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Observation of Patients' 3D Printed Anatomical Features and 3D Visualisation Technologies Improve Spatial Awareness for Surgical Planning and in-Theatre Performance

Toby M. Branson, Leonard Shapiro, and Rudolph G. Venter

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.

Keywords

Haptics · Spatial awareness · Cognitive neuroscience · Anatomy education · Drawing · Orthopaedic surgery · Observation · 3D printing

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2.1 3D Visualisation in Medical Education: A Foreword

An emerging field of visualisation technologies is 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.

2.1.1 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 and O'Malley 1982; Reid et al. 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 et al. 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 et al. 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.

2.1.2 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 the anatomical volume, and (iii) the cognitive conceptualisation and memorisation of an anatomical form 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 (Reid et al. 2019).

Six hand and digit movements have been identified in object exploration and the gathering of specific object information (Klatzky et al. 1987). These hand movements, termed 'exploratory procedures' (EPs), are employed both spontaneously and subconsciously (Klatzky et al. 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 (Reid et al. 2019; Shapiro et al. 2020). When observing using HVOD, one is primarily employing the following EPs: 'enclosure', 'contour following', and 'lateral motion' (Fig. 2.1).

2.1.3 Spatial Awareness and Spatial Ability in Anatomy

Contrary to popular belief, *the spatial 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*.

2.1.4 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 (Reid et al. 2019; 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 (Reid et al. 2019; Shapiro et al. 2020).

Exercise 1: Observation of the *External Volume of a* 3D Object

For this exercise, a 200 g (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 the use of the sense of touch as an important observation modality (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. 2.2a)

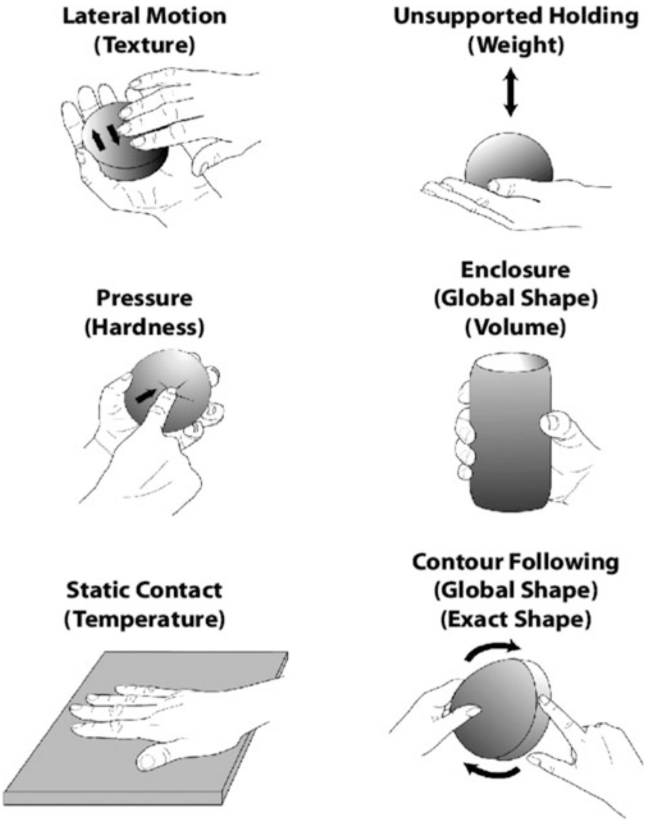

Fig. 2.1 Depictions of six manual exploratory procedures (EPs) and their associated object properties (Klatzky et al. 1987)

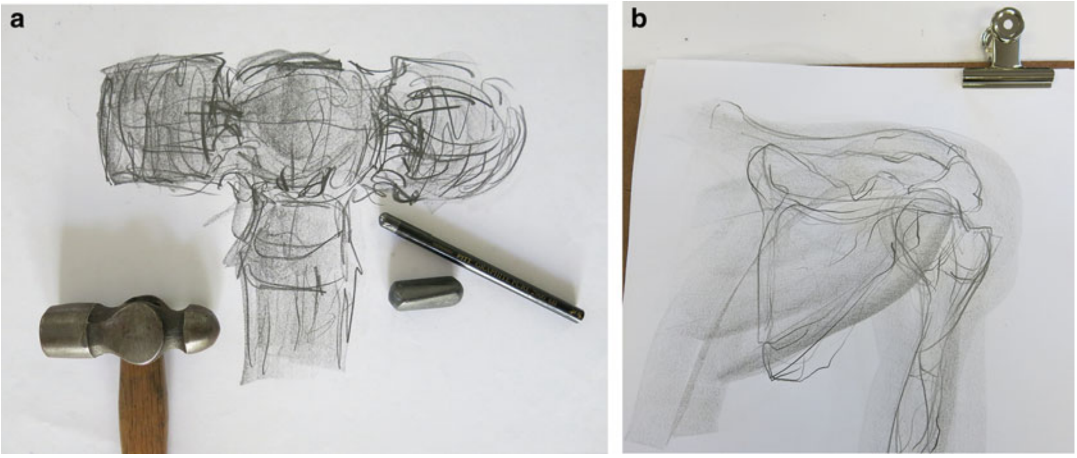

Fig. 2.2 (**a**) HVOD Exercise 1. Drawing made while haptically exploring the external volume of a hammer, by Graham Taschner—HVOD workshop at the University of Cape Town, 2015. (**b**) After learning to observe the hammer using HVOD, a drawing was made while haptically exploring an upper-limb prosection by Rivoningo Baloyi—HVOD workshop at the University of Cape Town, 2015

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 the 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. 2.2b).

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 23 cm × 15 cm × 15 cm. 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. 2.3).

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.

2.2 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.

2.2.1 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

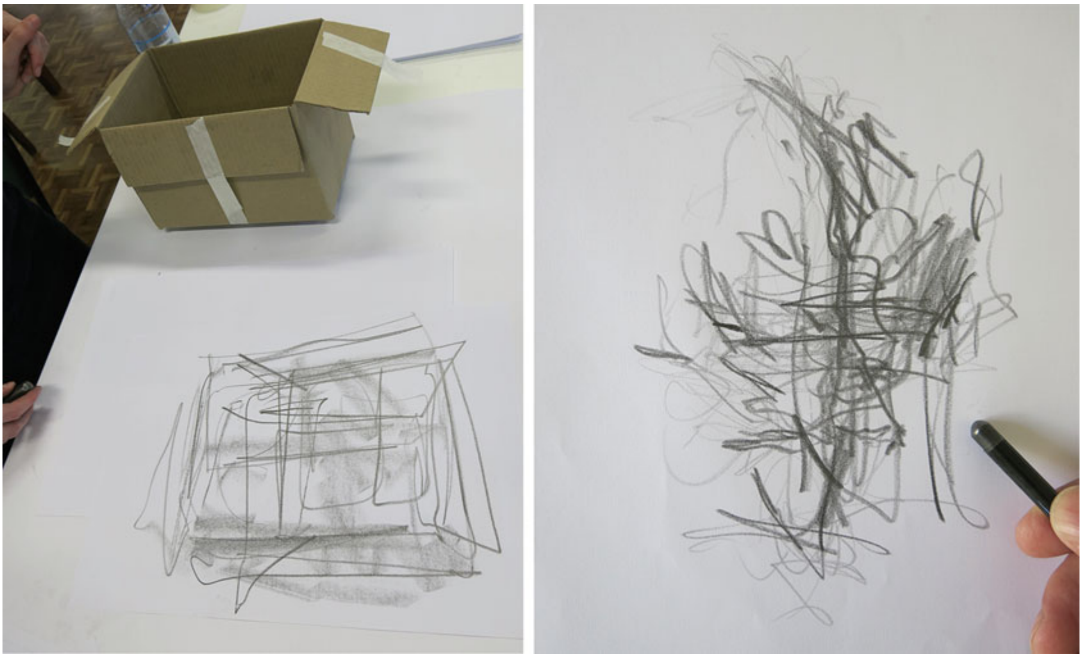

Fig. 2.3 HVOD Exercise 2. Haptic observing of the internal volume of a box *Left* Philippa Smart—HVOD Workshop University of Cape Town 2018. *Right*—Leonard Shapiro

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 is 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 et al. 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 et al. 2003; Miall et al. 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 et al. 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.

2.2.2 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 et al. 2003; Ferber et al. 2007; Miall et al. 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. 2.4a, 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).

2.3 Application Within 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.

2.3.1 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

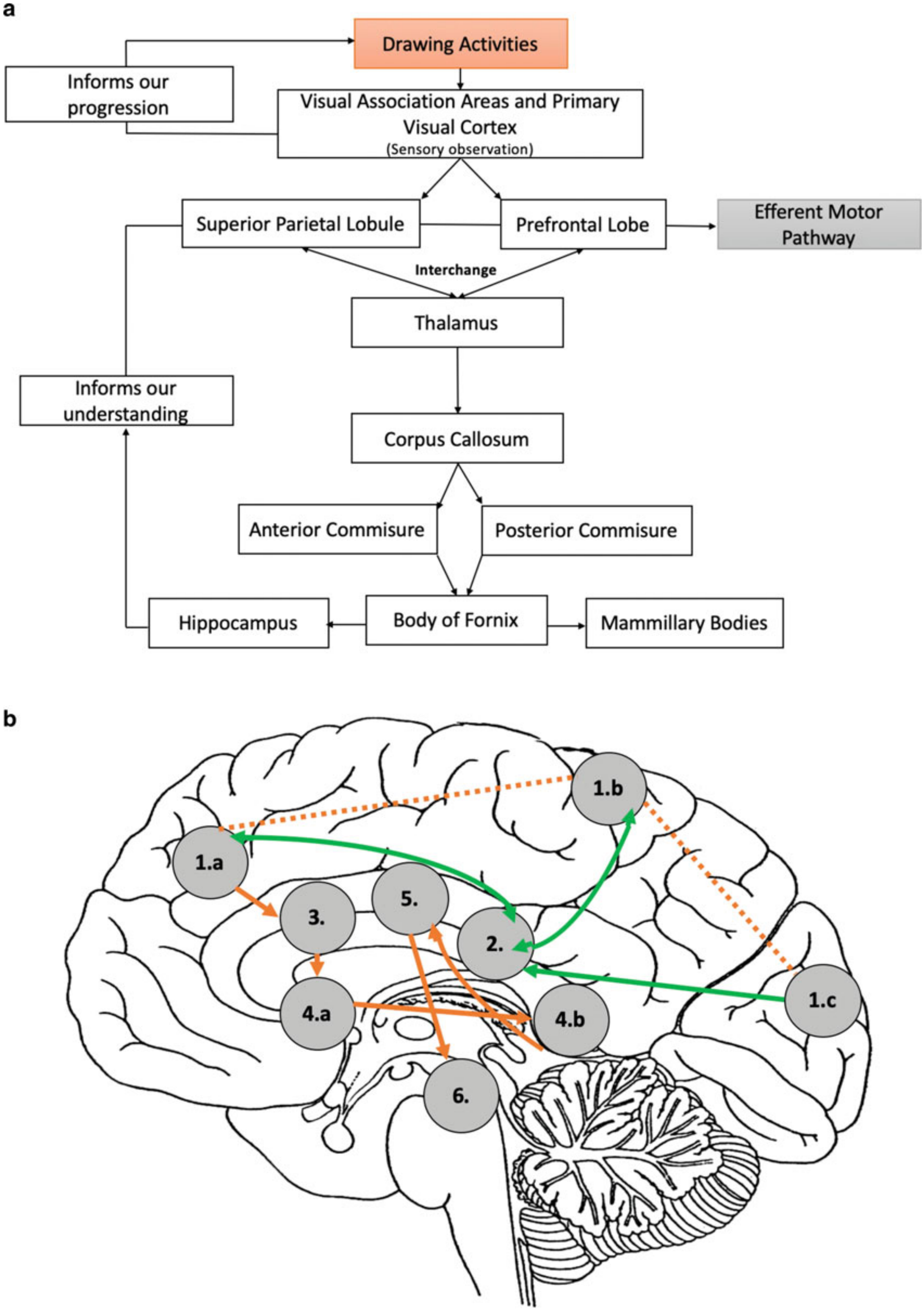

Fig. 2.4 (**a**) Flow chart of sensory neural activation pathways elicited in the feedback mechanisms required to further inform visuospatial understanding. (**b**) Pathway of sensory information gained through drawing—from cortex to limbic system. (1a) Prefrontal Cortex, (1b) Superior Parietal Lobule, (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)

equates to the experience of knowing what subtle clinical observations mean or what haptic sensations during surgery might imply. Much of this process is learned 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 exposure to these haptic experiences and learning how to respond to them appropriately.

2.3.2 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. 2.5a–c) (Jones et al. 2006; Keenan and Ben Awadh 2019; Reid et al. 2019). Alternatively, images can be loaded into autostereoscopic 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. 2.6). 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 and studying an anatomical feature using both autostereoscopic 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.

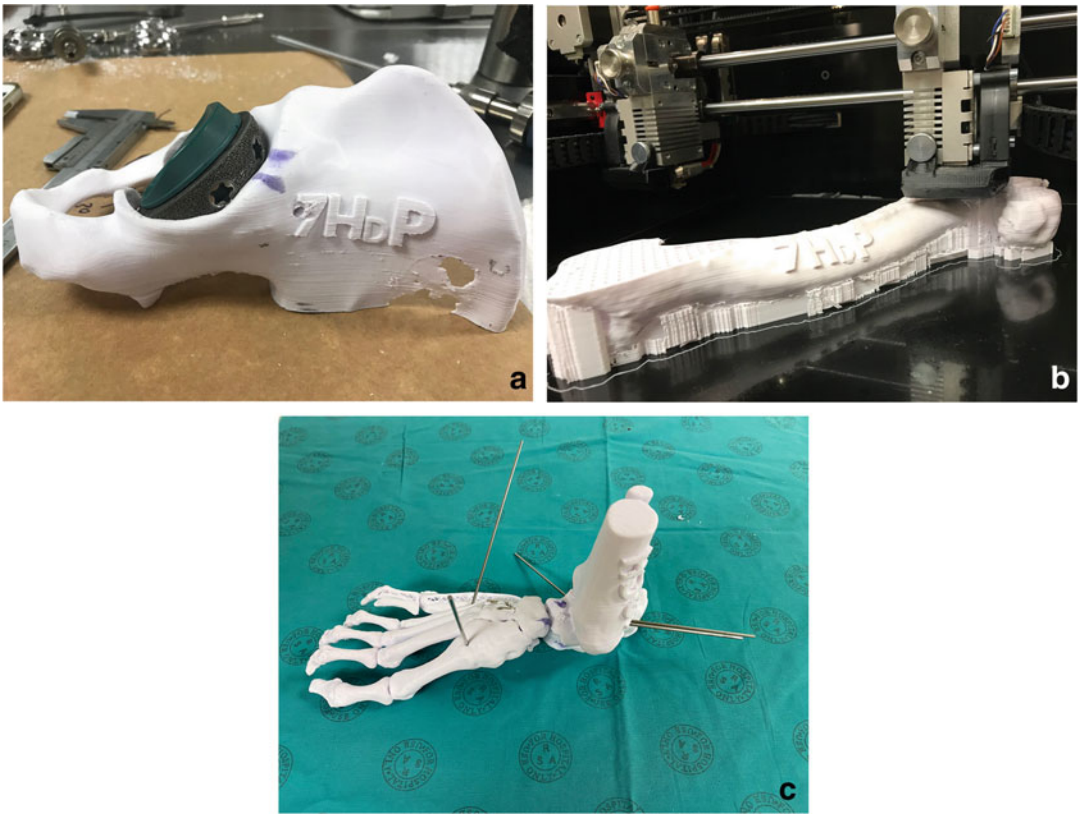

Fig. 2.5 (**a**) 3Dp model of a patient's pre-operative CT imaging used for surgical rehearsal and simulation. The left hemipelvis was printed, and a trial implant can be seen in the acetabulum. The patient, known with achondroplasia and short stature, required total hip arthroplasty, and there was uncertainty about the fit of normal prosthetic implants (image by Rudolph Venter). (**b**) 3Dp model of the patient as in (**a**). 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). (**c**) 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)

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

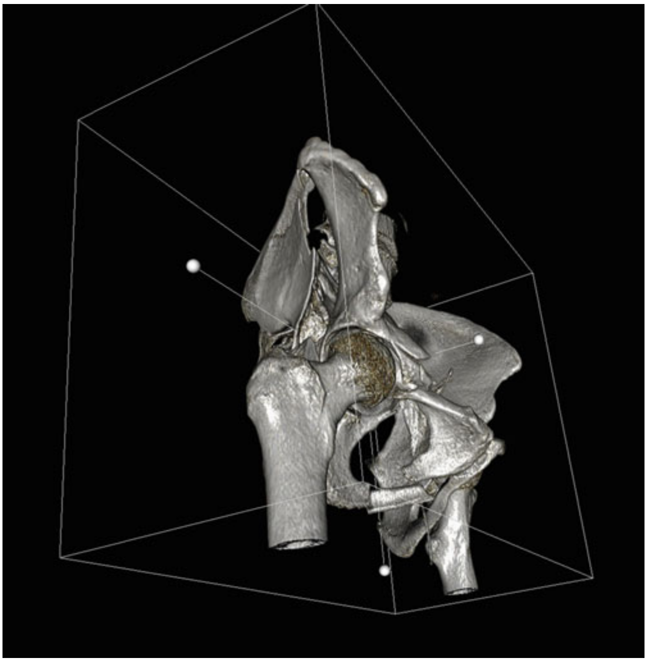

Fig. 2.6 AS3D image highlighting the anatomy of a hip-joint with the fractured pelvis (DICOM 3D Software)

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 (Reid et al. 2019; Shapiro et al. 2020).

2.3.3 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, which 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

Fig. 2.7 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)

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. 2.7) (Paxton et al. 2013; Kalamaras et al. 2016; Tetsworth and Mettyas 2016; Corona et al. 2018; Gao et al. 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 were: 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; Reid et al. 2019; 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 the 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).

2.4 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 the 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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