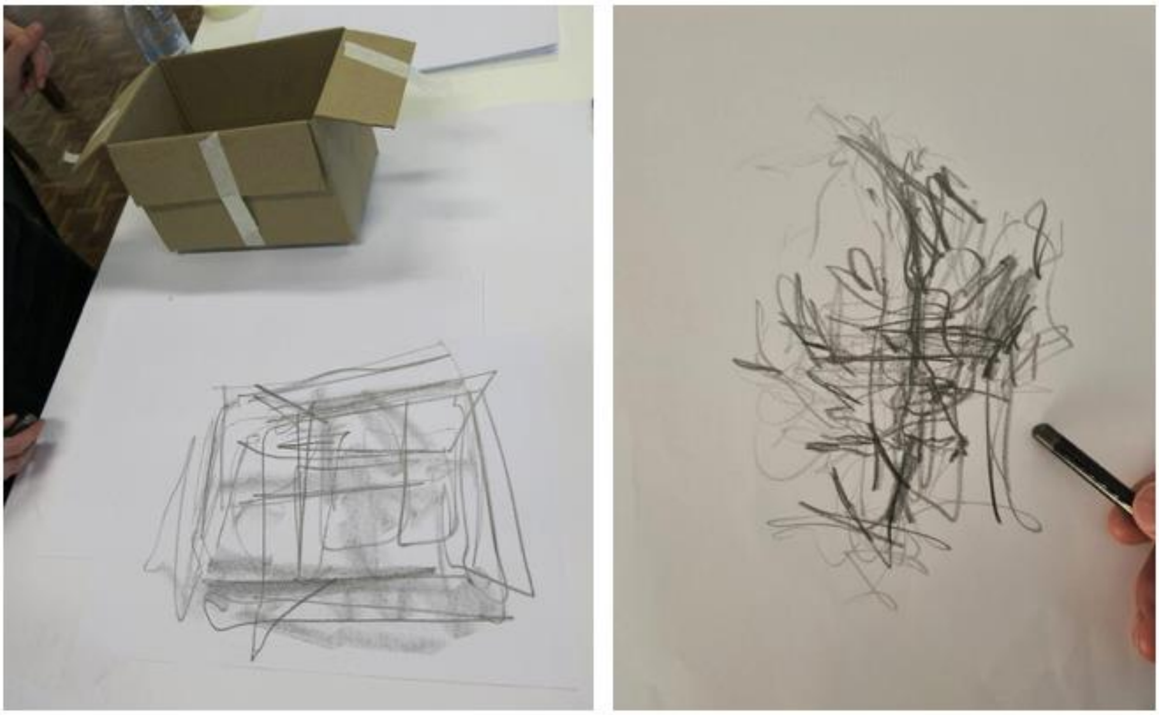

Figure 3. *HVOD Exercise 2. Haptic observing of the internal volume of a box Left Philippa Smart – HVOD Workshop University of Cape Town 2018. Right – Leonard Shapiro.*

2. Cognition and Visuospatial Attention

As outlined above, evidence supports the use of haptics in educational practice within academic literature. It might follow that these educational advantages and practical benefits are rooted in underlying neuroscience. Theories are numerous regarding the specific nature of this association:

- Is it an example of an increased or diversified working memory?
- Perhaps a greater facilitation and deeper understanding?
- An upregulated ability to consolidate information to long-term memory stores?

- The development or enhancement of intracortical mechanisms with which to access this information at a future point?
- Or is it simply a chance occurrence courtesy of the ‘novelty effect’ at play?

Confirmation for any one of these theories has yet to be confirmed, however the following section aims to highlight the underlying mechanisms that underpin both visuospatial education and haptic exploration.

2.1 *Cognition and visuospatial learning*

Sensorimotor information gathered in long-term memory centres can be called upon in aiding the processing of novel stimuli that may otherwise show no direct association with the original source of task encoding (Barsalou, 2010). This suggests that experiences involving sensorimotor interaction encode for and leave lasting mental representations, ensuring that these skills can be transferred to tasks in the future (Glenberg, 1997; Novak and Schwan, 2020). Unsurprisingly, haptic experiences in isolation have similarly been demonstrated to impose specific and enduring representations in these long-term memory centres, even without the presence of an extrinsic need to consolidate these skills (Hutmacher and Kuhbandner, 2018). When specifically applied in the fields of science and medical education, haptically studying 3D objects can boost conceptualisation of spatial orientations in varying capacities i.e. structural anatomy (Novak and Schwan, 2020).

Analogic thinking allows a connection to be made between multiple domains, it being a feature and target of many educational designs. Our sensory experiences form the basis of our cognition - understanding the psychological and neuroscientific basis for our analogic reasoning can explain how the HVOD approach is able to elicit a deeper awareness of 3D structure in students. Through the use of constructional apraxia, research has indicated that the parietal region of the brain plays a crucial role in underpinning our perception of multimodal data; our ability to simplify a variety of sources into a cohesive signalling pathway (Gainotti, D'Erme and Diodato, 1985). Neuroimaging studies have supported these findings, with the parietal lobe showing increased activity during several experimental conditions: when a participant has been asked to draw varying facial features of a human as opposed to figures comprised of geometric patterns, when drawing a structure from memory as compared with viewing that structure, and drawing a stimulus versus simply naming it (Solso, 2001; Makuuchi, Kaminaga and Sugishita, 2003; Miall, Gowen and Tchalenko, 2009).Furthermore, studies have implicated areas 1, 2 and 3 of the anterior parietal cortex in the processing of somatosensory information specifically – with this having been demonstrated by cells in those areas during both passive movements involving the hand and during physical manipulation (Albanese *et al.*, 2007; Kumar, Manning and Ostry, 2019). Additionally, during the performance of a visuohaptic task involving a delay, somatosensory cells in the parietal region are hypothesised to be involved in short-term retention of that visual component of input prior to a physical choice (Zhou and Fuster, 2000).An extrapolation of these findings can be made that those somatosensory cells associated with the cortical networks we know, are crucial at the interface of haptic feedback and short-term memory.

2.2 Sequencing of visuospatial comprehension in neuroscience

The fingers possess a large number of neural endings per square centimetre, and are required for our ability to produce fine movements. This results in a relatively large area of the somatosensory cortex in the frontal lobe of the brain being composed of sensory information from the hand and sensations of touch. Additionally, cells in the somatosensory cortex are involved in the short-term retention of tactile information, with an ability to retain visual information that has been associated with the touch of an object (Zhou and Fuster, 2000).

Supplementary functional studies have also indicated an increased involvement of the frontal regions, in particular those acting as supplementary motor centres, and the cerebellum – thus implicating these areas as being correlated with adeptness in drawing (Makuuchi, Kaminaga and Sugishita, 2003; Ferber *et al.*, 2007; Miall, Gowen and Tchalenko, 2009; Schlegel *et al.*, 2012). The parallels between this approach and the visuospatial activity exhibited during motor training are striking, suggesting that similar brain regions will be involved during both anatomical learning and motor training. These would include structures, identified through clinical pictures following stroke, like the precuneus for visuospatial attention and motor imagery, the temporal lobe for spatial memory, the cerebellum for motor memory and coordination and the frontal lobe for cognitive processing during the task (**Fig. 4a and b**) (Eichenbaum *et al.*, 2016; Xia and He, 2017). This correlation between specific brain regions and drawing outcomes is not limited to transient changes across the duration of the task being performed, with structural neural changes resulting from long term artistic training over time (Schlegel *et al.*, 2012). Beginners who underwent a structured drawing regime over several sessions were found, through functional classification, to have a sustained increase in right cerebellum activation, and through fractional anisotropy similar changes to inferior regions of the right frontal lobe (Schlegel *et al.*, 2012). Artistic training through the practice of drawing may now be thought of in the same context as training through other creative practices, such as playing a musical instrument, in the eliciting of a conformational change in brain structure over time (Gaser and Schlaug, 2003).

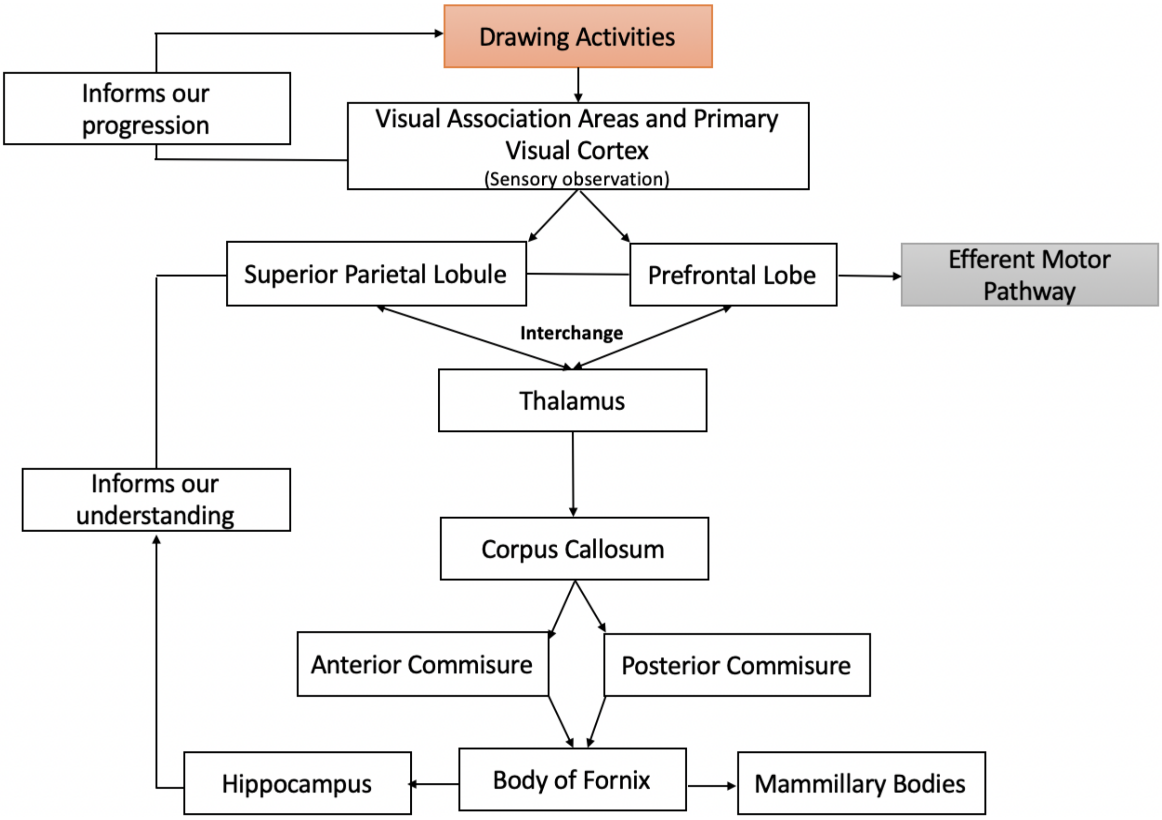

Figure 4a: *Flow chart of sensory neural activation pathways elicited in the feedback mechanisms required to further inform visuospatial understanding.*

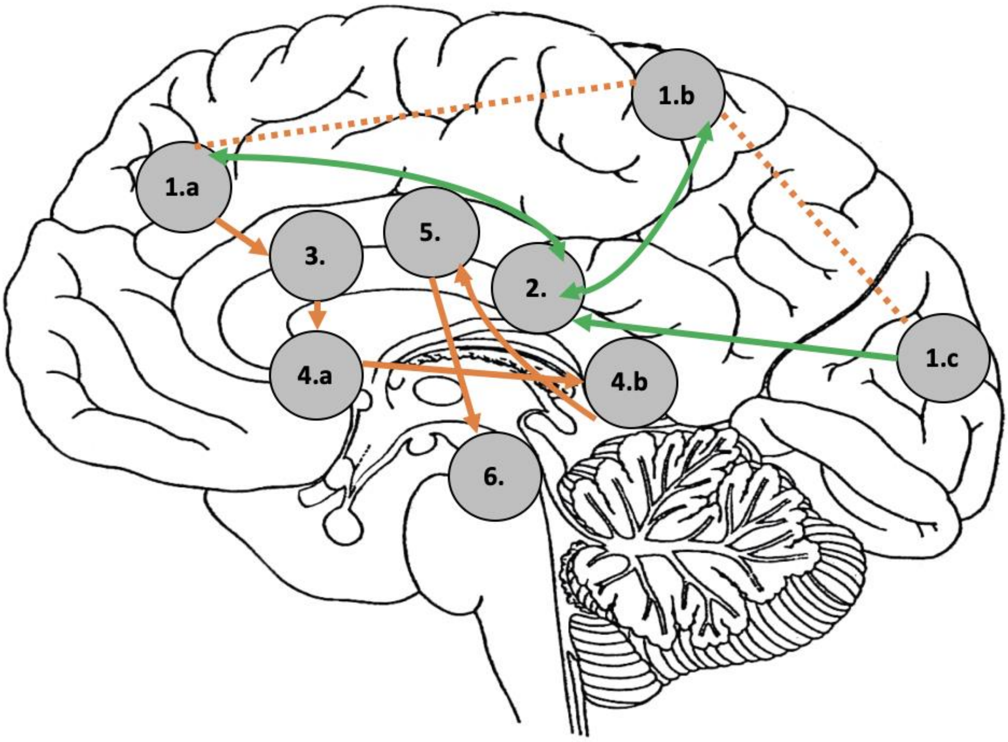

Figure 4b: *Pathway of sensory information gained through drawing – from cortex to limbic system. (1a) Prefrontal Cortex, (1b) Superior Parietal Lobule, (1c) Primary Visual Cortex, (2) Thalamus, (3) Corpus Callosum, (4.a) Anterior Commissure (4.b) Posterior Commissure (5) Body of Fornix, (6) Hippocampus (Author modified publically-available clip-art image).*

3. Application within a surgical setting

We have outlined the use of haptics medical education and explained the cognitive basis for these benefits. These same principles that were applied in medical education can also be transferred into a clinical setting. In this section, we will describe an application of this understanding to a specific aspect of medical practice, the use of 3D visualisation technology and 3Dp models derived from patient imaging for pre-operative surgical planning and rehearsal.

3.1 Haptic perception in surgical training

The process of training a medical specialist, especially in the surgical sciences, is a combination of factual study, attaining the correct attitudes and behaviours and developing a set of technical proficiencies to diagnose and treat. In a qualitative study in which 22 qualified surgeons and trainees were interviewed, six integral components of surgical training were identified: factual knowledge, motor skills, adaptive strategies, team-working and management, attitudes and behaviours and sensory semiosis (Cope *et al.*, 2015). Semiosis is defined as the process of attributing meaning to something perceived. In the context of surgical training, this equates to the experience of knowing what subtle clinical observations mean, or what haptic sensations during surgery might imply. Much of this process is learnt through supervised experience during clinical training, guiding the trainee through real-world situations where they learn to interpret the physical experiences of examining a patient or performing a surgical procedure. The concepts of *embodied learning* and *embodied cognition* have also been suggested to help make sense of this process, guiding surgical improvements in training (Cooper and Tisdell, 2020). As it relates specifically to orthopaedics, the sense of touch is critical in the physical examination and surgical treatment of patients. An essential part of orthopaedic surgery is the exposure to these haptic experiences and learning how to respond to them appropriately.

3.2 ***Visualisation technology in surgery – interpreting 'what the machine saw'***

It is one thing for the 'machine to look' and record in exquisite detail, but quite another for humans (and their cognitive faculty) to visualise and interpret *what* the 'machine saw' and recorded. A CT or MRI 'machine' can 'see' this, but it *still* requires a human to interpret 'what it saw'. To this end, an MRI or CT interpreter (an operator with heightened spatial awareness) will more accurately be able to extrapolate a 2D image slice produced by the 'machine', to its location within the 3D anatomical volume. Similarly, surgeons with heightened spatial awareness will be better able to extrapolate from a (2D) screen image of a CT slice, to its location within the (3D) volume of the anatomy under investigation. Most of what the surgeon is visualising is beneath the skin and naturally unseen to the naked eye, making good spatial awareness all the more important for spatial skills needed in surgical planning and execution.

It follows then, that surgical planning would similarly benefit from honed spatial awareness ability, whereby a patient's anatomical part or feature (to be the focus of a surgical procedure) is rendered for its interpretation. Established body composition analyses that aid these processes, such as magnetic resonance imaging (MRI) or computed tomography (CT) scans, have increasingly become further specialised in providing this spatial navigation, of which two specific options will be discussed.

Physical 3D printing (3Dp) can provide a deeper understanding of a specified area than that of conceptualising 3D images from 2D CT sections (that are used in generating the rendering). Prior research has supported the inclusion of these models within anatomical education, with 3Dp providing a tactile experience that imaging techniques fail to elicit (**Fig 5a-c**) (Jones *et al.*, 2006; Keenan and Ben Awadh, 2019; S. Reid, Shapiro and Louw, 2019). Alternatively, images can be loaded into auto-stereoscopic 3D (AS3D) software and rendered into 3D images produced by a prism display that does not require specialised eyewear to be worn concurrently.

An AS3D image lends itself to the presentation of detailed internal anatomical structures in all possible dimensions; the image appears to float in space *in front* of the prism display and can be rotated or manipulated for highly detailed analysis (**Fig. 6**). Because the image *appears* to the viewer as an actual 3D object in space, AS3D can be used successfully in combination with 3Dp. As a medium, AS3D adds multiple levels of *transparent* visual information to 3Dp analysis that 3Dp technology is not geared to achieve, by virtue of the nature of its manufacturing process and the materials it uses. These technologies supplement each other in the creation of a more holistic 'picture' of surrounding anatomy by providing both the physical *as well as* the conceptual AS3D image for the surgeon's reference. Studying an anatomical feature using both auto-stereoscopic 3D (AS3D) *as well as* 3Dp aims to amalgamate the distinct outputs (the one visual and the other haptic) from two related technologies, for deeper observation. While 3Dp technology is not (yet) suited to print transparent 3Dp with finely detailed internal anatomical features, an AS3D display rendering of the anatomical feature augments the 3Dp by displaying these details.

Each of the above technologies (AS3D and 3Dp) exhibit in 3D and yet have fundamentally distinct features; AS3D is observed by sight only while 3Dp can be observed by touch *as well as* sight. Both technologies call for already learned spatial awareness in order to better understand the 3D form and volume of the anatomical feature under investigation. The better the viewer's spatial awareness, the better their *understanding* of what is being visually and haptically observed. At the pre-operative planning stage, as well as in theatre, haptic exploration assists surgeons in visualising what lies 'beneath the skin', or informs decision making in instances where it is not feasible or pragmatic to gain a clear viewpoint of underlying structures. In this setting, haptic investigation can provide clinicians with an additional sense of the 3D anatomical morphology than when aided by medical imaging or a clear viewpoint alone (Keehner and Lowe, 2010). Spatial ability is a cognitive measure, and it is important to note that the combination of a 3Dp and AS3D imaging of a patient’s anatomical feature cannot *in itself* improve a surgeon’s surgical capability; it is the *application* of a surgeon’s spatial awareness, aided by the visual and haptic observation of the 3Dp anatomical feature, that can translate into an improved spatial *ability* and keen awareness of anatomical volume. The implication here is that a surgeon will be able to haptically observe the 3Dp (as an object, resulting in a deeper observation of the anatomical feature, the creation of a mental image of the form of the feature and improved understanding of the volume of the feature (S. Reid, Shapiro and Louw, 2019; L. Shapiro *et al.*, 2020).

Figure 5a*: 3Dp model of a patient's pre-operative CT imaging used for surgical rehearsal and simulation. The left hemipelvis was printed and a trial implant can be seen in the acetabulum. The patient, known with achondroplasia and short stature, required total hip arthroplasty and there was uncertainty about the fit of normal prosthetic implants (image by Rudolph Venter).*

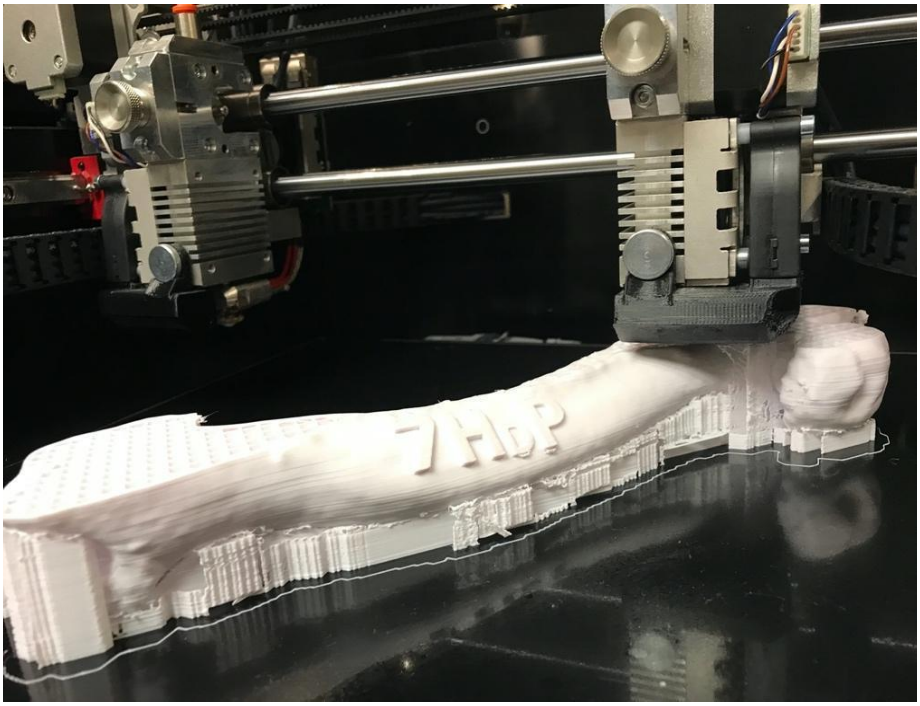

Figure 5b: *3Dp model of the patient as in Fig 6a. Illustrated is a model generated of the left femur being manufactured using a fused deposition modelling (FDM) printer using polylactic acid (PLA) filament (image by Rudolph Venter).*

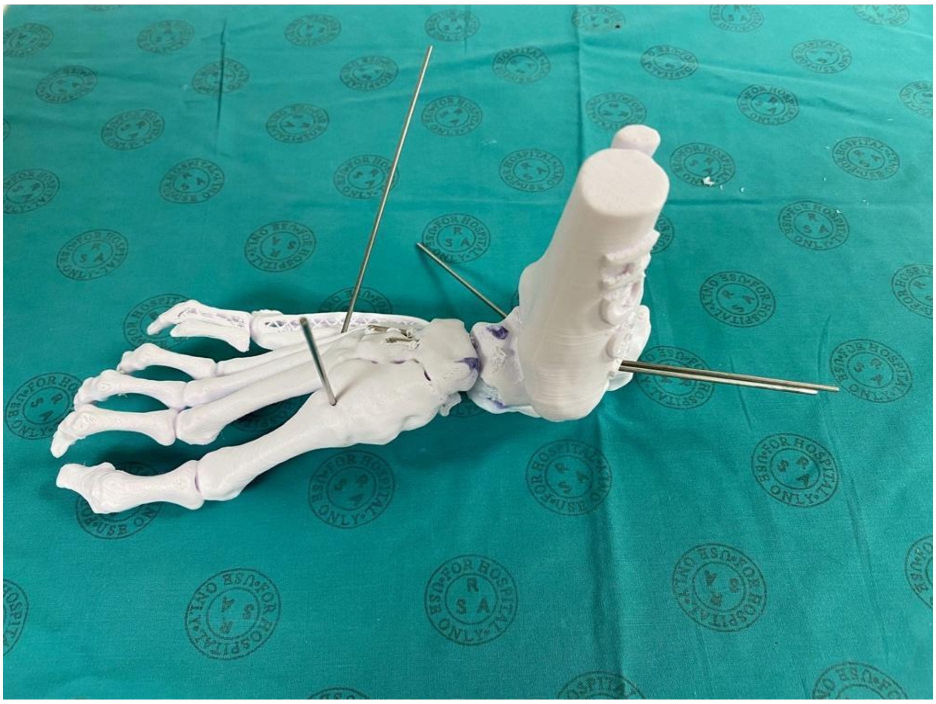

Figure 5c: *3Dp model of complex, three-dimensional deformity in an adult patient with residual clubfoot, generated from pre-operative CT scan. The surgeon deconstructed and reconstructed the 3Dp model of the patient's imaging prior to surgery, using wire pins to serve as reference axes and to allow movement at the joints. (image by Rudolph Venter).*

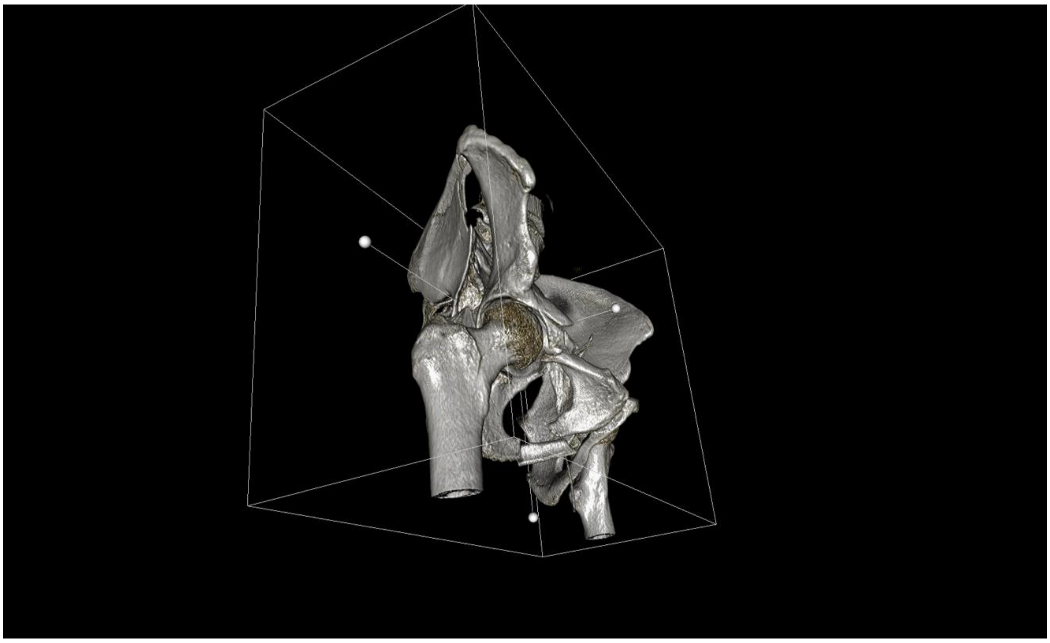

Figure 6: *AS3D image highlighting the anatomy of a hip-joint with fractured pelvis (DICOM 3D Software).*

3.3 ***Pre-operative planning assistance***

Pre-operative planning of orthopaedic surgical procedures has traditionally been undertaken by using *visual perception* to interpret imaging modalities in 2-dimensions. Recent advances in medical imaging technology have made it possible to digitally manipulate images. This facilitates the planning process by making it possible to superimpose images of the implants onto the patient images. The execution of the procedure however, is primarily reliant on *haptic perception* and situations arise where the visual perception has to be actively integrated with haptic perception as the procedure progresses. For example, in laparoscopic surgery, visual cues about how tissue deforms can inform the surgeon about the amount of force that needs to be applied even in the absence of adequate haptic feedback. In situations like these, where there is a mismatch of the sensory input to the processing modality, the conversion can cause significant strain on *working memory*.

Using 3Dp models of patient imaging allows visual and haptic planning pre-operatively as well as realistic simulation. This allows the surgeon to integrate the multimodal aspects of planning and rehearse in a stress-free environment pre-operatively, resulting in significantly reduced strain on working memory when the actual procedure is performed. Vaishya et al performed a bibliometric study in 2018, analysing the publishing trends concerning 3Dp in orthopaedics (Vaishya *et al.*, 2018). They detected a sharp increase in publications from 2013, that seem to have peaked in 2017 and is gradually decreasing. Most of these publications were about bio-fabrication and bioprinting, and the second biggest topic was about using 3Dp for surgical planning and patient specific instruments and implants. Surgical journals continue to feature case studies in the use of 3Dp for planning and rehearsal, with a recent example being that of using a 3Dp model to guide osteochondral allograft harvest: “a live model that can be manipulated while planning, rather than studying static two-dimensional images” (Okoroha *et al.*, 2018). A range of applications have been outlined for 3Dp models outside of surgical planning, such as the manufacturing of custom made instrumentation and patient specific implants (**Fig. 7)** (Paxton, Ostiguy and Cibula, 2013; Kalamaras *et al.*, 2016; Tetsworth and Mettyas, 2016; Corona *et al.*, 2018; Gao, Rivlin and Abraham, 2018). In a recent review of 3Dp in medicine, it was found that of the 227 papers reviewed, 45.2% concerned 3Dp in orthopaedics, with the most covered topics being the production of patient specific implants and anatomical models for planning. Of the papers included, 72.2% mention ‘improved clinical outcomes’, albeit with only a small number being able to support these statements with data (10%).

An alternate review, representing a dataset of 922 patients, specifically explored the use of 3Dp in the planning of orthopaedic trauma procedures. Chief among the results was: a 19.9% reduction in theatre time, 25.8% reduction in intra-operative blood loss and a 28.3% reduction in fluoroscopic imaging being used (Morgan *et al.*, 2020).They speculate that the reasons for the improvements include, amongst other things an improved understanding of the patho-anatomy “through geometric characterisation” hinting at the beneficial effect these models have on the cognitive load of surgeons (Keenan and Ben Awadh, 2019; S. Reid, Shapiro and Louw, 2019; L. Shapiro *et al.*, 2020).

Because 3Dp has been expensive and difficult to use, research has focussed on cost-benefit based outcomes such as theatre time, hospital stay, the use of fluoroscopy and intra-operative blood loss to justify its use. It seems likely that this trend is being driven by an intuitive understanding by surgeons that having 3Dp models provides them with definite advantages in planning and rehearsal of surgical procedures above and beyond mere cost saving. The fact that 3Dp has become more affordable and accessible now justifies investigation of the effect it has on the cognitive load of surgeons.

Converting patient imaging data into 3Dp presents a wide range of opportunities for medical and surgical training of all levels of experience. For the surgical trainee, the opportunity to plan and rehearse routine procedures in a simulated environment allows for the encoding of complex haptic experiences prior to patient contact. For a more experienced orthopaedic surgeon facing a particularly complex case, haptic rehearsal provides the opportunity to refine surgical plans in a ‘trial-and-error’ fashion. This allows for specific haptic experiences to be encoded prior to the actual procedure, significantly alleviating the strain on working memory, allowing the surgeon to focus on other factors influencing the surgical team and anticipate complications (Sweller and Chandler, 1991; Perreault and Cao, 2006).

Figure 7: *Surgeons using a 3Dp model of a patient's pre-operative CT imaging as a tactile intra-operative reference or 'haptic map' during surgery for tuberculosis of the spine (image by Rudolph Venter).*

Summary and future directions

Haptic exploration aids in facilitating the interchange between 2D representations, and comprehensive 3D understanding. This has applications in a wide variety of educational and practical modalities, including the example of medical training highlighted here. How this interchange occurs is yet unknown, however the prominent structures linking the complex circuit from cortex to limbic system are beginning to be established. Within a surgical environment, haptic exploration of 3Dp models of patient imaging provides clinicians with an ability to plan and rehearse a pre-operative plan with heightened spatial awareness, encoding a haptic experience and freeing up working memory capacity throughout the actual procedure. Our future work will further explore the capacity for haptic feedback within educational design, both in practice and cognition, and further probe the measures by which 3Dp can be used in various surgical domains.

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