Chapter 4
Human Factors in Acquiring Medical Skills; Learning and Skill Acquisition in Surgery

Mouret first performed laparoscopic cholecystectomy in the late 1980s. Previously, laparoscopic techniques were part of gynecological practice and it was not until the development of a video computer chip allowed the magnification and projection of images on to television screens that laparoscopic surgery became integrated into general surgery (Johnson et al. 1992). The main difference between laparoscopic and traditional open surgery is that there is no need for a single large incision; instead a number of small stab incisions are made in the patient's abdomen through which surgical instruments are passed via trocars. The surgeon views the operative site by means of a monitor image obtained by a CCD miniature camera attached to a laparoscope. Since its introduction into general surgery it has developed rapidly in both application and complexity and the laparoscopic cholecystectomy has now replaced the open cholecystectomy as the procedure of choice for the removal of the gall bladder (Centres 1991).

However, as we have seen in Chaps. 1 and 3, the widespread introduction of laparoscopic or minimally invasive surgery (MIS) in the 1980s had a number of unforeseen consequences. Introduced on a wave of enthusiasm surgical procedures such as laparoscopic removal of the gallbladder (laparoscopic cholecystectomy or LC) became the treatment of choice almost overnight. This was understandable given the benefits MIS conferred on both patients and hospitals. For the patient it meant that they were in and out of hospital quickly after having major surgery performed, e.g., LC in one or two days rather than more than a week. They also had reduced pain and scarring and returned to work more quickly (Peters, Ellison, Innes et al., 1991). The advantages for the hospitals were better bed occupancy rates. However, MIS imposed considerable difficulties on the surgeon. For example, the tissue being worked on could no longer be seen directly. Instead, the surgeon viewed the image captured by a single or triple chip charged coupled device camera on a monitor. Although the image was of extremely high quality, it was orders of magnitude poorer than would be viewed by the eye under natural viewing conditions (Reinhardt-Rutland 1996). There was also considerable decrement in depth cues.

As we have discussed in Chap. 3, laparoscopic surgeons need to form visual impressions of a 3-D structure – consisting of organs and instruments – from a

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2-dimensional television monitor. While this is often described as loss of binocularity, it is simpler and more accurate to call it loss of pictorial perception. So-called primary cues – binocular disparity and convergence, accommodation, and motion parallax – are present in abundance. The difficulty is that they (and other cues related to lighting and texture) yield a conclusion that is inimical to surgery: they specify that the structures in view form a single surface, virtually flat and usually vertical. A surgeon has to set aside that conclusion in order to register the information carried by subtler 'pictorial' cues; and to reconstruct the structure that they specify despite the incompleteness of the information provided by these cues. Individuals differ in this ability and such differences could clearly contribute to performance variability for pictorially guided laparoscopy. Most reports on the difficulties experienced by surgeons indicate the loss of tactile feedback because they must perform surgery with 18-inch long surgical instruments. As we have discussed in Chap. 3, this conclusion is inaccurate. Tactile feedback is still present but it is considerably degraded. Other difficulties include unintentional camera rotation by the camera holder and having to learn how to use an angled laparoscope, e.g., 30° or 70° (Gallagher et al. 2009). These difficulties can be corrected by increased care and attention and by proceeding with caution. In addition, one of the most important difficulties that the laparoscopic surgeon has to overcome is the 'fulcrum effect' of the body wall on instrument handling. When the surgeon moves his or her hand to the right, the working end of the instrument moves to the left inside the patient and on the monitor resulting in fundamental visual-proprioceptive conflict. This cannot be overcome with increased care and attention due to the attentional demands of surgery (Gallagher et al. 1998) but only with extended practice. All of these difficulties mean that the minimally invasive surgeons must operate at the very edge of their perceptual, cognitive and psychomotor faculties (Reinhardt-Rutland and Gallagher 1995). As MIS became more commonly practiced for procedures such as LC, it became clear very quickly that the laparoscopic approach was associated with a significantly higher complication rate (Peters et al. 1991), particularly during the early part of the surgeon's career. The Southern Surgeons Club (Moore and Bennett 1995) found that the probability of a bile duct injury was a function of the laparoscopic surgeons experience (Fig. 4.1). Risk was greatest during the first 10 cases that the trainee performed (approximately 2 in 50) and dropped off dramatically as the surgeon become more experienced at performing the procedure. Indeed, the probability of a bile duct injury had reduced from 1.7% during the first ten cases performed to 0.17%.

A number of reports that have shown that training junior surgeons during operating time adds considerably to the length and therefore to the cost of the procedure (Bockler et al. 1999). In the US it has been conservatively estimated that each operating room (OR) costs $30 per minute to run (excluding staff salaries). In an already hard-pressed health sector hospital, chief executives are finding the extra expense of surgical training increasingly unacceptable. Consequently, there is considerable pressure on surgeons to conduct as little training as possible during OR time. Most complications during MIS occur early in the surgeon's career, i.e., first 50–100 laparoscopic procedures (Gigot et al. 1997; Moore and Bennett 1995). It has also

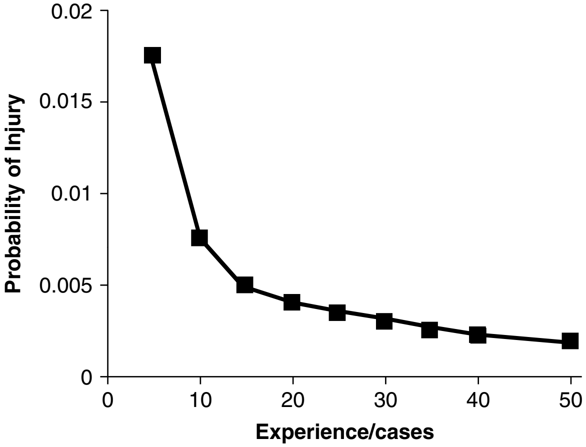

Fig. 4.1 This graph shows the probability of a bile duct injury as a function of surgeon experience/cases of laparoscopic cholecystectomy performed by them

been demonstrated that complications are also significantly more likely to occur if the surgeon performs a given procedure infrequently or if that procedure is performed infrequently in a hospital (Lerut 2000). The implications of these findings could have dramatic consequences for surgeons. Possible consequences of these types of data could include withdrawal of operating privileges for some hospitals and surgeons who perform too few of that type of procedure per year. This would mean that expertise would come to be concentrated in a smaller number of centers of excellence, which in turn would have implications for training junior surgeons and re-accrediting senior surgeons.

This evidence would seem to indicate that certain surgeons have difficulty acquiring and practicing the 'new' skills required for minimally invasive surgery. Furthermore, the surgical community seems to infer that the problem is simply a matter of acquiring the appropriate skill set. However, a small number of surgeons who were aware of the literature on human factors have realized that the answer probably is not that simple. Here we have two different approaches to solving the problem of higher complication rates associated with laparoscopic surgery. The traditional surgical approach was to recommend more, better or more specialized training. Indeed, this is what happened during the late 1990s and early part of the twenty-first century. Specialist units were set up to train the skills required for minimally invasive surgery. Trainers in these units developed different types of training tasks that encouraged the trainees to interact with and to learn the technology associated with the practice of minimally invasive surgery. Around the world these units became very well-known for their types of training, training tasks and new minimally invasive approaches to traditional open surgical procedures. For example, one of the surgical tasks that was commonly used in many of these surgical training units was intracorporeal suturing. We have discussed one example of a systematic training programme for the acquisition of these skills in detail in Chap. 2. While these tasks and training programs appeared to have achieved their goal, this was more by accident than design. In essence, this approach was too crude and gave very little insight into the underlying human factor reasons for the difficulty in acquiring the skills for minimally invasive surgery. Analysis of the underlying human factors is essential if tasks and training methods are to be developed which educate and assess these skills within an efficient and effective programme.

It is interesting to look at the efforts of Prof Sir Alfred Cuschieri and his team in Dundee. At the outset they seemed to grasp that a deeper level of analysis and understanding of the difficulties associated with the acquisition of minimally invasive surgical skills was required for the development of a long-term solution to the problem. One of the objectives of this book is to increase the fundamental understanding of the human factors involved in learning and practice of minimally invasive procedural medicine such as surgery. If the problem is understood in a holistic sense, efficient and effective solutions can be built taking this understanding into account. One of the concerns that we have with virtual reality simulation for training surgical skills is that the simulators are really no better than the novel laparoscopic surgical training tasks that were developed for training minimally invasive surgical skills. Moreover, we believe that virtual reality or simulation per se holds far greater potential than is currently being harnessed. Although we have applied our analysis to the skills required for the learning and practice of minimally invasive surgery, this analysis can be applied to any set of clinical skills in procedural medicine.

Psychomotor Skill

One of the ideas that we have tried to communicate in Chap. 3 is that important units of behavior such as sensing, perceiving and thinking do not occur in isolation. The human being (whether they are qualified in medicine or not), whilst going about their everyday life, is a unitary, integrated, highly complex biological system. The same is true for the practice of skilled performance such as in surgery. The accurate integration of spatial, perceptual, and psychomotor information is of fundamental importance in nearly every aspect of everyday life (such as running for a bus, catching a ball, reaching for an object across a table, threading a needle or indeed performing surgery). For instance, computation of direction and distance has to be made before reaching to the vicinity of a target object; not only in terms of global assessment before acting, but also by prospective evaluation of what is going to happen next and throughout the period in which the action takes place. Such anticipation relies on an implicit hypothesis about the stability of both the spatial position of the target object and the spatial position of the agent (Brooks et al. 1995). Thus both perception and action take place within a spatial framework (probably integrated in working memory).

Most of us are aware that we are constantly receiving information about objects and events in our external (and internal) environment. Yet few of us give more than a moment's thought to the information we continually receive about the position and movement of our own bodies. Proprioception is the general term used for the sensory system that provides such information. Unlike the six exteroceptive senses (sight, taste, smell, touch, hearing and balance) by which we perceive the outside world, and interoceptive senses by which we perceive pain and movement of internal organs, proprioception is the third distinct sensory modality that provides feedback solely on the status of the body internally. Proprioception is actually made up of two subsystems, i.e., the kinesthetic and vestibular systems. Although these two systems are anatomically distinct, they are closely coordinated in their operation, probably in a cognitive manner.

Kinesthetics

Psychomotor skill refers to the ability to accurately perform, learn or adapt to situations requiring fine and complex sequences of motor activity (Adams 1990). The process is dependent on the body's sensory information regarding the position and movement of its limbs. Fine motor skills are the coordination of small muscle movements which occur, e.g., in the fingers, usually in coordination with the eyes. In relation to the motor skills of hands (and fingers), the term (surgical) dexterity is commonly used and is widely accepted as an important attribute of the aspiring or practicing surgeon. Fine motor skills are those that involve a refined use of the small muscles controlling the hand, fingers, and thumb. As with many things, we tend to take for granted many human functional attributes until we try and replicate them. This is also true of the human hand. Figure 4.2 shows one of the best efforts to duplicate the functionality of the human fingers, thumb and hand. The 'Shadow Dexterous Hand' has been designed to have a range of movement equivalent to that of a typical human being. The four fingers of the hand contain two one-axis joints connecting the distal phalanx, middle phalanx and proximal phalanx and one universal joint connecting the finger to the metacarpal. The little finger has an extra one-axis joint on the metacarpal to provide the hand with a palm curl movement. The thumb contains one one-axis joint connecting the distal phalanx to the proximal phalanx, one universal joint connecting the thumb to the metacarpal and one one-axis joint on the bottom of the metacarpal to provide a palm curl movement. The wrist contains two joints, providing flex/extend and adduct/abduct. To mimic the hand, the Shadow Dexterous hand has 24 joints altogether, with 20 degrees of freedom. However, even with this degree of sophisticated engineering, its functionality comes nowhere close to the range and sensory sensitivity of the original model, i.e., the human hand.

Kinesthesia (or movement sensitivity) refers to the specialized sensor groups that provide information about the angles of the joints, the length of muscles, the degree of muscle tension, and the rates at which all these values change. Kinesthetic information is thus primarily gained from body movements whether self-generated or externally imposed (Clark and Horch 1986). Kinesthesis contributes to such basic abilities as walking, reaching and grasping. It is also critical for such highly skilled

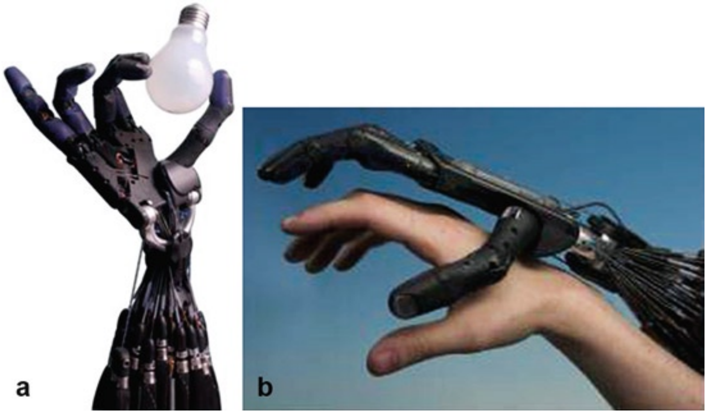

Fig. 4.2 The Shadow Dexterous Hand (http://www.shadowrobot.com/hand/) has been designed to have a range of movement (approaching) equivalence to that of a typical human being (27 DOF) with 20 degrees of freedom

activities as playing a musical instrument, signing your name or anything that requires precise control over the position and movement of body parts. The receptors for kinesthesis are located in the muscles and tendons and in the linings of the joints. These receptors respond to mechanical force, such as that exerted by the pull of a tendon, stretch of the muscle or the bending of a joint.

Vestibular System

The vestibular system refers to the overall position and motion of the body in space. In particular, it focuses on the orientation and movement of the head relative to gravity. Vestibular information can indicate such things as whether we are standing upright and whether we are falling to the left or to the right. It therefore plays an important part in maintaining balance and a number of other reflexive actions. One of the most important reflexes which is triggered by vestibular sensation is compensatory eye movements. An example of this compensatory action takes place every time we walk. When walking, as well as forward propulsion we shift from one foot to the other and our head bobs about so that we maintain a clear and focused view of our environment. It is our vestibular system that ‘smoothes’ out the images that we encounter. It does this by registering the direction and extent of head movements, and then uses this information to make automatic corrective eye movements in the direction opposite to the head movements. The result is a stabilization of the visual world. The two chains of anatomical structures that underlie the vestibular sense are the vestibular sacs which tell us about the orientation of the head when it is at rest and the semicircular canals which provide information about the rotation of the head. These structures are located in the innermost cavity of the ear although they are unrelated to hearing. Like other sensory systems, the vestibular system is especially attuned to changes in stimulation, e.g., for speeding up or slowing down rather than constant motion. For example, we are only aware of a lift leaving one floor and arriving at another, and in an aircraft we are only aware of takeoffs and landings and not the great speeds maintained during the flight travel (Carlson 1994).

Hand–eye coordination such as those required in surgery (whether open or minimally invasively) is the coordinated control of eye movement with hand movement, and the processing of visual input to guide reaching and grasping along with the use of proprioception of the hands to guide the eyes. It is a way of performing everyday tasks and in its absence most people would be unable to carry out even the simplest of actions such as picking up a book from a table or playing a video game. Studies have shown that when eyes and hands are used for search exercises, the eyes generally direct the movement of the hands to targets (Liesker et al. 2009). Furthermore, the eyes provide the initial information of the object, including its size, shape, and possibly grasping sites which are used to determine the force needed to be exerted by the fingertips for engaging in a given task. For shorter tasks, the eyes often shift on to another task in order to provide additional input for planning further movements. However, for more precise movements or longer duration movements, continued visual input is used to adjust for errors and to create more presision. For sequential tasks, it has been observed that eye gaze movements occur during important kinematic events like changing the direction of a movement, or when passing perceived landmarks. This is related to the task search oriented nature of the eyes and their relation to movement planning of the hands, and the errors between motor signal output and consequences perceived by the eyes and other senses which can be used for corrective movements. Furthermore, the eyes have been shown to have a tendency to ‘refixate’ upon a target in order to refresh the memory of its shape, or to update for changes in its shape or geometry. In tasks that require a high degree of accuracy it has been shown that when acting upon greater amounts of visual stimuli, the time it takes to plan and execute movements increases linearly as per Fitts’s law (Lazzari et al. 2009). This law proposes a model of human movement for human–computer interaction and ergonomics which predicts that the time required to rapidly move to a target area is a function of the distance to and the size of the target. Fitts’s law is used to model the act of pointing, either by physically touching an object with a hand or finger, or, virtually, by pointing to an object on a computer display using a pointing device. Fitts’s law is an unusually successful and well-studied performance model and experiments that reproduce Fitts’s results and/or that demonstrate the applicability of it in different situations are not difficult to perform. The data measured in such experiments invariably fit a straight line with a correlation coefficient of approximately 0.95 or higher which indicates that the model or ‘law’ is very good at accounting for the data.

Psychomotor Performance and Minimally Invasive Surgery

The vast majority of the motor difficulties in MIS are a result of the unique nature of the laparoscopic intervention and instrumentation. Several studies have demonstrated the effects of viewing monocular images (such as those on the surgical monitor display) on the performance of visually guided kinematic skills including moving, reaching and grasping. For example, Servos (2000) found that prior to the onset of movements, individuals greatly underestimated the distance and size of objects whilst under monocular viewing. Research by Haffenden and Goodale (2000)) have further indicated that under monocular viewing conditions, the relationship between individuals' estimation of the reach and grip necessary to obtain an object, and the objects size and distance specified by pictorial cues, required a period of learning and adaptation before an effective association could be formed. Thus, as a result of the MIS intervention, the interpretation of the monocular display (as on the surgical monitor) is likely to initially create psychomotor difficulties due to the distorted effects of depth and distance on subsequent movements. Marotta and Goodale (1998) illustrated that increased attention to evaluation in the field could be used as an effective cue to an object's distance and size, indicated by more accurate limb trajectories and grip estimation.

However, one of the greatest obstacles to the development of MIS skill is caused by the Fulcrum effect (Gallagher et al. 1998), which creates substantial difficulties in psychomotor coordination that result in a perceived inversion of movements. The Fulcrum effect (Gallagher et al. 1998) is directly caused by the unarticulated MIS instrumentation being limited to a fixed axis of movement through the wall of the body. The result is a first-order paradoxical movement (Patkin and Isabel 1993), similar to those experienced when operating a lever (such as the rudder of a boat or reversing a trailer). Consequentially, when the surgeon moves his/her hand to the right, the working end of the instrument within the body cavity moves to the left (and vice versa). This natural fulcrum affects both the horizontal and vertical movements displayed on the monitor. Thus as with perception, motor adaptation requires readjustments that seem to involve a period of learning. von Holst (Von Holst and Mittelstaedt 1950) stated that a fundamental aspect of motor adaptation involved establishing stable relationships' between the self-initiated movements of the body and the resulting changes in the patterns of information encoded by the sense organs, i.e., in surgical terms what they see or feel (and occasionally smell). The term reafference was used to refer to the feedback stimulation that resulted from self-produced movements, whilst the sensory information observed from changes in the external world was termed exafference. Effective perceptual-motor activity was then dependent on the individual's ability to distinguish between exafferent and reafferent stimulation. Von Holst (Von Holst and Mittelstaedt 1950) believed that the process of differentiation was mediated by efferent impulses (signals that initiated the movements) which in turn left behind an image or representation (the efferent copy) of the signal to be stored for comparison. According to von Holst, every movement by the body produces an efferent copy for comparison with the reafferent signal, thus enabling the individual to distinguish it from a change in the environment (exafferent information). Jeannerod (1999) also stated that movement and action were highly effective ways of differentiating the self from others.

Traditionally the assessment of visuomotor adaptation has involved creating a conflict between the actual visual scene, and the information experienced through the individual's visual reafferences. Motor and visual-motor studies generally require that a subject makes one or more movements of the hand and/or arm from a specific starting position to a target. Direction, amplitude and accuracy constraints are placed upon the movement by varying the target's location and size. Dependent variables include aiming error, reaction time and movement time (Fitts and Peterson 1964; Keele 1968; Wallace et al. 1978). A number of experimenters have used variations of visuomotor discordance to investigate the problems of adaptation. Harris (1963) showed the deterioration in performance of a drawing task when inverted by a mirror. However, Smith (1970) demonstrated that humans could adapt to writing in a mirrored reflection. The negative effects of inversion on the proprioceptive system during a simple movement task have also been documented by Mather and Lackner (1980).

Of course, in laparoscopic surgery, the visual discordance created by the fulcrum effect is the *normal* viewing condition, and it should really have come as no surprise to the surgical community that it would cause significant difficulties in developing the skills necessary for the practice of MIS. Gallagher et al. (1998) quantitatively demonstrated the detrimental impact of the 'fulcrum effect' on the performance of novice subjects during a simulated laparoscopic cutting task. The two studies showed that for laparoscopic novices the normal laparoscopic condition resulted in a significantly degraded technical performance. The influence of the fulcrum effect as an obstacle to motor adjustment in MIS was further demonstrated by the statistically significant improvement in novice performances, when the image on the monitor was inverted around the Y-axis (resulting in a left-right movement by the hand being displayed as such on the screen). Research by Held and colleagues have demonstrated the necessity for active movements in the process of motor adaptation (Held and Gottlieb 1958; Held and Rekosh 1963). The experiments involved measuring the adaptation of self-produced activity in comparison to passive movements whilst under conditions of displaced visual viewing. The results indicated that only the self-movement group had adapted, as illustrated by a compensating shift in the accuracy task as a result of the visual displacement. Thus, even though all the participants received the same visual input concerning hand movement, the passive condition alone was insufficient to produce adaptation due to the lack of connection between the sensory output and visual input (i.e., no formation of an efferent copy). Held and Rekosh (1963) concluded that the process of adaptation was dependent on individuals adjusting their judgments of spatial relationships according to the modified reafferent information. These findings therefore demonstrate the necessity for active psychomotor practice in order to effectively adapt to the discordance difficulties imposed by MIS. The research indicates that whilst adaptation is possible (Crothers et al. 1999) it requires a prolonged period of learning, practice, and attention (Gallagher et al. 1998). Furthermore, if adaptation was simply just 'more practice' the tasks developed by laparoscopic surgical training units around the world would have been sufficient to solve the problem. However, they were not. These training units simply produced trainees who on graduation had considerable variability in skill levels including some who were no more skilled than when they entered the training program.

Theories of Psychomotor Learning

Newell (1991) has proposed that a behavior could be identified as skilled or a skill when it was

1. Directed toward the attainment of an identifiable goal;
2. Organized so that the goal was reliably achieved with economy of time and effort; and
3. Acquired through training and practice.

Research on motor skills has primarily focused on the hand as the effector system for manipulative skills (such as the instrumentation in MIS), and the trunk and limbs as the principle effectors of whole body skills (Adams 1987). Another important effector includes the ocular-motor (eye-movements) system, which is involved in spatially orientated behavior, specifically tracking and localization (Courjon et al. 1981). These varied effector systems have different physical properties that must be taken into consideration in any theoretical analysis of control mechanisms (Annett 1969). The skeletal effectors are essentially lever systems in which the angle at the joint is controlled by balanced groups of muscles, the agonists and the antagonists. The eye, in contrast, has low inertia that enables it to make fast saccades to pre-selected locations, an essential requirement for spatially directed behavior (Newell 1991).

The combination of the properties of object (size, distance, structure etc), the type of movement required, and the effector systems involved are all important in determining the kind of control that is needed for the task (Lee et al. 1995). Generally motor skills are dependent on two kinds of control laws, characterized as feedforward and feedback information. In a feedforward system, output (i.e., muscular activity) is controlled by a program or set of stored instructions that are initiated by a starting signal in much the same way as a home computer runs through a series of actions when a particular program is set up and initiated. In a feedback system, a target value for one or more variables is set (the set point) and the output is controlled by a signal proportional to the difference between the currently sensed value and the set point. Fitts (Fitts and Peterson 1964) used simple positioning tasks (placing a peg in a hole) to illustrate how the two types of control can operate in one movement; an initial pre-programmed ballistic or "open loop" phase, followed by a controlled or closed loop second phase of sensory adjustment. The pre-programmed phase represents typical feedforward control in which a pattern of motor impulses may be computed on demand or may be drawn from a memory bank (Annett 1969). The initial entry and movement of the laparoscopic instruments toward the target area of the operation is an example of a feedforward controlled movement in MIS; whilst the slower and continually adjusted movements to accurately obtain the target (e.g., tissue on needle for suturing) represent actions under the control of feedback information. A skill such as performing a laparoscopic procedure must therefore (by its very definition) be specifically learned and invariably taught. However, the process of skill acquisition is not simply a matter of continual practice. For example, early studies from trainee Morse telephonists showed that the number of signals correctly transcribed per minute rose steadily over the first three to four months of practice remained roughly constant (at a plateau) for the next two months, and then began to rise again (Annett 1996). The later acceleration in learning was accompanied by a change in technique (i.e., receiving and writing down whole words rather than transcribing each individual letter).

It is therefore recognized that practice results in both quantitative and qualitative changes in performance (Chaiken et al. 2000). Indeed, this plasticity of skilled behavior created many problems for the early theories of performance and resulted in the abandonment of the linear information-processing models of the 1950s. The fundamental concept of a capacity-limited processing channel that accounted for choice reaction time data (Hick 1952) and the trade-off between speed and accuracy in rapid movement tasks (Fitts and Peterson 1964) collapsed when it was demonstrated that extended practice changed the relationship between stimulus information and performance (Annett 1969). Given the quantitative changes that occur with practice, several researchers have attempted to define the process in more complex mathematical terms. Fitts (Fitts and Peterson 1964) indicated that for simple repetitive skills, the logarithm of time for each repetition was a linear function of the logarithm of the number of practice trials. Thus a log-log linear law of learning could be formed, and its apparent simplicity suggested that there might be a single underlying learning process. Newell and Rosenbloom (1981) maintained that a power function provides a better fit to skill acquisition data. The power law of practice was based on results from both motor and mental skills, and proposed that the central principle component of learning involved “chunking” the information. Information was said to be chunked when it was dealt with as a single unit.

However, Annett (1996) indicated that the log-log linear law was most probably not representative of a single slow acting process, but rather a population of ways of learning that are successively drawn upon until exhausted. Thus, in the early stages, relatively rapid progress can be made by imitating the method of a skilled model or taking advice of a trainer, whereas much later in practice, when major sources of improvement have been exhausted, repetition may refine perceptual and temporal judgments or facilitate the connections between task elements. These studies and theories suggest that the development of MIS skill is likely to come from a relatively short initial period of rapid improvement, followed by a much longer period of sensory refinement and adjustment which seems to fit well with the data shown in Fig. 4.1. Adams (1971) closed loop theory of motor learning represents one of the most influential and holistic approaches to the process of skill adaptation. The model was based on the premise that the combination of sensory feedback and knowledge of results (KR) were used as a means of correcting motor errors. The theory poses that a motor trace (a record of the individual’s movement) for the required action response is stored and compared to a perceptual trace (a record of sensory feedback). He suggests that sensory feedback is a function of error and is used to adjust movements until the desired goal is achieved. Repeating the movement brings the anticipatory arousal of the perceptual trace to which the ongoing motor feedback is

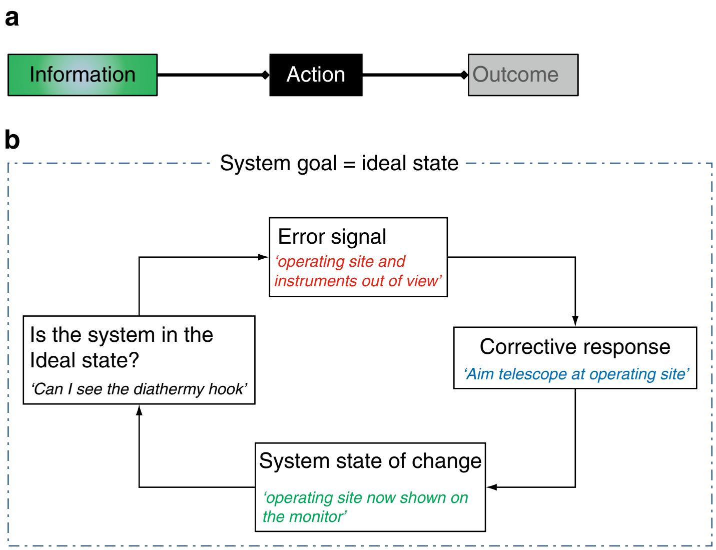

Fig. 4.3 (**a**) Operation of a simple open-loop control system, (**b**) Operation of a simple closed-loop control system for the simple skill of holding the camera and the laparoscope during an MIS procedure

continually reconciled. A positive relationship is formed when the perceptual trace confirms the implicated goal of the movement sequence. Practice strengthens the perceptual trace such that the sensory consequences of the motor outputs are anticipated. Frequently one will observe a very experienced (and usually talented) laparoscopic surgeon insert both of his operating instruments and 'check' that tissues and organs are located in depth of field at the distances and locations he remembers. It also accounts for why the same surgeon progresses cautiously around the triangle of Calot during a laparoscopic cholecystectomy, i.e., anatomy included the cystic duct, the common hepatic duct, and the cystic artery which can be easily damaged during the surgical procedure. This anatomy can present unusual configurations. Injury to the bile duct can lead to bile leak and liver damage and cause a painful and potentially dangerous infection requiring corrective surgery.

Systems, in general, may be characterized as Open Feedback or Closed Feedback and we have given examples in Fig. 4.3a, b. Open systems have outputs which are conditioned by information inputs but the outputs or outcomes themselves have no influence on the inputs. It is possible to think of an open feedback system in terms of the simple schematic shown in Fig. 4.3a. An open loop control system is not aware of its own performance, so that past action does not have any influence on future behavior, nor does it monitor and respond to current performance. All in all it is a very passive system.

By contrast, most processes have a structure in which the actions or behavior are shaped and influenced by past and current performance, which feeds back into system behavior to bring about some adjustment and change. The human body contains a number of excellent examples, one of which is the temperature regulation system. The body is designed to operate at 36.4°C, so that if exercise is taken which raises body temperature then perspiration occurs, leading to the appearance of moisture on the skin's surface which evaporates, thereby cooling the body. Conversely, if the body temperature falls below 36.4°C, muscle activity is in the form of shivering which causes the body's temperature to rise. This process, known as homeostasis, is fundamental to the control of the body and many other biological systems. The feedback in the system operates to make use of the current value of some quantity to influence the behavior of the system as a whole. We can represent the feedback in this system as a Closed Loop control system and we have given a schematic example in Fig. 4.3b.

The goal of the control system is to attain and maintain the 'ideal state'. The example provided in Fig. 4.3b is of a trainee surgeon or a senior medical student holding and navigating the laparoscope for the operating surgeon. The 'ideal state' is for the operating surgeon to clearly see the tissues and structures being operated on with an electrocautery instrument. The operating surgeon 'instructs' (error signal) the trainee that they cannot see the operating site nor the working end of the instruments. The trainee's response is to correct the aim of the telescope so that it is pointing at the operating site (corrective response). This means that the operating surgeon can now clearly visualize the operating site and the working end of the surgical instruments. Thus the trainee will maintain this view until required to change it by new information. All real-life systems exhibit some or all of the characteristics of this feedback process, where information continually arrives and is acted upon to produce an effect which shapes and influences the activity or inactivity to maintain an ideal state. All feedback within systems may be classified into one of two forms: positive (or reinforcing) feedback and negative (balancing) feedback. The feedback either acts to increase the probability that the exhibited behavior will continue to move the system in the same direction as the initial impetus, or else the feedback operates to decrease the probability that the exhibited behavior will continue, thus countering the initial impetus for change in the direction.

The closed loop theory of motor learning has been used to explain the processes involved in learning, developing, and maintaining laparoscopic ability through experience and practice based on the empirical findings of Crothers et al. (1999). The analysis of the results in terms of Adams' theory explained why surgeons perform significantly better than the novice under normal MIS conditions. The surgeons had already adapted to the contradiction between the perceptual trace (sensory feedback) and the motor trace caused by the fulcrum effect, and had thus stored the correct motor output necessary to perform the procedure. In contrast, the novice group was just starting the process of adaptation by correcting for the error between output and feedback. The theory further accounted for why the inversion of the monitor image around the *y*-axis had such a detrimental effect on surgeons' performance. The surgeons, through substantial experience and practice (>50 MIS operations), had become automated in their movement patterns. Automation occurs when the motor output can be pre-selected based on its expected sensory outcome. The perceptual traces as a result of significant experience eventually become so strong that the task can be performed without the need for feedback (previous conscious movements have become automatic). Inverting the image resulted in a disruption of the surgeons' automated processing and caused paradoxical feedback to their learned patterns. The inverted condition means that the surgeons must concentrate on adapting their motor outputs to be counter-intuitive to their adapted patterns and so compensate for the fulcrum effect. The fast rate of learning found for the group illustrated that the surgeons already knew how to perform the procedure, but needed to adapt their movement patterns once more. The process of motor learning also explained why the *Y*-axis inverted condition caused a significant improvement in novice performance, inverting the MIS image compensated for the perceptual and cognitive problems posed by the 'fulcrum effect'. Thus, the novice group was presented with a more 'natural' representation of their actual movements, as conflicting feedback between the perceptual and motor traces had been eliminated (i.e., moving the instrument right resulted in the monitor image of the working end moving to the right).

Schmidt (1975) extended Adam's closed loop theory to account for a more generalized (one-to-many) memory construct through the concept of the "schema". Schmidt's theory suggested that the choice of motor outputs was related to their expected sensory consequences obtained from previous response specifications, sensory consequences, and outcomes; that is, whether or not the sensory consequences would signal a desired state of affairs. The various sources of information are then consolidated into a 'recognizable schema' or 'chunk' that encodes the relationships between sensory consequences and outcomes, and a recall schema that relates outcomes to response specifications. Horak (1992) used a simulated neural network to represent Schmidt's recall schema in the learning of a uni-dimensional ballistic skill (such as throwing an object at a target under varying distances). The results demonstrated that the network learned to match its variable force output to the different inputs representing the variations of target distances, by changing the weights of interconnections between its elements (analogous to individual neurons) according to performance outcomes. In a sense, the network discovers the rule relating perceived target distance to appropriate force output in much the same way as suggested by Annett's (1969) account of the role of knowledge of results in learning.

The significance of the models of Adams (1971) and Schmidt (1975) of motor learning and adaptation is that they offered theoretical frameworks which were testable and refutable, which is the starting point for science. Another strength was that they demonstrated that the development of a skill did not simply rely on habit (continual repetition), but involved a substantial cognitive component (such as the evaluation of differences between the motor and perceptual traces and formation of schemas). Indeed, the role of cognition in the development of skill had received modest attention compared to the study of sensory information for most of the twentieth century. The theories, however, implicated the necessity of cognitive processing to encode, compare, evaluate and adjust movements within a developing framework of performance. As a result the 1980s saw a surge in empirical studies investigating the role of cognition in psychomotor learning and indicated several cognitive concepts that are likely to help explain the development of MIS skill.

Although closed loop models of learning seem to provide a reasonably good account of skill acquisition and to facilitate the duplication of similar processes by computer scientists, on closer scrutiny they are overly simplistic. One of the problems of closed loop theory of learning is that it ultimately reduces skilled performance to a response chain in theory. By this we mean that each movement or component of a movement is assumed to be triggered by perceived error feedback. Yet many movement sequences can be performed effectively when feedback is removed. Complex movements can often be performed effectively (or at least significantly reduced) without proprioceptive or other forms of feedback. For example, during intracorporeal suturing performed robotically by the surgeon they have *no* tactile or haptic feedback and yet most surgeons can learn to suture safely with this device. Even under laparoscopic conditions this is a difficult task but robotically the surgeon has to ensure that they do not break the needle or thread or damage the tissue they are suturing. Another difficulty with the closed loop theory is that it predicts incorrectly that the more knowledge of results a learner receives the more effectively they will perform. However, in a study by Winstein and Schmidt (1989), they observed results that contradict this prediction. In this study, two groups of subjects were trained to reproduce target movements with their arm. One group of subjects had knowledge of results on 100% of the training trials and the other group of subjects was given knowledge of their results on 50% of their training trials. During training the performance levels of both groups did not differ and neither was there a difference between the groups in an immediate retention trial in which knowledge of results was withheld from both groups. However, in delayed retention tests given a day later, the group that was given knowledge of results on only 50% of the training trials performed best.

Another problem with the closed loop theory of learning is that it is possible for humans to accurately perform novel movements that they have never performed before. For example, it is possible for someone who has only ever played soccer to start playing rugby and play well, despite the fact that they have never played the game before and it has entirely different rules and shape of ball. Closed loop theory cannot explain the accurate performance of the novel movements required to play rugby in the absence of prior sensory feedback. An integral part of closed loop theory learning is the formation of a perceptual trace for learned movements. The difficulty with this hypothesis is that it would be impossible to conceptualize of a separate perceptual trace and memory store of every movement ever performed.

Before the birth of the proceduralization concept, theories of motor learning have been influenced by the open-loop versus closed loop system distinction (Adams 1971; Schmidt 1975). The original formulation of the closed-loop view on motor performance and learning build on the momentum of internal feedback from executed movements, which allow for error detection and adjustment of actions through the process of contrasting perceptual traces against memory representations (Adams 1971). Motor learning was accordingly seen as dependent on repetition, accuracy, refinement and synchronization of a series of called-up movement units (i.e., open-loop structures) that are regulated by closed-loop structures.

In response to this view, a different open-loop perspective emerged, namely the one of motor programs (Schmidt 1975). The learning of motor skills was thereby seen in terms of the build-up, modification, and strengthening of schematic relations among movement parameters and outcomes. This learning results in the construction of "generalized motor programs" (i.e., a sequence or class of automated actions) that are triggered by associative stimuli, habit strengths and re-enforcers, and can be executed without delay (Anderson et al. 1996; Schmidt 1975; Winstein and Schmidt 1989). The advantage of Schmidt's theory was that he proposed that motor programs do not contain the specifics of movements, but instead contain a generalized rule for a specific class of movements. He predicted that when learning a new motor program, the individual learns a generalized set of rules that can be applied to a variety of contexts. Schmidt proposed that, after an individual makes a movement, four things are available for storage in short-term memory: (a) the initial movement conditions, such as position of the body and the weight of the object manipulated; (b) the parameters used in the generalized model program; (c) the outcome of the movement in terms of knowledge of results; and (d) sensory consequences of the movements, i.e., how it felt, looked and sounded. This information is stored in short-term memory only long enough to be abstracted into two schemas: (1) the recall schema (motor) and (2) the recognition schema (sensory).

The *recall* schema is used to select a specific response. Each time a person makes a movement with a particular goal in mind, they use a particular movement parameter such as movement force and they then receive input about the movement accuracy. After making repeated movements using different parameters causing different outcomes in the nervous system, these experiences create a relationship between the size of the parameter and the movement outcome. Each new movement added contributes to the internal system to refine the rules associated with that action class. After each movement, sources of information are not retained in the recall schema but only the rule that was created from them. The recognition schema is used to evaluate the response. The sensory consequences and outcomes of previous similar movements are coupled with the current initial conditions to create a representation of the expected sensory consequences. This is then compared to the sensory information from the ongoing movement in order to evaluate the efficiency of the response and performance modified on the basis of this feedback.

Observational Learning

In medicine, an important part of a surgeon's training is observing experienced surgeons performing operative procedures. Whilst previous studies have demonstrated the importance of action in motor adaptation, there is also good evidence to suggest that simply observing activities improves the formation of skill. Ferrari (1996) suggested that observational learning involved two complementary types of observation: the observation of the process, which allows one to imitate and to understand a modeled demonstration; and self-observation, which allows one to deliberately regulate one's own motor learning and performance. The deliberate self-regulation of action, in turn, assures a more efficient and effective learning of the skilled behavior. Some other major influences on observational learning include the properties of the model (e.g., level of skill, social status etc.); the nature of the task (e.g., its familiarity, salience, complexity, functional value etc.); and observer determinants. These include self-regulation of learning, self-efficacy beliefs, comprehension of the demonstration and feedback, all of which have been found to improve skill acquisition and performance (Druckman and Bjork 1992).

Bandura's (1982) theory of observational learning essentially states that individuals acquire new motor skills by attending to salient aspects of the modeled performance and by coding the received information into cognitive representations that can later be recalled. These representations allow the learner to produce novel motor performance through observation by using these representations as an internal standard against which to monitor the correctness of their produced movements. Research by Jeannerod (1999) has demonstrated support for Bandura's theory by illustrating similarities in cortical stimulation between individuals performing a motor task and those observing the activity. These findings support the efficacy of laparoscopic trainees observing operations as a means of accurately shaping and representing MIS skill. These results also highlight the importance of observing effective and reliable performance of the task to avoid developing inappropriate representations of the model. However, in procedural medicine this can sometimes be problematic as some very senior physicians may have acquired their seniority and rank on the basis of good, management ability, science (papers and grant income) and patient care but are not quite as technically proficient. Unfortunately some of this influential group are blissfully unaware of this fact and indeed some are firmly of the belief that they are technically highly skilled. Whilst this may not be a problem for their consultant peers who recognize the quality of technical skills for what they are, it most certainly can be a problem for more junior colleagues who equate seniority and career success with technical proficiency. A young colleague informed us one day of his experience learning how to perform laparoscopic cholecystectomy with a fairly senior academic surgeon. It was not until this colleague moved to his next rotation that he discovered it was not part of the 'normal' surgical procedure to puncture the gallbladder.

How do we recognize technical skill? As in other domains, experts in motor skill achieve a higher quality of performance by achieving more efficient movements with less wasted motion or power (Cheng 1985) and by appreciating ever more specialized prototypic situations or conditions to which specialized actions are attended (Anderson 1982; Ericsson and Kintsch 1995). However, experts do not excel when they cannot use their superior knowledge of the activity (i.e., when the elements of a situation or task are not arranged in a meaningful pattern). Norman et al. (1989) examined the diagnostic skill in dermatology at five levels of expertise. As expertise increased, correct diagnosis was associated with shorter response times while errors were associated with longer response time (suggesting greater deliberation for erroneous responses). Atypical slides continued to account for a constant proportion of error at all levels of expertise, suggesting that experts do not use more elaborate classification rules. These findings are comparable to the reported results of Crothers et al. (1999) illustrating the considerable degradation in performance of y-axis image inversion on the performance of experienced laparoscopic surgeons (due to the disruption of their ‘fulcrum effect’ automation).

While experts may not be proportionally more likely to recognize marginal cases, they have more knowledge with which to judge possible alternatives. However, if experts proceed habitually, they may fall victim to what Langer and Piper (1987) termed premature categorization. Premature categorization was found to occur when experts did not actively use contextual cues to help interpret novel instances or similarities but rather relied on prototypical instances with which they are familiar (Gick and Holyoak 1987).

Acquiring Technical Skills: Efficient Learning and Performance Strategies

Phases of Learning Skill

Motor learning involves the acquisition of a sequence of highly coordinated responses that are systematically related to one another and each response or component response is intricately related in a chain-like manner. Sensory motor learning involves the sensory systems such as seeing and hearing both in directing the motor pattern on and in providing feedback including knowledge of results. Motor learning, in contrast to other areas of learning such as conditioning and rote memorization, appears to be an ongoing process of refinement and improvement.

There are at least two ways to conceptualize the stages in motor learning. The first involves tasks or situations that consist of a series of levels. Consider the skill of typing. The first stage in acquiring this skill requires learning finger control and location of the keys. During this stage, the learner shows rapid improvement in terms of both speed and accuracy although the novice typist may feel that their initial progress seems slow. The next stage of their learning involves moving from letter to word habits and from word to phrase habits. During each stage, initial improvement in performance tends to be followed by a plateau showing little improvement until the learner moves to the next higher stage. What appears to be going on here is the cognitive consolidation of skill acquisition and neuropsychological evidence of this process has now started to emerge from imaging studies (Dudai 2004).

Another way to represent the stages of motor learning was provided by Fitts and Posner (1967). They focused on the stages that the individual passes through in the process of skill acquisition. They identified three clear stages.

Cognitive: In the first stage the learner needs to know what the elements of the task are in terms of expected performance. During this stage of learning, the novice draws upon reasoning abilities and past experiences which appear to relate to the performance of the task. This information (and 'rules') will be modified as they gain experience with the task.

Associative: The associated stage commences as other prior cognitive activities begin to drop out. Major errors are greatly reduced during this stage and the learner refines responses. In the initial cognitive stage, the learner places great emphasis on what responses are required and in what order. The learner tends to concentrate on how best to coordinate and to integrate those respondents and identify which ones are redundant or inefficient.

Autonomous: The third stage of motor learning refers to extremely advanced levels of performance. At this stage errors have been greatly reduced and the learner seems to perform the task automatically, i.e., their skills have become automated. It is at this stage that less attention is required to perform the task and so these attentional resources can be devoted to the performance of other activities at the same time. Once a skill has become automated, we can say that it has become programmed. The learner has established a sequence of highly coordinated movements that are integrated in time and are characterized by a rhythmic structure of their own. These highly integrated motor programs are acquired during advanced stages of motor learning and are very robust against interference from other tasks and also from extinction. Examples of the former come from evidence of highly skilled individuals being able to perform apparently incompatible tasks at the same time, e.g., a professional typist can work effectively and efficiently whilst reciting nursery rhymes from memory. Another example is the ability to ride a bicycle on holidays despite not having practiced or used the skills for many years. It is as though the basic elements of the skills have become so highly integrated that they were retained as an intact unitary skill.

The process of skill automation is a particularly important one for minimally invasive or endovascular surgeons. As described in Chap. 3, these types of interventions make unique and challenging demands on the surgeon which is especially true when they are operating on a patient. One particular aspect of cognition that has received minimal consideration in the surgical literature is 'attention' but it is of paramount importance to the surgeon while learning a new task or set of skills. In our review of working memory in Chap. 3, we have touched on this subject. Attention usually refers to the ability to concentrate mental powers upon an object such as careful observing or listening, or the ability to concentrate mentally. It has been known for at least half a century that human beings have a limited attentional capacity (Broadbent 1958). This means that we can only attend to a finite amount of information or stimuli at any given time. Figure 4.4 shows a diagrammatic representation of attentional resources used by a master surgeon, a junior surgeon and a novice surgeon for different aspects of operative performance. All three surgeons must allocate some of their attentional resources (consciously or unconsciously) to psychomotor performance and judgments about depth and spatial relationships. They must also attend to the patients vital signs on instrument read-outs. However, the distribution of this resource allocation differs depending on the experience of the surgeon. When a novice is acquiring a new skill such as those required for laparoscopic surgery, he/she must use more of these attentional resources to consciously

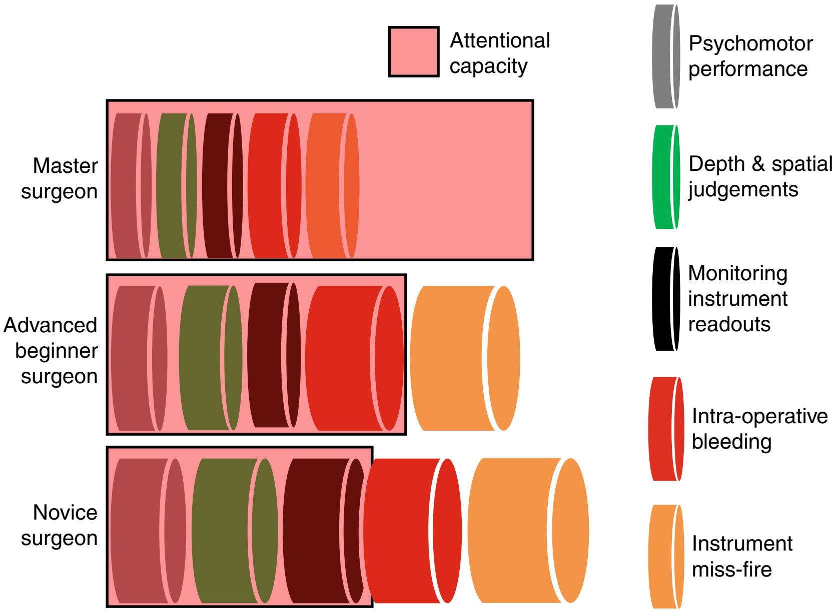

Fig. 4.4 Hypothetical model of attentional resource allocation of three surgeons with different levels of experience and skill during a laparoscopic surgical procedure

monitor what their hands are doing and where in space they are doing it while trying to remember the details of the surgical task they are performing and the order these tasks are to be performed. Consequently, if they are learning these skills whilst performing surgery on a patient, much of their attentional resources (which are limited) are already used up. When an intra-operative event such as bleeding occurs, they may not have the attentional resources available to even notice the event. The more experienced junior surgeon would notice due to the fact that some of their skills have automated and require less conscious attention. However, if a second intra-operative event occurs, they could quickly exceed their available attentional resources whereas the master surgeon simply attends to and deals with these events.

It has been quantitatively demonstrated that this is one of the fundamental problems posed by the fulcrum effect on instrument handling in the acquisition of laparoscopic skills (Gallagher et al. 1998) and that this situation improves with training, practice and experience (Crothers et al. 1999). This happens because basic skills such as simple hand–eye coordination that are being learned will eventually ‘automate’ as these skills can be practiced proficiently with minimal attentional demands. These attentional resources are thus free to attend to other aspects of the task such as surgery, while the rest of the team are doing and mentally rehearsing how the surgery will proceed. This automation process is represented in Fig. 4.5. There are two collateral pressures impinging on the reduction of attentional resources. The first is the skill level of the surgeon, the second is the experience they have gained. Experience or the learning curve of the surgeon is what most surgical

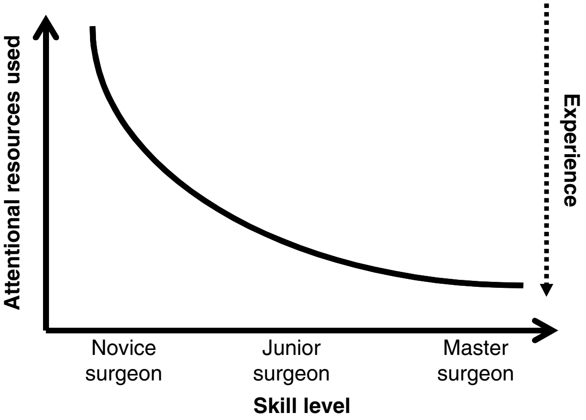

Fig. 4.5 Hypothetical model of attentional resources used as a function of task demands, attained skill level and operative experience

disciplines have concentrated on. However, the surgeon's learning curve will interact with their innate ability. The more innate visio-spatial, perceptual and psychomotor ability the learner has, the faster they will acquire the surgical skills thus automating faster and requiring fewer attentional resources to monitor basic aspects of the task they are performing, e.g. surgery, Figure 4.5 should be familiar to most surgeons as it appears to resemble the 'learning curve' associated with skill acquisition shown in Fig. 4.1. This is because the learning curve has been used as a proxy indicator for skill level and thus attentional automation are almost always linked to operative experience. However, as many surgeon educators are all too aware, the number of procedures performed by a learner is at best a crude predictor of actual operative performance. A better predictor is objective technical skills performance. The goal of any surgical training program should be to help the junior surgeon automate these basic psychomotor skills before they operate on a patient. This is one of the major advantages of simulation; it allows the trainee to automate in a risk-free environment and the trainer to monitor the automation process. Establishing when automation has been achieved will be dealt with later in Chap. 8.

Observational Learning

Perhaps the very fact that observational learning is so obvious helps explain why it was a relatively neglected area of research by psychologists until the late part of the twentieth century. Observational learning is the tendency of humans and many animals to learn by imitation. One explanation for the widespread importance of observational learning is its efficacy which means that learners can frequently avoid the tedious trial and error procedures that are characteristic of instrumental conditioning. Another advantage is that they will also know whether the efforts of the actor have been successful or not. Factors which appear to influence the effectiveness of observational learning are, for example, the status of the model (i.e., a consultant,

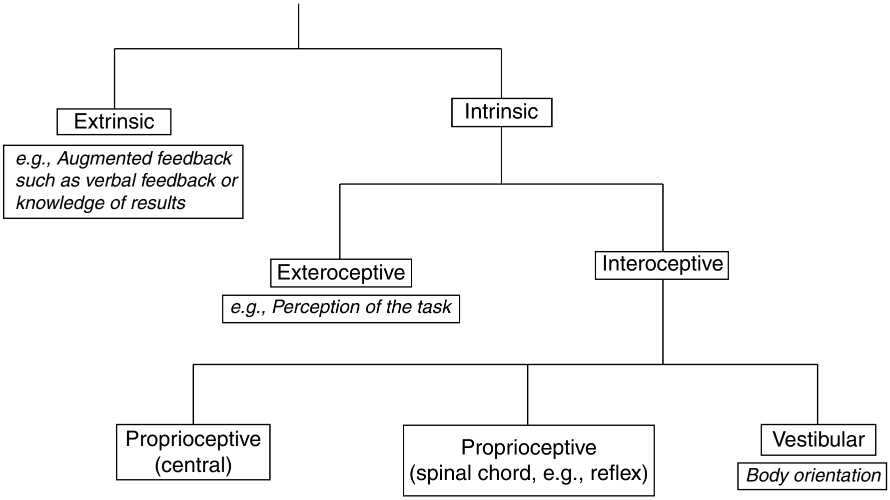

Fig. 4.6 Different types of feedback that may be used for regulation of performance

modeling the skills to be learned will be more effective than those of a peer) and levels of reinforcement. This means that the trainee is more likely to repeat performance characteristics that have a successful outcome or which have been rewarded. We will return to the issue of observational learning in Chap. 9 when we discuss the issue of didactic education and training and Chaps. 10 and 11 when we discuss how better use could be made of online learning.

Feedback: Knowledge of Results

For the operating surgeon proximal feedback on their performance is crucial. Figure 4.6 shows the different types and sources of feedback the surgeon can access to regulate and modify their performance. Extrinsic feedback from their environment is available from a wide variety of sources such as their trainer, knowledge of their results etc. Feedback can also come from a number of intrinsic sources such as perception of the task (visual, tactile, haptic, auditory and olfactory). It can also come from interoceptive information sources which provide information on the movement of internal organs and whether the body is moving with the correct effort. Proprioceptive information also comes from the final chords (reflects) type actions. Lastly, the surgeon can access information from the vestibular system which provides information on body orientation and location in space. One of the most valuable and efficient sources of feedback information is from the visual system. This is not really a problem in open surgery, but for any type of image guided surgery it becomes an issue if the surgeon cannot see images in real time. In image guided interventional medicine such as MIS, visualization in real-time is of crucial importance. Visualization of a dynamic process milliseconds after it's occurrence requires rapid information processing. Traditionally our reference point for real-time imaging has come from the film and TV industry. Image presentation is measured in Frame rates at which an imaging device produces unique consecutive images called frames. The term applies equally to computer graphics, video cameras, film cameras, and motion capture systems. Frame rate is most often expressed in frames per second (FPS) and in progressive scan monitors as hertz (Hz). In the United Kingdom, the TV and film industry generally uses 25 FPS and in the USA 30 FPS and these are regarded as real time. The reason real-time imaging is considered crucial by surgeons who operate with image guidance is that they need feedback on the impact of the working end of the instrument on tissues while they are operating. If they do not receive this information in real time and are operating close to vital structures such as an artery, they could inadvertently cause very serious and even life-threatening injuries. It is this speed of image processing that has delayed the expansion of tele-robotic surgery over great distances especially in deep space travel.

Real-time rendering is one of the interactive areas of computer graphics. It means creating synthetic images fast enough on the computer so that the viewer can interact with a virtual environment and is vital for high-fidelity virtual reality simulation. The most common place to find real-time rendering is in animated movies or video games. The rate at which images are displayed is also measured in frames per second (fps) or Hertz (Hz). In this instance, the frame rate is the measurement of how quickly an imaging device produces unique consecutive images. If an application is displaying 15 fps, it is considered real time.

Feedback: Metrics (Augmented Knowledge of Results)

Metrics are a standard set of measurements by which a plan, process or product can be assessed and that quantify these elements of performance. In terms of training in surgery, metrics are best considered as an extrinsic augmented form of feedback, which gives detailed information on knowledge of results. As indicated above, this type of information helps to optimize the learning experience and allows the trainee to acquire the desired skills in a more efficient manner. We shall discuss this very important issue of metrics in some depth in Chap. 5, but it is fair to say that valid and reliable metrics which are easily accessible should be an integral part of any good simulation that purports to train medical skills. The formulation of metrics requires breaking down a task into its essential components (task deconstruction) and then tightly defining what differentiates optimal from suboptimal performance. Unfortunately this aspect of simulation has been given all too little attention by the simulation industry. Drawing on the example from the MIS community almost all of the VR simulators use time as a metric. Unfortunately time analyzed as an independent variable is at best crude and at worst a dangerous metric. For example, in the laparoscopic environment being able to tie an intracorporeal knot quickly gives no indication of the quality of the knot. A poorly tied knot can obviously lead to a multitude of complications. There are only a few reports in the literature that use objective end product analysis (Hanna et al. 1997) due to the difficulty in acquiring this type of information. For example, Fried and Satava have reported the metrics for the entire endoscopic sinus surgery procedure in Otolaryngology Clinics of North America (Satava and Fried 2002). There is no magic solution to the issue of metrics and it is almost certain that good metrics will have to be procedure specific. For example, time may not be the most crucial metric for MIS simulations (within reason), but for fluoroscopically guided procedures in interventional radiology or cardiology, time and resultant radiation exposure are very critical. Whatever the metrics or procedures used, a finding that appears with regularity is that performance variability and errors appear to be key indicators of skill level, i.e., senior or experienced operators perform well, consistently and make few errors (Gallagher and Satava 2002; Van Sickle et al. 2005). The most valuable metrics that a simulation can provide are on errors. The whole point of training is to improve performance, make performance consistent and reduce errors. One of the major values of simulators is that they allow the trainee to make mistakes in a consequence-free environment, before they ever perform that procedure on a patient. The errors that each simulator identifies and provides remediation for will certainly be procedure specific, and the absence of error metrics should cause trainers to question the value of the simulator as a training device. Well-defined errors in simulation allow trainees to experience the operating environment and include risks such as bleeding without jeopardizing a patient. Thus trainees can learn what they have done wrong, and NOT to make the same mistakes *in vivo* when operating on patients in the future. Learning is optimized when feedback is proximate to when the error is committed. If simulators are to be used for high stakes assessment such as credentialing or certification, then the metrics for that simulator must be shown to meet the same psychometric standards of validation as any other psychometric test. This is a matter of some gravity because metric-based assessment of physician performance could make the difference between an individual progressing to the next stage of their career (or not) and whether an experienced physician can continue to practice. We address the issue of metric validation in some detail in Chap. 7 and come to some rather stark conclusions about respected validation evidence.

Training Schedule

There is no research available which outlines the schedule of initial training required to attain stable performance in the operating room. Extensive research has been conducted to determine the effects of practice schedules on the acquisition of simple motor skills (Catania 1984). Among the possible variables affecting the acquisition of motor skills none has been more extensively studied than the practice regime.

Distribution of practice refers to the spacing of practice sessions either in one long session (massed practice) or multiple, short practice sessions (interval practice). Metalis (1985) investigated the effects of massed versus interval practice on the acquisition of video-game-playing skill. Both the massed and interval practice groups showed marked improvement, however, the interval practice group consistently showed more improvement. Studies conducted in the 1940s and 1950s attempted to address the effects of massed as compared to interval practice. The majority of these studies showed that interval practice was more beneficial than massed practice and this is what Gallagher et al. (2005) counseled in their review of skill acquisition factors in surgery. Moulton et al. (2006) assessed the validity of this advice and confirmed its accuracy. At present, new MIS skills are taught in massed sessions often lasting one or two days. The surgeons are often considered trained in this new technology after such a short course and the issues of competence and supervision of the newly trained surgeons are relegated to the individual hospital. Why is interval practice a more effective training schedule than massed practice? A likely explanation is that the skills being learned have more time to be cognitively consolidated between practices. Consolidation is the process that is assumed to take place after acquisition of a new behavior. The process assumes long-term neurophysiological changes that allow for the relatively permanent retention of learned behavior. Scientific evidence for this process is now starting to emerge (Louie and Wilson 2001).

Random vs Blocked Training

In the massed versus distributed learning example we have discussed above, the same amount of training was given but the period of time in which it was given was varied. Another variant on training schedule is whether different tasks should be learned individually, practiced in blocks, or whether the tasks are practiced in a random order. It might be assumed that it would be easier to learn each task in a blocked design. However, this is not the case. Although performance is better during the acquisition phase with the blocked design training conditions, when tested on the transfer task, performance is actually better in randomly ordered conditions. In a study by Jordan and colleagues (2000), they investigated four different types of training programmes intended to help laparoscopic surgeons automate to the ‘fulcrum effect’. All subjects received 10 two-minute training trials under one of four practice conditions. Three other groups had blocked training trials which were: (1) full binocular viewing conditions; (2) *Y*-axis inverted viewing conditions; and (3) normal laparoscopic viewing conditions. The fourth group received the same amount of training as the other three groups but the image and a practice on was randomly alternated between *Y*-axis inverted viewing conditions and normal laparoscopic viewing conditions for the ten training trials. All of the subjects were required to complete the exact same task that they had trained on but under normal laparoscopic viewing conditions. In this test, the group who trained under the randomly alternating imaging conditions outperformed the other three groups, i.e., they made significantly more correct responses and significantly fewer objectively assessed errors.

This type of training programme, although highly effective, may not suit all learners or tasks to be learned. Randomly alternating practice appears to be most effective when used with skills that require different patterns of coordination, and thus different underlying model programs (Hall and Magill 1995). In addition, characteristics of the individual such as the level of experience may also influence the effectiveness of random practice. For example, Goode and Magill (1986) found that random practice may be inappropriate until learners understand the dynamics of the task being learned.

Task Configuration and Training Strategies

When someone is learning a new set of skills such as hand–eye coordination of laparoscopic instruments, some thought should be given as to the type and difficulty of the tasks that trainees should practice first. Skill acquisition should be as free from frustration as possible. When attempting to acquire difficult skills, if the trainee experiences a high failure to success ratio they are unlikely to persist with training. We continually see this when we are trying to train residents to suture and knot-tie intracorporeally. Training tasks should start simple and gradually progress in difficulty. This is known in the behavioral science literature as '*shaping*'. This term simply means that successive approximations of the desired response pattern are reinforced until the desired response occurs. What is accepted as 'consistently' must be explicitly defined for the specific task. (This issue will be revisited when we discuss performance criterion levels.) To be fair, many of the simulators that currently exist for training laparoscopic skills do indeed use shaping as their core training methodology. Tasks are configurable from easy, medium and difficult settings and tasks can be ordered so that they become progressively more difficult. However, it is not clear whether the software engineers were aware that this was what they were doing when they wrote the software. Also, this is only one training strategy that could be used.

Another training strategy is '*fading*' and is used by a number of simulators such as the GI Mentor II (Simbionix, Cleveland, USA) and Endoscopic Sinus Simulator (ES3, Lockheed Martin). This strategy involves giving trainees major clues and guides at the start of training. Indeed, trainees might even begin with abstract tasks that elicit the same psychomotor performance as would be required to perform the task in vivo. As tasks become gradually more difficult, the amount of clues and guides are gradually faded out until the trainee is required to perform the task without support. For example, the ES3 simulator on the easy level requires the trainee to navigate an instrument through a series of hoops, the path of which mirrors the nasal cavity. The abstract task teaches the trainee the optimal path without having to worry about anatomical structure. The intermediate level requires the trainee to perform the same task; however, on this setting, the hoops are overlaid on simulated nasal cavity tissue and anatomical landmarks. The third and more difficult level gives no aid. This aid has in effect been faded out.

A very effective training strategy, i.e., '*backward chaining*' (Catania 1984) does not appear to have been used by any of the simulation companies. While shaping starts at the very beginning or basic steps of a skill or psychomotor task and gradually increases the complexity of the task requirement, backward chaining starts at the opposite end of the task, i.e. the complete task minus one step. This training strategy was developed for tasks that are particularly difficult and frustrating to learn. A good example of a task that would fit this category is intra-corporeal suturing and knot-tying and the procedure is broken down into discrete psychomotor performance units (task deconstruction).

A number of researchers have done this for their teaching curriculum but then proceeded to require trainees to perform the complete task (Rosser et al. 1998). The problem with this approach is that the trainee has a high failure to success ratio resulting in frustration, which in turn usually means that they give up trying to learn suturing. Backward chaining specifically programs a high success to failure ratio thus reducing or eliminating learner frustration. Using the example of tying a laparoscopic sliding square knot, tasks would be set up so that the trainee does the last step first, i.e., tying the final square knot. Trainees would continue to do this until they could do it proficiently every time. The next training task would involve trainees cinching or sliding the knot down into place and then squaring it off. Both steps would continue to be practiced until they are being performed consistently. The next training task would involve the square knot to a slip knot and then the two previous steps. This process would continue all the way back to the first step, i.e., the formation of ‘C’ loop and the wrap and so on. The benefits of this approach to training is that only one new step is being added with each backward step or ‘chain’ and that the forward chained behaviors have already been mastered, ensuring a high level of task success and a low level of frustration. In the box-trainer environment, this approach would have been very time consuming with the trainer having to prepare the backward chained task configuration; in addition, the task is difficult to assess. These difficulties disappear in virtual space. Furthermore, at least three VR companies currently have suturing tasks that could be configured this way (Mentice AB, Sweden, SimSurgery AS, Norway, Surgical Science AB, Sweden).

Simulation Fidelity

In the fields of modeling and simulation, fidelity refers to the degree to which a model or simulation reproduces the state and behavior of a real world object, feature or condition. Fidelity is therefore a measure of the realism of a model or simulation. While one of the advantages of training on a high-fidelity, full procedural simulator may be additional knowledge accrual, this should not be interpreted as a mandate that all types of computer-based simulation must be high-fidelity. In reality, there are many other means of conveying this knowledge-based information that will be equally or more effective with considerably less cost. The main function of a simulator is in fact for technical skills training, and knowledge should be acquired prior to training on the simulator. As simulator fidelity increases so does the price with some current high-fidelity devices costing between $100,000 to over $1 million.

Thus end users of surgical simulation must assess how much fidelity is required to achieve the greatest return on investment. The data from the MIST VR clinical trials clearly demonstrate that a low-fidelity simulator can consistently improve intra-operative performance. However, this does not mean that simulation fidelity is unimportant. Consider, a straight-forward laparoscopic cholecystectomy performed by a surgical resident under the direct guidance of an attending/consultant surgeon in the operating room. This is not a particularly high-risk situation and the probability of a life-threatening or life-altering complication is very low (Derossis et al. 1999). Conversely, an endovascular surgeon performing a carotid angioplasty and stenting procedure carries more risk. Results from the only multi-specialty prospective randomized trial on this procedure performed by experienced physicians showed that the risk of stroke or death at 30 days was as high as 4.6% (Yadav et al. 2004). In a high-risk procedure such as carotid artery angioplasty and stenting, the fidelity of the simulator should be maximized in attempts to replicate the exact procedure as closely as possible, to take every procedural step possible to minimize patient risk.

Another important point to make about fidelity of a simulator is that fidelity goes beyond computer graphics and presentation. Unfortunately many surgeons are over-awed by, and place too much emphasis on, the pure graphics aspect of the simulator. In a high-fidelity simulation, the tissue and instruments should behave as closely as possible to how they do in a patient. The instruments must not behave as if there is a predefined path for them and tissue behavior should also be as realistic as possible. A high-fidelity simulator must allow the trainee to err and learn from these mistakes and their performance must be meaningfully quantified, with well thought out metrics that distinguish between those who are good at the procedure and those who are not. If surgeons ignore or fail to appreciate this issue, we risk spending large amounts of resources for simulators which will not meet our needs.

Transfer of Training and Skills Generalization

Although these two learning phenomena are related and both refer to the process of skill acquisition, they are fundamentally different. *Skills generalization* refers to the training situation where the trainee learns fundamental skills that are crucial to completion of the actual operative task or procedure. *Skills transfer* refers to a training modality that directly emulates the task to be performed in vivo or in the testing condition. A practical example of the difference between skills generalization and transfer can be taken from the game of golf. Every golf pro will have beginning golfers practice swinging without even holding a club. This would be skills generalization. The swing is crucial to executing any golf shot, but swinging without a club does not directly relate to a shot. An example of skills transfer would be a golfer repeatedly hitting a sand wedge out of the right side trap near the 18 green. If during the next round the golfer finds himself in that trap, the practiced skills will directly transfer to his current situation. In the world of simulation, a good example of skills generalization is the MIST VR laparoscopic surgical training system.

This system teaches basic psychomotor skills fundamental to performing a safe laparoscopic cholecystectomy (LC) as well as many skills required in advanced laparoscopic procedures. The VR tasks do not resemble the operative field, but it has been clearly demonstrated that subjects who trained on the MIST VR performed a two-handed LC faster with fewer intra-operative errors (Seymour et al. 2002). It has also been demonstrated that these skills improve laparoscopic intra-corporeal suturing (Pearson et al. 2002). These are two good examples of skills generalization, which represents a very powerful, but misunderstood learning and training methodology. Simulators which rely on skills transfer might include mannequin type simulators such as TraumaMan™, (Simulab Corp, Seattle, USA), high-end VR simulators such as both the Lap Mentor and GI Mentor II (Simbionix, Cleveland, USA), the VIST (Mentice AB, Gothenburg, Sweden), and the ES3 (Lockheed Martin, Bethesda, MD). The simulated procedures look and feel similar to the actual procedures and will train skills that will directly transfer to the performed procedures.

A common mistake made by many trainers is that only simulators that provide a high-fidelity experience improve performance. This is inaccurate as is clearly demonstrated by the Yale VR to OR study mentioned above which used a skills generalization-based VR trainer. The question that should be asked is ‘does the simulator train the appropriate skill to perform the procedure? It should also be noted that as fidelity increases, so does price. One of the most sophisticated VR simulators in the world is the VIST system (Mentice AB, Gothenburg, Sweden) which simulates in real time a full physics model of the vascular system (with fluid dynamics). However, it costs $300,000 per unit. Not all training programs can afford this level of simulation. Trainers must look beyond face validity of simulators and ask more important questions such as ‘does it work? (i.e., train the appropriate skills), how well does it work? and how good is the evidence? This may involve trainers developing realistic expectations of what simulators should look like, which in turn will involve a genuine understanding of what simulations should be capable of achieving in a training program.

Whole vs Part Training

Simulation has been available in some form in medicine for at least four decades. Anesthetists were one of the early groups in medicine to recognize the advantages of this training methodology. They also have been very strong supporters of the group training for the whole procedure. In contrast, laparoscopic surgeons have attempted to use part task emulators and virtual reality simulators. The difference in approach between these two groups of physicians to solving the problem of training may have more to do with the resources available to them than what they would have preferred. Anesthetists pioneered the use of full body mannequins (or high-fidelity simulation) while laparoscopic surgeons required simulations of instrument tissue interactions in real time. This latter type of simulation required huge computer processing capacity, which until relatively recently was very expensive (even if it was available in the 1990s). In the second decade of the twenty-first century, this is less of an issue and we have seen some surgical simulations move to a full procedure, e.g., laparoscopic cholecystectomy, produced by Simbionix. However, the issue of whole versus part training is not simply a matter of the types of simulations that are available, but more to do with training effectiveness and efficiency. We shall discuss this matter in more detail in Chaps. 8 and 10.

At this point, it is fair to say that research has shown that whole-task training is the preferred method if the task is simple and can be reasonably approximated by the simulation. However, if the task is dangerous or highly complex and can be easily divided into subtasks, part-task training is the better choice. Context-dependent methods are favored over context-independent methods for recall and recognition. If the acquired knowledge and skills must be selectively applied in a variety of situations, context independent presentation methods are recommended.

Summary

Skill acquisition for the practice of MIS has been an issue for trainee surgeons which has been repeatedly found to be associated with increased complication rates during the learning phase. A considerable volume of well-founded scientific knowledge currently exists about the anatomy and neuropsychology of skill acquisition structures and processes which academic surgery has yet to fully embrace. This knowledge should help drive the design and implementation of efficient and effective training programs. It should also inform the design of simulations that support and help to deliver skills training as part of the curriculum. One of the most important parts of that curriculum (no matter how or on what type of simulation platform it is delivered on) is feedback. This is a crucial aspect of an objective, effective and efficient learning process. It occurs as a natural consequence of our interaction with our environment. Unfortunately, we may miss the feedback or the delay between performance and feedback may be so large that the contiguous relationship that did in fact exist is lost, as is the opportunity for learning. Simulation affords the opportunity to the surgical trainer and trainee to augment feedback on performance and ensure that it is delivered to the trainee in a timely, salient and effective manner during training. This feedback is called metrics which we will deal with in detail in Chap. 5.

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