Simulation in Aviation Training

Edited by
Florian Jentsch, Michael Curtis and **Eduardo Salas**

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Simulation in Aviation Training

Critical Essays on Human Factors in Aviation

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Series Preface

Human Factors is a science – an applied science trying to understand how individuals, teams, collectives and organizations work and what can be done to improve their effective functioning. It is a science that through the guidance of well grounded theories, the execution of robust methods, the use of practical tools and the application of proven principles, helps optimize human-systems integration at all levels. That is, human factors is a science aimed at improving human performance in complex systems – like aviation – by integrating its socio-technical system, increasing efficiency, minimizing errors and promoting safety. This is a science that has, indeed, helped the aviation community in many aspects – from the design of cockpits to the training of crews and controllers to the development of tools required for safe operation in the crowded skies. Much of what we know about human-systems integration (and human factors) has come by studying the aviation world; hence, the motivation for this series.

The series is about the science of human factors and its influence in aviation. It is about documenting, in focused volumes, the most influential scientific and practical essays published. Each book seeks to provide those in science as well as those in practice in the aviation world (and maybe beyond), with a collection of critical essays all conveniently accessible in one volume. The volumes contain essays, selected by notable editors from a variety of sources, which are deemed critical to the understanding of the topic. These editors also offer insightful overviews and draw conclusions about their collection of essays. These volumes offer an invaluable source to pilots, crews, flight attendants, aviation executives, regulators, air traffic controllers, training designers, safety officers, scientists, and students and to all of those who seek the safety of our skies. Furthermore they serve to guide practice, provoke thinking, promote research and illuminate how the science of human factors has served the aviation world well.

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Introduction

In modern aviation, flight simulations are deeply ingrained into the training curriculum. Stepping out of a session in a full-motion flight simulator today can evoke feelings of awe for those who know the history of simulators in aviation training. Modern simulation technology has made it possible for a pilot to experience a near replication of flight while never actually getting more than a couple of feet off the ground. Considering the earliest conception of simulated flight training was little more than a box mounted on a universal joint, one can better appreciate the technological, methodological, and research advances that have resulted in the simulations used today.

This book is comprised of a collection of critical essays devoted to simulation in aviation training. By way of introduction, we begin with a short historical perspective regarding aviation training, and how simulation is intertwined in its history. Following that, we describe our approach to selecting the essays presented here. Then we outline the structure of the book, providing a brief description of each part and of the chapters within each. Finally, we reassert our goals with this volume. We welcome the reader to explore these essays not as the final word on these topics, but as an opening for a dialogue that will drive the research and application of simulation in aviation training into the future.

What is Simulation in Aviation Training?

Simulation is a broad term used to describe any method of replicating real-world tasks, mainly for training or research purposes. A simulation can be comprised of computer-generated virtual environments, actor-driven interactive role-play, or even a simple instrument panel mock-up. Regardless of the method or technology employed, the objective of simulation is to provide an alternative exposure to real world tasks that are either difficult to access, too dangerous, or too costly to conduct in the real world.

For many in the aviation industry, the word simulation stirs thoughts of high-tech computer-generated replications that mimic the cockpit's appearance and function very closely. As alluded to in the first paragraph above, however, simulation began from a much more humble background. Not long after the breakthroughs of the late 1800s and early 1900s that produced controllable, engine-propelled flight, the possibilities for what flight could offer multiplied. Instead of flight being limited to a small group of adventurers who flew for novelty's sake, manned flight was quickly adopted not only for transport, but also for many other civilian and military uses. Almost as soon as the aviation industry exploded onto the scene, questions about how to quickly and effectively train pilots arose. Because of the danger that early flight posed for pilots, several efforts were undertaken to produce simulated flight for training purposes (Reid and Burton, 1924; Clark, 1962). However, the sheer number of individuals that required efficient training in early military aviation fleets, rendered many early conceptions of simulated flight useless (Rolfe and Staples, 1987). As a result, most early aviators were relegated to sitting in class lectures, followed by live flight training exercises. Since engineers were still unlocking the mysteries of effective aircraft design, flying could be considered hazardous, even for experienced pilots. Naturally, this danger was compounded for inexperienced pilots in training. The burden of cost in lives and aircraft alone lost during training drove the development of flight simulators to improve safety in training.

In the late 1920s, the Link Trainer also known as the 'Blue Box', was introduced. It is widely recognized as the prototype for modern flight simulation. Adhering to early theoretical conceptions of training fidelity (Thorndike, 1931; Osgood, 1949), the Link Trainer, an airplane-shaped box mounted on a universal joint, ushered in several decades of flight simulation development that fixated on optimizing realism for improved transfer of training. Steadily increasing aircraft complexity, growth of the aviation industry, and improved computer technology all served to propel simulation development. The result of these developments produced a flight simulation industry largely driven on a 'bigger is better' mentality that continues to be evident today in flight simulation. In fact, there is little question about the level of realism that can be achieved in flight simulation. Realistic cockpit functionality, computer-generated representations of real environments, and motion platforms that closely mimic the feel of flight are all possible. Further, while aviation may be one of the first industries to adopt simulation training as a viable methodology, simulation as a whole is now a billion dollar industry impacting a wide range of domains. For example, simulation training is becoming more established in training nuclear power plant operators (Maddox et al., 1985), military operators (Karr et al., 1997), emergency responders (Kincaid et al., 2003), medical specialists (Gaba and DeAnda, 1988), dentists (Buchanan, 2001), educators (Huppert et al., 2002), ground transport workers (Roenker et al., 2003), and even business managers (Summers, 2004). Because simulation training for aviation personnel preceded many of these, the lessons learned from research and development of aviation simulation has served to guide development in many of these domains.

Simulations are used for a wide range of skill development in aviation. In the past, the simulator was largely dedicated to the development of technical skills, such as stick and rudder control (Williges et al., 1973) or instrument flight procedures (Caro, 1972). In the last two decades, however, simulator training programmes like Line Operations Flight Training (LOFT; Butler, 1993) have widened the scope of training to include not only technical skills, but also team communication and coordination skills, such as in Crew Resource Management (CRM; Helmreich et al., 1999). Consequently, a large portion of the current commercial aviation training curriculum relies on hours in full motion simulations. Considering the number of new hire, recurrent, and upgrade trainees that require simulator time each year, the use of simulators is already at a premium. As we look to the future, FAA initiatives such as the Advanced Qualification Program (AQP; FAA, 2006), which encourages the development of innovative training techniques, and NextGen (Piccione, 2008), which will alter air to ground information exchange altogether, will undoubtedly change aviation training and simulation. As a result, it is important for researchers and practitioners to have a solid understanding of what we know about how simulation impacts training. Armed with this knowledge, practitioners and researchers will be better equipped to develop training and research that will guide simulation implementation in the evolving future of aviation.

Book Development

In aviation, the use of simulations for training purposes has been a long-standing practice. In fact, modern aviation simulation has become a nearly indispensible facet of the aviation training curriculum. Despite constant demand for large scale, full-motion simulators, the technological gains that drive the simulation industry do not guarantee training success. Instead, effective aviation training should utilize simulators in accordance with the application of principles from theories of learning, training, physiology, and performance. Only this will ensure useful training outcomes. The purpose of this book is, therefore, to provide a reference of important theoretical and applied writings in these topic areas that are relevant to simulation training in aviation.

Constructing a critical essays volume can easily turn into the task of assembling a compendium of the most-cited works in a given topic area. While we feel that peer reference is an important gauge of an article's impact, we chose to take a broader approach to selecting material in the hope that this volume provide access to a diverse collection of: (a) classic essays that have stood the test of time; (b) theoretically important works that may not be as well cited; and (c) recent writings that address current affairs related to simulation as used in aviation training. To accomplish this, we felt it important to draw not just from our own experience, but also from the research community for expert input. Using an email list server, we solicited both the Aerospace Systems (ASTG) and the Training (TTG) Technical Groups of the Human Factors and Ergonomics Society (HFES) for individual ratings of the 'Top 3' articles in the areas of simulation and aviation training. We felt that these subgroups of HFES, which comprise somewhere around 700 members in a range of academic, industry, and government positions related to training and aerospace science, would be well suited to respond to our request. It is interesting to note that the majority of those who responded were often unable to narrow their response to a 'Top 3', and instead provided anywhere from four to ten selections which they felt were most influential. In some cases, the respondents suggested entire edited books on the topic area, such as Swezey and Andrew's *Readings in Simulation and Training* (2001) or Hays and Singer's *Simulation Fidelity in Training System Design* (1989), instead of listing specific articles from these volumes. Nevertheless, the input provided by the community was helpful, especially since it allowed us, as editors, to compare the selections to our own lists of top articles in the field.

In addition to soliciting input, we ran a parallel search of article databases such as PsychInfo, EBSCOhost, IEEE Explore, and Google Scholar using keywords such as 'aviation simulation' and 'simulation training'. Using articles recommended from the email solicitation and those resulting from our own search, we also conducted both forward and backward citation searches to capture as many relevant articles in the area as possible. After compiling our solicitation and search results, and due to the sheer volume of material that was available in the broad topic of simulation in aviation training, we determined our next step should be to narrow our selection parameters. We did this by identifying topic groupings that emerged in the search process. From this, we selected five that we felt provided an optimal sample of important writings relevant to simulation in aviation training. They are: (a) using simulation for training, (b) simulation fidelity, (c) physiological responses and simulation sickness, (d) simulation as training and method, and (e) training evaluation using simulation. In addition, we added a sixth category – simulation beyond aviation. This last was included to account for the growth of simulation training outside of the aviation domain. After agreeing on the six grouping sections of the book, we began the process of narrowing down the collection of essays. In our efforts to do so, we tried to organize each group so that it contained at least one highly cited work and at least one recently published work. We felt that to structure each section this way would provide a more accurate cross-section of the past, present, and future of research in this area. Ultimately, we agreed upon 25 essays for inclusion in the book. In the following section, we further discuss the section groupings that we felt most adequately covered each topic area.

Book Organization

As mentioned in the previous section, this collection is organized into six parts that provide a multifaceted approach to simulation training in aviation. Although simulation training has a long history in aviation, we elected not to include a section specifically geared to historical contributions in the field. While there are some classic works in this volume, we felt that a strict historical perspective would deviate from our vision for the book. Additionally, we omitted a section dedicated to technical simulation (as in 'modelling') in aviation. Although this is a relevant topic for aviation training, we felt that to include an additional section would limit adequate coverage of each category colvered. Also, since this was the topic area which we were least familiar with, we omitted it in the hopes that more experienced modelling experts could one day compile more comprehensive coverage.

The resulting volume provides only a sample of the large quantity of writings associated with simulation training in aviation. Despite this, it provides coverage of influential works relevant to theory, development, application and evaluation of simulation training as applied in aviation. In the following sections, we provide further descriptions of each part of this book.

Using Simulation for Training

Despite the notable advances in technology for aviation simulations, one must continue to consider an important point that was earlier made by researchers almost four decades ago: the simulator is a tool for training, not – in itself – training. In fact, by itself, having and using a flight simulator does not constitute training. Consequently, Part I of this volume presents articles which address the importance of considering learning objectives when using simulation for training. Although simulation training is firmly entrenched in aviation training, there are still many instances where simulation is used ineffectively. The chapters in this section discuss common issues associated with the implementation of simulation training and how consideration of educational and general training theory are critical first steps to building an effective simulation training programme. The section opens with an essay by Paul Caro (Chapter 1), which discusses the importance of closely matching flight simulator use to educational objectives. Despite being written 35 years ago, the key theme that building a realistic or technologically advanced simulation is only part of training development still resonates today. Next, in Chapter 2, David Dorsey, Gwendolyn Campbell, and Steven Russell review theory from both education and training literature. Specifically, the authors attempt to apply an instructional science paradigm to simulation (virtual environment) training. This essay is followed by one in which Eduardo Salas, Clint Bowers, and Lori Rhodenizer draw from psychology and cognitive engineering disciplines to discuss several commonly used, but invalid assumptions regarding simulation implementation (Chapter 3). Salas and colleagues offer suggestions for addressing these assumptions and improving the quality of simulation training. Chapter 4, by Clint Bowers, Florian Jentsch, David Baker, Carolyn Prince, and Eduardo Salas, provides a description of a specific tool for simulation training intended to improve the scenario development process. Finally, in Chapter 5, Stephen Alessi presents a framework for developing simulation. His essay suggests that keeping training outcomes in mind in the development process will produce more valuable simulation training products.

Simulation Fidelity

As alluded to earlier, the simulation industry has largely been driven by improved realism. Despite being able to achieve high levels of fidelity, researchers and practitioners alike have questioned the level of fidelity that is necessary to produce targeted training outcomes. In Part II, we offer a selection of essays representative of research and theory addressing simulation fidelity for aviation training. The first essay, Chapter 6 by Pieter Padmos and Maarten Milders, discusses the importance of image quality in simulators. By presenting a comprehensive list of image variables, the chapter illustrates the complexity of generating simulated images and considerations that developers face. Next is an essay by Daniel Gopher, Maya Weil, and Tal Bareket (Chapter 7) that describes a study investigating the transfer of skill from a computer game to flight performance. The results of this study suggest that specific flight skills can be trained using lower-fidelity training devices. Following this is an essay by Florian Jentsch and Clint Bowers (Chapter 8) which further discusses the utility of lower-fidelity devices for simulation training. In particular, Jentsch and Bowers address important validity considerations in relation to the implementation of PC-based simulation training. Part II closes with an essay by Nicklas Dahlstrom, Sidney Dekker, Roel van Winsen, and James Nyce (Chapter 9). In this, the authors discuss the prospect of supplementing high-fidelity training with low-fidelity trainers for less procedure-based training like crew resilience training.

Physiological Responses and Simulation Sickness

In aviation, human perception plays an integral part. In flight, there is a wealth of perceptual stimuli both inside and outside the cockpit for pilots to attend. In some cases, simulations of these perceptual stimuli are easily accomplished. For example, inclusion of auditory cues in a simulation can help pilots learn to react to the range of warnings and alerts that may occur. Since flight relies heavily on visual and vestibular cues, and these two perceptual systems are closely linked, there can be physiological implications when these are simulated. Part III, therefore, provides a sample of essays representative of the research involving the physiological aspects of simulator training. More specifically, we present a number that discuss the occurrence of simulator sickness and how simulator motion influences training goals. The first of these, an essay by Randy Pausch, Thomas Crea, and Matthew Conway (Chapter 10), provides a review of research associated with the phenomenon of simulator sickness. Focusing on the military domain, this chapter touches on topics such as simulator lag and after-effects of simulator use to provide a comprehensive picture of factors that influence simulator sickness. Next, in Chapter 11, Robert Kennedy and Jennifer Fowlkes discuss the limitations of experimental measures used for simulator sickness research. These authors suggested that simulator sickness is a polysymptomatic and polygenic phenomenon and offered a cost-effective method of measuring it. The final chapter in Part III is a slight departure from the simulator sickness theme of the first two essays. Here, in Chapter 12, the discussion centers on the need for motion in flight simulation. Judith Bürki-Cohen, Nancy Soja, and Tom Longridge provide a comprehensive review of research that addresses the impact of full-motion simulation, and present insight into the importance of this type of simulation for aviation training.

Simulation as Training and Method

In aviation, training is a career-long commitment. While the most intensive instruction occurs in initial flight training, pilots are required to continue training to learn new technologies, fly different aircraft, upgrade to captain, or just stay current with the aircraft they fly. As a result, there is a continually growing population of pilots who require training time, year-round. In commercial aviation, because of full-motion simulator cost and availability, this causes a bottleneck of training. In view of this challenge, it is important to understand the simulation training methods that optimize skill development, both in full-motion and in lower-fidelity simulation devices. Doing this can help aviation training professionals produce more efficient simulation-based training curriculum. Part IV provides a sampling of the wide range of simulation training methodological approaches in application and research related to aviation. The first chapter in Part IV, by Walter Schneider (Chapter 13), provides a discussion on training complex skills. By bringing to light common fallacies of complex skill acquisition, Schneider was able to present some guidelines for training development. Next is an essay by Dennis Wightman and Gavan Lintern (Chapter 14) which serves as a discussion on part-task training of specific aviation skills. The authors explain part-task methods such as segmentation, fractionation and simplification, and close by touching on how to reintegrate part-task trained skills into overall tasks. To follow that, we selected an essay by Gavan Lintern, Stanley Roscoe, Jefferson Koonce and Leon Segal (Chapter 15) which illustrates one application of simulation training. The study described in this chapter investigated the training benefit of a simulator in the development of specific flight skills in the landing phase of flight. Then, in Chapter 16, Jan Cannon-Bowers and Eduardo Salas, demonstrate another specific application of simulation for training, drawing from theory and research to support the Tactical Decision Making Under Stress (TADMUS) programme. The final essay in Part IV is a contribution from Herbert Bell and Wayne Waag (Chapter 17). Their focus was on identifying the effectiveness of implementing flight simulators for combat skill training.

Training Evaluation using Simulation

When considering simulation for training many people at the same time, it is necessary to think about technological advancement and method of presentation as the drivers of successful training. Although each of these factors influences simulation training, sometimes another important factor – training evaluation – gets overlooked. Training evaluation makes up two important aspects of simulation training. The first, simulation evaluation, is involved with evaluating the effectiveness of the overall simulation training protocol. The second, performance evaluation, is associated with the metrics used to evaluate trainee performance in the simulator. This ranges from subjective ratings based on evaluator observation to automatically recorded flight data from the simulator. Part V provides a representative sample of essays that address evaluation in simulation training in aviation. The first of these, by Robert Hays and Michael Singer (Chapter 18), provides a discussion about the importance of evaluating simulation training effectiveness. By covering a wide range of topics from reliability to cost, this chapter offers a good overview of the multitude of considerations when evaluating simulation training. Following this chapter are three that focus more specifically on performance evaluation. Chapter 19, by Michael Brannick, Carolyn Prince, and Eduardo Salas, examines instructor rating reliability in a simulated scenario for both procedural rating and CRM ratings. By looking at both rater and item reliability, this chapter provides an analysis in global and specific behavioural contexts of aviation performance evaluation. Following this, we include an essay by Richard Schmidt and Gabriele Wulf (Chapter 20), which addresses the impact of feedback in simulation training. Through the analysis of continuous concurrent feedback in simulation training, the authors presented compelling findings for how feedback affects performance in training and transfer to the real task. Part V concludes with a chapter by Eduardo Salas, Michael Rosen, Janet Held, and Johnny Weissmuller (Chapter 21) that gives a current review of performance measurement in simulation-based training. The essay focuses on performance measure theory and methodology, and concludes with best practices for future development of performance measure.

Simulation beyond Aviation

Although aviation may have been the birthplace of modern simulation, the practice of using simulation for training purposes has expanded far beyond the flight simulator. For many years, industries looking to explore the use of simulation for training would turn to research in aviation to help guide simulation development. Now that there is a wealth of industries actively using simulations for training purposes, the concentration of research in simulation training has shifted to such fields as medicine, business, and the military. Although there is still important research conducted within the aviation simulation domain, it is important to look at innovation in method and theory that is surfacing in these other domains. Part VI of this volume offers a small collection of essays from outside of aviation but related to simulation training; in some cases, these make direct reference to aviation simulations, while others serve to illustrate the growing importance of simulation training in a broadening number of domains. The first essay, by Jeffrey Beaubien and David Baker (Chapter 22), is a selection from the growing field of simulation training in medicine and health care. It draws specifically from aviation simulation research to guide discussion on fidelity in health care simulations. Following this, Chapter 23 by William Hamman also discusses lessons learned from aviation simulation research in health care. Hamman's discussion is geared toward development of core simulation-based training for team training in health care. Next, in Chapter 24, Andrew Feinstein and Hugh Cannon delve into topics of fidelity and verification for implementation of simulation training for business professionals. The final essay, by Rosemary Garris, Robert Ahlers, and James Driskell (Chapter 25), was included to represent the growing interest in instructional games for training and education, also known as serious games. This chapter addresses ways to optimize learning goals through game-based training. In some respects, serious games were born out of commercial off-the-shelf flight simulations so we felt it appropriate to include an essay from this growing field.

Conclusion

From cockpit instrumentation to air traffic management, the aviation industry is rife with change. Considering the continued evolution of the aviation landscape, it should not come as a surprise that training needs are also in flux. In a recent *Wall Street Journal* article (Pazstor and Carey, 2009) a number of high-level executives at regional airlines opened up about the training challenges they are facing, including the practice of reducing experience requirements for new hires to meet flight demands. The growing demand for capable pilots has two important implications to consider for training: first, experience requirements for pilots are reducing at some airlines; and second, training simulator time is becoming an increasingly scarce commodity. As a result, training developers and researchers are seemingly forced to burn both ends of the candle trying to provide more experience for low hour pilots, while at the same time maintaining or reducing the amount of simulator time required. Although full-motion simulation is the industry standard for aviation training, the current training demands should help to emphasize the importance of optimizing training use of full-motion simulation while also looking to alternative simulation techniques to supplement skill development. Fortunately, through FAA programmes like AQP, there is government and industry support for training innovation. Beyond gathering support, however, researchers and practitioners can benefit most from familiarizing themselves with the science behind simulation training. The objective of this volume is to present a sample of relevant essays regarding simulation in aviation training with this benefit in mind. While the collection presented here is certainly not a complete coverage of the topic area, we felt that the articles chosen serve to inform a wide range of important topics within the broader scope of simulation training in aviation. We intend for our readers, by using this book as a reference, to walk away with a better-informed understanding of theoretical and applied utility of simulation in aviation training.

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Part I
Using Simulation for Training

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[1]

Aircraft Simulators and Pilot Training

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Flight simulators are built as realistically as possible, presumably to enhance their training value. Yet, their training value is determined by the way they are used. Traditionally, simulators have been less important for training than have aircraft, but they are currently emerging as primary pilot training vehicles. This new emphasis is an outgrowth of systems engineering of flight training programs, and a characteristic of the resultant training is the employment of techniques developed through applied research in a variety of training settings. These techniques include functional context training, minimizing over-training, effective utilization of personnel, use of incentive awards, peer training, and objective performance measurement. Programs employing these and other techniques, with training equipment ranging from highly-realistic simulators to reduced-scale paper mockups, have resulted in impressive transfer of training. The conclusion is drawn that a proper training program is essential to realizing the potential training value of a device, regardless of its realism.

INTRODUCTION

I would not consider the money being spent on flight simulators as staggering if we knew much about their training value, which we do not. We build flight simulators as realistic as possible, which is consistent with the identical elements theory of transfer of Thorndike, but the approach is also a cover-up for our ignorance about transfer because in our doubts we have made costly devices as realistic as we can in the hopes of gaining as much transfer as we can. In these affluent times, the users have been willing to pay the price, but the result has been an avoidance of the more challenging questions of how the transfer might be accomplished in other ways, or whether all that complexity is really necessary (Adams, 1972, pp. 616-617).

Personnel responsible for the design of flight simulators are almost exclusively engineers. Sometimes they are assisted by psychologists, but, as may be inferred from the above quotation, the influence of this latter group is minimal. In view of the identical elements orientation of most simulator designers and the large amounts of money available to satisfy their strivings for system identity and engineering excellence, the results are as might well be expected: most aircraft simulators are land-locked duplicates of their flying counterparts.

THE ROLE OF SIMULATORS IN PILOT TRAINING

It is not at all surprising that flight simulators are built as realistically as possible. It is not surprising, either, that pilot-training program designers and administrators have tended to rely upon such realism to assure adequate pilot training. Too often many of these individuals appear to forget that the simulator does not train. *It is the manner in which the simulator is used that yields its benefit.*

Gagne (1962) pointed out that transfer of training is a function of factors such as training objectives and instructional quality as well as of the fidelity characteristics of synthetic training equipment, and Muckler, Nygaard, O'Kelly, and Williams (1959) identified instructional techniques and instructor ability as important variables involved in transfer of training in flight simulators. Prophet (1966) stated that the flight simulator is only the vehicle for the training program and is often less important than are the synthetic training instructor and the organization and content of the synthetic training program.

There probably has never been a serious challenge to the suggested importance of the manner in which simulators are used. Gagne, Muckler, Prophet, their associates, and many others who could be cited, have stated no more than that which is obvious to all. In spite of this apparent consensus, however, it is my observation that very little attention is devoted to simulator training programs in many pilot training organizations, certainly much less attention than is devoted to the design of the simulators themselves.

The Traditional Role

In many pilot training programs, simulators are used as an adjunct to training conducted in flight. Their use is intended principally to effect a reduction in the overall cost of flight training, but in many instances (in fact, in almost all military training programs) there is little evidence that simulators have led to reduced training costs. In one such program, synthetic training was shown to add to the cost of pilot training without demonstrable transfer of training benefits (Isley, Caro, and Jolley, 1968; Jolley and Caro, 1970).

In these traditional or adjunct programs, there is often a division of responsibility between aircraft and simulator instructors. The former are the *real* instructors, while the latter are second-class citizens and are sometimes known as "device operators" rather than instructors. Because of their lower status, communication between the device operators and the pilots who *really* teach flying is infrequent, and students soon learn to revere the real instructors and tolerate the operators and the simulators they use.

Training tasks are also divided between the aircraft and the simulator in such programs along status lines. In spite of the sophisticated engineering features and dynamic realism of many modern simulators, they seldom are used to their full capabilities. A survey of simulator utilization in the Air Force (Hall, Parker, and Meyer, 1967) found that device instructors, probably because of their limited ability and a lack of command emphasis upon their jobs, tend to concentrate upon procedural tasks in simulator training and deemphasize or ignore completely the training value of simulators with respect to dynamic flight tasks. It appears that if a task can be taught in both a simulator and an aircraft, it will be taught in a simulator only if the flight instructor finds it boring to teach in the aircraft.

The Emerging Role

Fortunately, instances of the traditional role of simulator utilization are being encountered less frequently as economic pressures upon pilot training organizations are forcing management to be concerned over the relatively high costs of conducting training in aircraft that can be conducted in simulators. The airline industry has been a pace-setter for much of the new emphasis upon simulator training, possibly because of the high cost and adverse publicity associated with accidents during in-flight training activities. But, for whatever reasons, a new role is emerging for simulators in pilot training programs.

The new role is characterized by emphasis upon simulators as primary vehicles for pilot training and is a natural outgrowth of the application of systems engineering concepts to the design of total training systems (Hall and Caro, 1971; Prophet, Caro, and Hall, 1972). To an increasing extent, pilot training is being conducted in simulators with the exception of a

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few maneuvers that, because of engineering state-of-the-art limitations, cannot be performed in present-day simulators (American Airlines, 1969) and for the flying necessary to confidence-building or equipment-familiarization purposes (Caro, 1972).

The shift of training from the aircraft to the simulator, while in itself a major break with traditional pilot training programs, is not the most important aspect of the emerging role of simulators. It is the manner in which these devices are being used that makes the biggest difference. Training program content has begun to become more responsive to mission requirements; the instructor has become a training resource manager; and the goals of training are beginning to be viewed in objectively measurable performance terms, rather than primarily in terms of flight hours logged. It is becoming evident in these programs that the training vehicles—the simulators principally, but also the training aircraft—are less important in many respects than are the instructors and the organization and content of the training programs.

SIMULATOR TRAINING PROGRAMS

Some of the newer flight simulators have hardware features that are intended solely to enhance the training value of the equipment rather than to duplicate aircraft features (Caro and Prophet, 1971). In some instances, these devices incorporate deliberate deviations from realism in attempts to improve, from the transfer-of-training standpoint, upon the relatively poor learning environment of the design-basis aircraft. But, with or without such advanced design-for-training features, it is still necessary to have an appropriately designed training program for use with these simulators if we expect to make significant gains in pilot training efficiency and effectiveness.

Most readers are already familiar with such terms as "systems engineering of training", "task analysis", "specific behavioral objectives", and "commonality analysis". Military and commercial pilot training programs have made much use in recent years of concepts underlying such terms in defining more objectively the required content of training. Because of the resulting critical training program content reviews, many programs now are devoted largely to "need to know" skills, rather than the mass of miscellaneous "nice to know" and curiosity information that still clutters up many traditional training programs.

Along with better training simulators and more clearly defined training program content has come new status for the simulator instructors. They no longer are viewed as second class citizens who use make-do equipment to accomplish uninteresting aspects of training. Instead, they are *the* instructor, often the best qualified personnel available, and they conduct or oversee all training received by their students. The resources these instructors need to attain their training objectives, *e.g.*, an aircraft, a simulator, programmed learning material, and personnel to assist as might be required, are all under their control.

These features of modern simulator training programs—better simulators, clearly defined content, and well-qualified instructors—provide the essential ingredients for effective and efficient training, but they are nothing more than that. They still do not constitute a training program. A training program is the manner in which the well-qualified instructor uses the appropriately designed simulator to establish the clearly defined course content within the skills repertoire of the trainee.

In our work in Army and Coast Guard aviation during the past decade, we at the HumRRO Aviation Division have devoted considerable effort to the methodology involved in the use of simulators and other synthetic flight training equipment in modern training programs. We have been involved in the full range of activities associated with pilot training, including definition of the training requirement itself (*e.g.*, Hall, Caro, Jolley, and Brown, 1969), design of aircraft simulators (*e.g.*, Caro, Hall, and Brown, 1969), development of simulator training programs (*e.g.*, Caro, 1971), evaluation of simulator training program transfer of training (*e.g.*, Caro, 1972), evaluation of off-the-shelf training devices and simulators (*e.g.*, Caro, Isley, and Jolley, 1968), and investigation of costs associated with simulator training programs operation (Jolley and Caro, 1970).

During these activities, our purpose has been to bring into pilot training programs the advances made through applied training research in a wide range of training settings. We believe we have been reasonably successful in our early efforts in this regard, and we believe our success has been largely due to our orientation that training is a technology which can be engaged in, after appropriate training, by reasonably bright and adaptable people, not an art which is an inherent characteristic of the "good instructor". We note also that our view of training is not unique. Training programs of several other pilot training agencies are employing many of the same techniques we are using.

Some of the training techniques currently being employed are described in the paragraphs below.

Functional context training. Pilot training programs have been organized around a functional context, *i.e.*, around sets of meaningful, purposeful, mission modules. Course content is taught within the context of the mission-oriented purpose it supports. For example, aircraft maneuvers such as descending turns are taught to undergraduate level instrument flight trainees within the functional context of a simulated instrument approach, rather than as an exercise, *per se*, as is done during early stages of some traditional instrument training programs.

Individualization of training. The pace and redundancy of training—all aspects of training, including supporting "academic" activities—are adapted to the rate of learning of each student. An individually-paced student, thus, is advanced to the next set of instructional content only after he has demonstrated to his instructor a specified level of mastery of an earlier set.

Sequencing of instruction. The order of instructional content is arranged so as to assure that students have been taught (and have mastered) prerequisite knowledges and skills before training in a new set is undertaken.

Minimizing over-training. Steps are taken to assure that training time is restricted to that time needed to bring a trainee to the required level of training and no more. In some cases, this means overriding an instructor who feels that a particular trainee can achieve higher skill levels even though his performance at the time has already reached the specified requirements for that phase of training.

Efficient utilization of personnel. Each instructor is optimally qualified for his task, is provided the tools he may require for efficient use of his time and talents, and is trained to administer the particular course of instruction in a standardized manner. In this regard, it should be noted that an optimally-qualified instructor in the aircraft is very likely to be optimally qualified to instruct in the simulator as well. Our most productive approach has been to assign both jobs to the same individual.

Use of incentive awards. Motivation to achieve in-flight training is largely a manipulable, rather than an inherited, characteristic. The behavior control techniques of "behavior modification" or "contingency management" have been found useful in flight training, as well as in other training situations. We have found, for example, that incentive awards such as free time for both the trainee and his instructor are effective "motivators" for the achievement of stated performance goals in less training time.

Crew training. Simulators lend themselves to simultaneous pilot and copilot training much more readily than do the aircraft they simulate because of the need for the instructor to occupy a pilot seat in the latter for safety reasons. By deviating from this real-world model and moving the instructor to another

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seat position, we have found that effective training can be given in both pilot and copilot tasks simultaneously, thus effectively increasing the availability of simulator seats for training.

Peer training. Trainees, themselves, are used to assist fellow trainees in many simulator training activities. This technique has been found particularly useful with respect to cognitive problem-solving activities such as those which occur during navigation problems. Simulators are particularly well suited for peer instruction because the instructor can be removed from the cockpit area without creating flight safety problems with relatively unskilled trainees.

Minimizing equipment costs. To the extent that it is efficient, medium- to low-fidelity training devices, or other less expensive equipment, can be substituted for the much more expensive training in simulators. Training tasks should be allocated among the various training vehicles principally on the basis of cost effectiveness.

Objective performance measurement. All training goals are stated in objective, measurable terms which relate to the performance of the trainee or the simulator (or aircraft) he controls. With objective data, the usefulness of observations does not depend upon who is doing the observing, and there can be assurance that the proficiency data obtained are a dependable measure of the performance in question rather than a reflection of personal or other factors in the evaluation situation. Reliable data obtained through objective performance measurement can provide a basis for the standardization of the products of training. In our pilot training programs, objective performance measurement is a technique employed throughout training, not just for checkrides.

The techniques described above can be employed with almost any training equipment from simple paper mockups to operational aircraft themselves. They are not limited in their applicability to simulators, *per se.* In contrast, there are other training techniques which can be used only in those cases where specific provision is made for them in simulator design. Such training techniques include automated instruction and performance monitoring, feedback augmentation through video and simulator performance recording techniques, modeling through simulator programing, and trainee-initiated and trainee-paced instruction. For a more systematic discussion of such design features, see Caro and Prophet (1971).

TRANSFER OF TRAINING EVIDENCE

The various pilot training programs in which we have employed the training techniques described above have been quite successful. For example, in an Army undergraduate helicopter instrument-pilot training program, in which a new and quite realistic simulator was used, all of the described training techniques were incorporated into training program design at the time the simulator was introduced. The result was a 90% reduction in the amount of aircraft time required to attain the course objectives (Caro, 1972).

In that particular instrument-training program, prior to introduction of the new simulator training program, 60 hours aircraft time and 26 hours training-device time, using a modified 1-CA-1 trainer, were devoted to instructing aviators in instrument flight techniques and procedures. Graduates of the course were awarded an Army Standard Instrument Card. When the new simulator, the 2-B-24, and its specially-designed training program were introduced, the same training goals were achieved after only 6½ hours aircraft time and just under 43 hours simulator time, on the average. In addition, the total calendar time required to accomplish the training was reduced from 12 to 8 weeks.

The introduction of new training equipment often provides an opportunity to introduce new training program concepts, as is illustrated by the above instance. A similar opportunity was provided when new trainers were obtained for a fixed-wing instrument course. The training device in that instance was a commercially-available instrument trainer, the GAT-2, which was modeled after a "generalized" light twin-engine aircraft, *i.e.*, it clearly was not a "simulator" and many training activities could not be conducted in it. Nevertheless, impressive transfer of training benefits were shown when the trainer was used in conjunction with a training program incorporating the training features described above (Caro, 1971).

The training goals of the fixed-wing course included transition to a twin-engine aircraft as well as qualification for a Standard Instrument Card. The programmed allocation of aircraft time between these two goals was 10 hours for twin-engine transition and 50 hours for instrument training. Additionally, 21 hours of training in a 1-CA-1 trainer were included in the course prior to the introduction of the new commercially-available trainer. Using the new trainer with the training program we developed for it, a total of 25 hours of instruction resulted in a reduction of the 60 hours training time in the aircraft to only 35 hours—approximately 5 hours for twin-engine transition and 30 hours for instrument training. In spite of the fact that substantial savings were realized with respect to the VFR transition training goals in this course, it should be noted that there was no synthetic visual display associated with the new trainer.

In another study where device realism might be considered exceptionally low, five instructional periods in a cockpit mockup made of plywood and photographs by unskilled labor (psychologists) at a cost of about $30 were found to be about as effective as five hours of instruction in the aircraft itself (Prophet and Boyd, 1970). The training task in that study consisted of aircraft pre-start, start, runup, and shutdown procedures for the OV-1 Mohawk aircraft. The training consisted of a highly-structured program which incorporated most of the techniques described above. The same training program was used in the mockup and in the aircraft. For the tasks involved, pilots trained in the mockup were found to be as proficient in the aircraft as were pilots who received comparable training in the aircraft itself.

In another course, where a slightly more realistic mockup built by the Army at a cost of about $4,300 was introduced, again with a training program incorporating many of the techniques described above (Caro, Isley, Jolley, and Wright, 1972), the instructors reported impressive transfer-of-training results. The course was a transition course for the Army's U-21 aircraft, and it consisted of 25 hours instruction in the aircraft. When the mockup and its training program were added, without any change in the 25 flight hours, there was about a 10% increase in the amount of that time each trainee spent in learning to fly instead of sitting on the ramp learning procedures. Although no attempt was made to measure the increased pilot proficiency which presumably resulted, it is evident that they at least had 2½ hours more actual flight experience upon graduation with no increase in programmed flight hours.

To complete the description of instances of training device utilization, I shall mention one more item. We also have obtained substantial, demonstrable transfer of training using reduced-scale paper mockups when an appropriately-designed training program is used with them. Admittedly, the amount of training which can be undertaken with such simple devices is limited. On a cost-effectiveness basis, however, simple devices can often be much more efficient training vehicles for the tasks for which they were designed than more realistic simulators.

CONCLUSIONS

At this point it is appropriate to return to the quotation which introduced this paper. I

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am of the opinion that we know more about the training value of simulators than the quotation implies, although I do not suggest that we know very much. Perhaps we build simulators as realistically as possible because people who design them do not know much about training. Or, perhaps it is because those who design them know that those who use them do not know much about training, and the safest thing to do is to build simulators like aircraft. In that way, at least, instructor pilots will be able to get some training value out of them by using simulators just like they would aircraft.

It is true that the users have been willing to pay the price for simulator realism, although in some instances realism was bought for the sake of realism, not to meet known training goals. In spite of such affluence, the question of how transfer might be accomplished in less expensive ways is not being avoided altogether. It is receiving attention in research centers such as that which I represent. Even now, there is substantial applied research evidence that much of the training being conducted in expensive simulators could be accomplished in less expensive devices *if* the training programs used with them were properly designed and conducted.

Finally, let me acknowledge that the present state-of-the-training art is relatively primitive, and I do not suggest we should cancel all orders for realistic simulators. I do believe that in many cases we are paying for realism where it cannot be justified from a transfer-of-training standpoint. A proper training program can compensate for lack of physical similarity between the training device and the aircraft, but a realistic simulator is a poor substitute for competent training. Obviously, transfer of training from a device to an aircraft is limited to the tasks which can be performed in the device. But, whether that limit is reached is a function of the way in which the device is used. There probably would have been zero transfer, or even a great deal of negative transfer, in all the instances of device utilization I described above had they been used with inappropriate training programs. The key is the program, not the hardware.

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[2]

Adopting the instructional science paradigm to encompass training in virtual environments

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The science of instruction and training is founded on decades of research and practice. Moreover, the field continues to evolve as new theories, methods and practices emerge. A modern driver for this evolution has been the development of a vast array of instructional technologies. One of the newer technological advances is the use of virtual environments. This article considers how fundamental theories and findings from educational and training psychology may or may not apply in the world of virtual environments. In addition, apparent gaps are highlighted in the current knowledge base in order to foster ideas for future research.

Keywords: virtual environments; training; learning theories; instructional strategies

1. Introduction

Sound the trumpets! Roll out the red carpet! A new training technology has taken centre stage. This is called the 'virtual environment'. Using blindingly fast processing speeds, massive amounts of electronic storage and a plethora of other advances in software and hardware technologies, a student can be immersed in a simulation of an experience that he or she might face sometime in the future. This simulation can be used to teach the student everything that he or she will need to know and be able to do in order to triumph in the real world. The potential benefits are impressive. The question is: do we know how to use this power?

Note that we have been here before. From blackboards to whiteboards, videotapes to interactive videodisks, printed media to multimedia, instructional technology is constantly changing and each new advance spurs a glut of research into its instructional requirements and implications. Why does each new technology require so much research? Don't we already know how people learn? Aren't the basics of good instruction the same, regardless of the technology being used? It turns out that the answers to these questions are neither simple nor intuitive.

This article considers how fundamental theories and findings from educational and training psychology may or may not apply in the world of virtual environments (VEs). In addition, apparent gaps in the current knowledge base are highlighted in order to foster

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ideas for future research. First, parallel overviews of research in basic and applied instructional/training psychology are presented. Then, the characteristics and capabilities of VE training systems are described. Finally, in the remainder of the article, principles and findings from previous research, which should be applicable in VE training, and those unique aspects that may well require additional research are identified.

2. Whirlwind tour of literature

Within the history of twentieth century psychology, the study of learning has gone through some dramatic changes (Greeno 1980, Shuell 1986, Gagne and Glaser 1987, Glaser 1990). Early theories of learning emphasised the relationship between changes in an environment and changes in a subject's behaviour, without addressing internal mental processes. Eventually, the phenomena that could not be explained with this approach, such as natural language, grew too numerous and significant to ignore and the field shifted to a cognitive perspective. This perspective yielded insights into learning, as well as the fundamental cognitive mechanisms that underlie complex performance.

Given both the breadth and depth of the history of learning research, it would be unreasonable to attempt to present a thorough or rigorous review of learning research within the context of this article. Instead, the basic issues and major theoretical perspectives that have furthered the ability to support learning are highlighted. Even this task would be daunting without some structure and so this paper begins by presenting an organisational framework.

2.1. *Organisational framework*

Just as the empirical study of learning began with memory research, the framework that has been adopted in this article was originally developed to help organise the results of memory studies. (While originally designed to organise memory research results, researchers have employed Jenkins' Tetrahedral Model to organise and interpret learning research results (e.g. Rieber 1994, Najjar 1998) and, while alternative organisational frameworks do exist (e.g. Thomas and Rohwer 1993, Siegler 2001), they feature highly similar variables.)

While serving as a discussant at a conference on memory research, Jenkins (1979) proposed a 'Theorist's Tetrahedron' to help categorise and compare the widely diverse collection of studies and results. In particular, Jenkins identified four clusters of variables that were potentially relevant to the outcome of any single study. These four clusters include: (1) the nature of the materials being learned; (2) 'orienting tasks', which encompasses the instructions given to a subject and the behavioural and mental activities engaged in by the subject in order to learn the materials; (3) the characteristics of the subjects themselves; (4) 'criterial tasks', which refers to the type of test that a subject must pass in order to demonstrate learning (e.g. recognition, recall, problem solving).

2.2. *Review of educational psychology (academic perspective)*

2.2.1. *Nature of the materials*

Two orthogonal tracks of research have developed on this particular vertex in Jenkins' Tetrahedron. Many researchers characterise the materials to be learned according to the parent domain of those materials. Thus, there are streams of research investigating learning and instruction in such domains as reading, mathematics and science (e.g. Sandoval 1995, Voss *et al.* 1995, Kalchman *et al.* 2001). Researchers with this focus investigate all relevant aspects of the learning domain, from remembering the simplest facts to solving the most complex problems. They analyse the structure of specific material and use that structure to determine optimised instructional approaches (e.g. Reigeluth *et al.* 1978). They also look for unique aspects of that domain that pose instructional challenges and require specialised instruction. For example, in the domain of scientific knowledge, it has been determined that many people arrive at the instructional setting with intuitive, naïve theories about the natural world (Sandoval 1995).

Alternatively, other researchers have looked for commonalities across domains and proposed generic taxonomies of learning outcomes. Gagne (1984) is credited with prescribing the most commonly used taxonomy. He proposed that there are five categories of learning outcomes, including: (1) motor skills (e.g. serving a tennis ball, riding a bike or tying a shoelace), which are distinguished by gradual skill acquisition and learning through repetition; (2) verbal or declarative information (e.g. facts, memorised passages, schemas and scripts); (3) intellectual skills, by which he meant procedural knowledge or the ability to apply rules (e.g. solving long division problems, troubleshooting faulty avionics equipment); (4) cognitive strategies, sometimes thought of as higher-order cognitive skills, which represent the conscious control that a learner exerts over his or her learning (e.g. using a visualisation strategy to help memorise a list of unrelated words, monitoring progress on a complex task); (5) attitudes, which stand in contrast to the other learning outcomes, in that attempts to explicitly teach them typically fail (as any parent of a teenager can attest).

Both the nomenclature and the specific details of such categorisations have been fluid and many variations of this taxonomy have been proposed. However, the commonalities among the various taxonomies far outweigh the differences and significant work has been undertaken in determining effective ways to facilitate (through instruction) each type of learning (e.g. Schneider 1985, Gagne and Driscoll 1988, Glaser and Bassok 1989, Farnham-Diggory 1994, VanLehn 1996).

While there is significant agreement in many areas of learning research, one issue that has been contested is the extent to which it is possible to teach (and people actually use) general, rather than domain-specific, cognitive skills and strategies (e.g. Glaser 1984, Sternberg 1985). Research into the nature of expertise has determined that skilled problem-solving performance usually depends on a tremendous amount of domain-specific knowledge and processes. Simultaneously, research attempting to encourage students to apply general strategies across multiple problem contexts and domains has typically produced disappointing results. These two findings are not encouraging. On the other hand, it has been argued that there are generalisable skills that are already being successfully taught, such as reading (Perfetti 1989), scientific reasoning (Reif 1995, Voss *et al.* 1995) and argumentation (Stein and Miller 1993, Voss *et al.* 1995). As with many debates in psychology, the answer to this conundrum lies undoubtedly somewhere in between the two extreme positions. Alternatively, both positions may be 'right', in the sense that a moderating variable (such as training context or setting) may influence the relative efficacy of general *vs* domain-specific skills.

2.2.2. *Nature of the activities*

The research literature on the nature of the activities that best facilitate learning is messy and confusing. One challenge is that studies vary in the extent to which they focus on an instructor's perspective *vs* the learner's perspective of the activities. For example, to an instructor, giving a lecture and leading a group discussion are completely different activities. However, from a student's perspective, any instructional technique can be implemented poorly or well (both a lecture and a discussion can be boring and uninformative; Reigeluth and Curtis 1987).

Many researchers take a learner-focused perspective when identifying and describing those activities that are likely to facilitate learning. Learner-focused research is usually guided by a theoretical description of learning. Following the 'cognitive revolution', many learning theories emphasise the mental structures and processes of the learner and describe learning as an internal change, rather than a change in behaviour (Wittrock 1974, Anderson 1984, Shuell 1986, Gagne and Glaser 1988). This perspective emphasises the active role that the learner plays in processing new materials and acknowledges limitations on this processing that are imposed by the cognitive system. More specifically, meaningful learning is thought to take place when learners connect new information to existing knowledge. A wide variety of instructional techniques are attributed to this theoretical perspective, including discovery learning, conceptual change instruction, inquiry instruction, (Collins and Stevens 1982) and requiring students to generate elaborations (Reder *et al.* 1986) or take notes during lessons (Peper and Mayer 1986).

Somewhat more recently, the social nature of learning has become a prominent element addressed in theory and research (Voss *et al.* 1995). According to this perspective, society establishes the performance goals and context for learning, and interaction both motivates and scaffolds cognitive effort and development. Specific instructional techniques that are often attributed to this perspective include collaborative group learning (Springer *et al.* 1999), cognitive apprenticeship and reciprocal teaching.

So, with all these theories and instructional techniques, what is really known about the nature of activities that facilitate learning? First and foremost, front-end analyses – task analyses, cognitive analyses, environmental analyses – of the learning goals, learners, experienced performers and performance context are key. Anderson *et al.* (1998) emphasise: (a) the need to identify the components of complex skills; (b) the likelihood that part-task training will provide an efficient and effective first step in a more complex (ultimately situated) training process. It is widely agreed that the more precisely one can specify the performance context for a learning goal, the more effectively one can design instruction that supports the appropriate level of transfer across, but not beyond, that context. The importance of analysing learners is highlighted by the fact that active processing of new material, which is usually influenced by pre-existing knowledge, is the strongest predictor of learning outcomes (Bloom 1976).

Active processing can take many forms, such as making connections to existing knowledge, generating summaries, explanations and/or elaborations of new material and applying deductive or inductive processes to the new material. There is no 'one size fits all' answer to the question of how explicit and all-inclusive instruction should be *vs* leaving the responsibility on the student's shoulders to locate, collect and process information. In large part, the right answer depends on the student's aptitude. Ideally, each student should be given just enough support (or scaffolding) to allow that student to achieve the learning goal within the available amount of time, and no more. This dependency is complicated by the fact that student aptitudes can vary across time and topics.

Finally, social contexts are not always appropriate for facilitating learning. For example, there is a lot to be gained by practising specific psychomotor skills in isolation (possibly with a coach) until they become automated or 'compiled'. In other instances, social contexts may be critical for fostering motivation and promoting transfer.

2.2.3. *Characteristics of the learners*

One of the most enduring truths of human nature is that people who are treated the same respond differently. Interestingly, the field of psychology is divided in terms of how to deal with this fact. Mainstream experimental psychology tends to treat these differences as error variance, while differential psychologists believe that individual differences are the very things that need to be studied and understood. In his presidential address at the 65th convention of the American Psychological Association, Cronbach (1957, p. 681) called for the two disciplines to come together and proposed: '... an educational psychology, which measures readiness for different types of teaching and which invents teaching methods to fit different types of readiness'.

So, with almost 50 years of research between Cronbach's address and today, which individual differences, or learner characteristics, appear to be important in determining learning outcomes? A large segment of research in educational psychology has gone into developmental issues, *à la* Piaget, asking how cognitive and psychomotor capabilities change as a child matures into adulthood. However, of more relevance to this paper is the concept of 'aptitude' as described by Corno and colleagues (2002). These researchers defined 'aptitude' as a person's readiness to learn (or perform) and reported that aptitude comprises three independent dimensions: cognitive; conative; and affective. Broadly speaking, the cognitive dimension reflects both the presence of relevant precursor knowledge and skills and the intellectual capability to reason, analyse and interpret new information. The conative dimension reflects a learner's motivation and executive control and the affective dimension reflects personality and emotion.

Of course, each of these dimensions has been defined in much greater detail. Probably the most extensively studied of the three is the cognitive dimension. A number of taxonomies of cognitive or intellectual ability have been put forth, including Thurstone's (as described in Corno *et al.* 2002) set of six primary mental abilities (spatial transformations; number facility; word meanings; word fluency; associative memory; reasoning) and Carroll's (1993) epic work reanalysing more than 450 datasets. Carroll's efforts highlighted a multilevel hierarchical structure, including numerous ability factors in 10 domains (language, reasoning, memory and learning, visual perception, auditory reception, idea production, cognitive speed, knowledge and achievement, psychomotor abilities, personal characteristics and higher-order cognitive factors).

According to Corno *et al.* (2002, p. 85), the affective dimension of aptitude includes: (a) relatively stable aspects of a person's temperament, such as sociability, activity level, impulse inhibition and emotionality; (b) characteristic moods, such as positive and negative affect, flow and feelings of constraint. Finally, the volition component of the conative dimension of aptitude includes self-regulation and learning styles, while the motivational component of the conative dimension includes motivational orientations, achievement-related attitudes and interests and beliefs about self (*ibid*, p. 88).

The importance of each of these learner characteristics for predicting learning outcomes varies. Across the three dimensions of aptitude, measures of cognitive ability are the most consistently predictive of success in an educational setting (Bloom 1976, Corno *et al.* 2002). Within the conative dimension, self-regulation skills, self-efficacy, interest in the subject matter and a mastery orientation to learning have also been shown to account for unique variance in learning outcomes (e.g. Bloom 1976, Dweck 1986, Chi and Bassok 1989, Glaser 1990). There is less agreement about the strength of the relationship between factors along the affective dimension and learning outcomes. Some researchers report little evidence to support this claim (e.g. Corno *et al.* 2002), while others report substantial evidence (e.g. Lievens *et al.* 2005). One possible explanation is that the relationship may be context dependent. For example, Corno *et al.* (2002, p. 126) report one training context – diving training in the Belgian Navy – in which the personality variables of anxiety (low being optimal) and assertiveness (high being optimal) were predictors of success. They attribute this relationship to the stressful nature of the learning environment, relative to a typical academic setting.

2.2.4. *Nature of the test*

Even after specifying the nature of the material to be learned, the learning activities that are conducted, and the characteristics of the learner, the outcome of the event is likely to depend on the nature of the test (i.e. test or criteria characteristics). Superficially, tests can vary in the format of their items, ranging from multiple choice to 'hands-on' work samples. However, there is a more important and fundamental issue regarding the nature of the test that is orthogonal to the format of the test items. Specifically, the amount of similarity between the context established in the test items and the context established during learning is crucial. A general and enduring principle of cognition is that the more similarity exists between two contexts, the more likely it is that the same knowledge and skills will apply (Thorndike and Woodworth 1901, Guthrie 1952, Tulving and Thomson 1973, Singley and Anderson 1989). Conversely, educators usually place the most value on knowledge and skills that are broadly (and appropriately) applied across a wide variety of different contexts. This is called phenomenon 'transfer' and instructional techniques are often evaluated on the basis of how well they facilitate transfer.

There is some debate about the prevalence of transfer (which is highly related to the debate about general *vs* domain-specific skills). Detterman (1993), for example, suggested that true instances of transfer are few and far between, while Bassok and Holyoak (1993) paint a much rosier picture. There has also been debate about the cognitive mechanisms underlying transfer; some researchers have used a production rule model (e.g. Larkin 1989), while others have used a schema-based model (e.g. Bassok and Holyoak 1993, Reed 1993). A key goal of researchers in this area is to specify what type(s) of knowledge will transfer (e.g. Larkin 1989) and the conditions that facilitate or hamper transfer among domains (e.g. Bassok and Holyoak 1993).

While most educators freely use terms such as 'near transfer' and 'far transfer', researchers generally acknowledge the fundamental problem of quantifying the similarity between contexts. Butterfield *et al.* (1993) point out a more subtle issue, namely that the amount of similarity between two contexts will also depend on the level of analysis. It will always be possible to select an abstract level at which two contexts are highly similar, just as it will always be possible to specify a detailed level at which those same two contexts will be quite different. Despite the aforementioned debates, it is still reasonable to attempt to foster a broad and appropriate application of knowledge and skill and researchers have provided guidelines for promoting transfer (e.g. Bransford *et al.* 2000).

2.3. *Review of instructional/training psychology (practitioner perspective)*

Although many of the academic principles articulated in this review of educational psychology hold equal value for training practice, practitioners often view training interventions from the more global view of the assess, design, develop, implement and evaluate (ADDIE) framework (Teachout and Hall 2002). Following ADDIE, training interventions often start with some type of front-end needs assessment. Such assessments take a variety of forms and can occur at multiple levels. Examples of needs assessments include strategic needs assessment, competency-based assessment, job and task analysis and training needs assessment (Gupta 1999). In conducting an appropriately thorough needs assessment, each of the elements outlined in Jenkins' Tetrahedral model should be considered. That is, content needs, needs for changes in instructional strategies, needs reflecting deficits in performance criteria or needs to adequately understand characteristics of learners may all surface during assessment.

Following needs assessment, training design and development occurs. An adequate design/development process also calls for recognition of the factors discussed previously (e.g. the Jenkins model). In addition, to the degree that designers (and/or instructors) have a specific theoretical orientation towards learning (e.g. constructivist, cognitive), their choices regarding instructional strategies will be influenced. Following design, implementation requires attending to factors such as resource acquisition and management, managing stakeholder expectations and involvement and attending to organisational context factors such as existing policies, structures and processes (Teachout and Hall 2002).

Finally, following implementation, professional guidelines call for some type of evaluation. Evaluation has received a great deal of focus, as organisations are under increasing pressure to demonstrate the effectiveness and impact of training. Traditional evaluation models, such as Kirkpatrick's (1998) model, include measures of student reactions, learning, behaviour changes on the job, overall organisational results such as profit or productivity and, occasionally, return-on-investment (ROI). Although there is an abundance of research and practical advice on the topic, evidence indicates that few organisations actually implement training evaluation in a comprehensive manner. For example, in a recent survey, the American Society for Training and Development reported that only 14% of organisations measure the extent to which training results in behaviour changes on the job, and only 8% measure the extent to which training contributes to organisational results (American Society for Training and Development 2004).

Note that variations on the ADDIE model have been proposed. For example, one interesting variant proposes a 'backward design process' (Wiggins and McTighe 1998). In the Wiggins and McTighe model, instructional designers are first asked to identify desired learning results, then determine acceptable evidence of learning and only then design learning experiences and instruction.

An example of a specific training model that is consistent with the ADDIE framework and is particularly relevant to instruction in virtual and simulation-based environments is the event-based approach to training (EBAT; Cannon-Bowers *et al.* 1998). EBAT is a process model which incorporates a number of facets of the broader ADDIE framework. EBAT features the use of simulated scenarios and planned or 'trigger' events that facilitate the use of and evaluation of specific skills or competencies. In the EBAT model, the scenario(s) itself is viewed as the curriculum (Salas 2001).

Even though academic work has offered an enlightened view of the mechanisms and processes of learning and practical frameworks to guide effective training practice have been developed (e.g. ADDIE, EBAT), a major challenge facing practitioners is to build instruction based on scientific theories and evidence of effectiveness rather than individual preferences and methods of convenience. As summarised by Merrill (1997, p. 51): '... which learning strategy to use for a particular instructional goal is not a matter of preference, it is a matter of science'. Despite the obvious value of science-based instruction, typical training practice lags behind the knowledge of the 'science of training' (Salas and Cannon-Bowers 2001). This is particularly true in technology-enabled learning environments, where the technology is often viewed as the intervention. Such a technology-centric view may be problematic when it leads to interventions that consist merely of unguided practice and 'free play', which might reinforce the use of counterproductive strategies and approaches (Salas 2001).

3. Technological revolution: virtual environment training systems

VE training systems immerse users in a three-dimensional (3-D) world, allowing for real-time interaction with a synthetic environment and objects within it. Trainees perceive this computer-generated environment using visual, auditory and/or haptic (touch) cues. Visual cues may be presented using a head-mounted display or desktop computer, or projected onto a wall screen or similar surface. Interaction with the VE takes place via sensors that detect the operator's body movements or with auxiliary hardware such as joysticks or wands. In general, three basic types of tasks are performed in VE systems: navigation and locomotion through the environment; selection of objects in the environment; and object manipulation (Gabbard 1997). Ideally, users have a feeling of 'actually being there' (Wilson 1999). The degree of immersion is an important factor in the design of VEs. Moreno and Mayer (2004) found that although students in highly immersive VEs reported greater feelings of physical presence than those in low immersive VEs, high immersion was not accompanied by improved learning in a problem-solving task. When learning objectives are strongly associated with visual–spatial skill or procedural knowledge (e.g. learning to fly an aircraft), however, high immersion may be more critical.

In many contexts, training in a VE provides key advantages over the same training conducted in the real world. Perhaps the most obvious advantage is the ability to train skills in otherwise dangerous or risky real-life situations (e.g. firefighting, combat and medical procedures). VE is also appropriate for unique or logistically difficult training contexts, such as training for low base rate events of high criticality and training for work in remote locations (including outer space). In fact, increased accessibility can be the deciding factor in choosing a training intervention. Finally, VE may curb the costs associated with expensive real-life training materials (e.g. medical training requiring human or animal cadavers; Scerbo 2005). Wilson (1999) and others report that VE-based training systems have the added benefit of motivating users.

The capabilities of VEs for training include architecture applications, engineering design, data representation and visualisation, teleoperation, checking emergency or standard operating procedures, planetary surface exploration, video game development, large-scale simulation networks and even interactive art (Ellis 1994, Wilson 1999). In military settings, VE technology has been used to train naval officers in ship manoeuvring and soldiers in battlefield strategy (Rose *et al.* 2000). In medical settings, virtual reality (VR) simulators of minimally invasive procedures have been used to interact with 'virtual' organs. In fact, physicians wishing to treat patients suffering from plaque build-up in the carotid artery must now undergo FDA-approved VR training on the use of specially constructed wire stents to improve blood flow (Scerbo 2005). VE applications such as 'virtual workbench' and 'responsive workbench' feature the projection of stereoscopic images onto a horizontal display surface to produce 3-D fields. Multiple users (even geographically distributed teammates) can stand around the workbench and interact with the VE using hand-held wands. Creem-Regehr *et al.* (2004) used a semi-immersive locomotion interface called 'the Treadport' to study perceptions of geographical slant (i.e. the slope of a hill). Students wearing a mechanical harness walked along a treadmill surrounded on three sides by projected landscape images.

How effectively does VE-based training transfer to real-world tasks? The results appear mixed, though on balance, VE training does appear to work well for many important skills. For example, many studies have demonstrated that VE technology effectively trains route learning and spatial knowledge in real-world settings (e.g. Witmer *et al.* 1996, Bliss *et al.* 1997, Farrell *et al.* 2003). Farrell *et al.* (2003), however, found that VEs added no incremental value over simply studying a map. In contrast, Scerbo (2005) reports that medical residents trained on a VR simulator more effectively performed a real-life gall bladder removal than residents trained using traditional methods. Perhaps most impressive was the pioneering use of VE-based training by NASA in the early 1990s. When NASA astronomers discovered some flaws in the optical system of the Hubble space telescope (HST) in 1990, a crew of over 100 flight controllers underwent repair and maintenance training using head-mounted VE technology. The VE enabled crewmembers to become familiar with the location, appearance and operability of various HST components, including maintenance components of the space shuttle payload bay. The training was viewed positively by users and resulted in real-life success (Loftin and Kenney 1995). Because VE technology is still in its infancy, training effectiveness studies conducted 10 years ago may be outdated already. It is a safe bet that the product market will continue to witness the introduction of new and improved display and input/output devices coupled with decreases in cost.

4. New technology, old paradigm: assessing the fit

Having conducted a 'whirlwind' tour of the literature on education/instructional psychology and having reviewed basic, defining elements of VE- and simulation-based systems, this paper now looks at the intersection of these two domains. Specifically addressed is the fundamental questions of 'What models, methods and findings from prior educational and training research are still relevant in the world of VE systems, and where does prior research fall short in offering guidance on the development and deployment of VE-enabled interventions?' These questions are assessed using the general framework of: (1) learner characteristics; (2) the nature of instructional materials, processing and instructional strategies; (3) types of tests/criteria.

4.1. *Learner characteristics*

While many characteristics of learners have a universal impact – knowledge, motivation and abilities affect performance and learning in any setting – some individual differences may have a greater or lesser effect in VEs. For example, Wilfred *et al.* (2004) investigated relationships among individual differences, VE experiences and learning outcomes. The individual differences studied included 'immersive tendency', defined as 'a psychological state characterised by perceiving oneself to be enveloped by, included in and interacting with an environment that provides a continuous stream of stimuli and experiences' (Wilfred *et al.* 2004). These researchers found that measures of this construct were related to learning outcomes in a virtual training environment. Such efforts indicate some interesting future directions. For example, Wilfred *et al.* (2004) discuss the possibility that avid 'gamers' (i.e. individuals who routinely play computer games) may find it easier to immerse themselves in VEs, thus positively influencing the capacity to learn and perform. Such a finding would be in line with some of the educational technology research, which shows a positive correlation between presence and learning (Winn 2002).

The possibility that individual differences affect learning outcomes in certain interventions or learning environments raises the issue of aptitude by treatment interactions (ATIs). The ATI paradigm postulates that individual differences in aptitudes may be used to tailor instructional strategies (Kyllonen and Lajoie 2003). While research on ATIs has shown mixed results, recent efforts that focus on new definitions of 'aptitude' have yielded more evidence of interactions (Kyllonen and Lajoie 2003). Moreover, two aspects of the ATI debate are particularly relevant to VE-enabled training. First, technology itself may be a moderating influence on learning and performance. For example, Hesketh and Neal (1999) proposed a person by technology ($P \times T$) interaction model of performance. Specifically, these authors suggest that how an individual chooses to use technology is an important performance component (and possibly an important component of learning). Second, VEs may present an important platform for ATI and $P \times T$ research. Specifically, these environments present a general platform for contrasting various instructional techniques and evaluating their efficacy against known individual differences. In addition, since various technologies can be readily incorporated or simulated in VEs or virtual worlds, the impact of how individuals use various technologies (i.e. $P \times T$ interaction) can be studied directly. More research is needed to evaluate such ideas.

Whether the ATI paradigm is ultimately supported or not, use of VEs may open new lines of research on individual differences. Specifically, researchers have begun to ask how VEs might facilitate new ways to assess individual differences. Upon reflection, it is clear that VEs afford opportunities to 'tap' a broad array of individual differences, including constructs such as spatial ability, complex problem solving and critical thinking, declarative and procedural knowledge, tacit knowledge, memory, interpersonal skills, new constructs such as 'immersive tendency' and physiological reactions (e.g. motion sickness). In fact, the capability to conduct 'full spectrum' individual differences measurement could be facilitated by the emergence of rich, VE-type environments.

Of course, a good deal of research is needed to know when (and if) VE-based measurement offers advantages over traditional techniques (e.g. paper and pencil instruments). Initial research in complex individual difference domains, such as foreign language acquisition, indicates that VE- and simulation-based systems hold a great deal of promise (Mote *et al.* 2004), particularly in terms of developing and delivering tailored instructional feedback. One research domain that might benefit from VE-based assessment is the study of non-cognitive predictors of performance (e.g. personality). Given serious concerns about 'faking' on non-cognitive instruments, alternative, high-fidelity assessment approaches may prove valuable (Peeters and Lievens 2005).

4.2. *Nature of instructional materials, processing and instructional strategies*

As discussed above, VE and other simulation-based training approaches afford rich opportunities to give trainees 'learner control' (Winn 2002) and to address hard to train skills, such as dimensions of teamwork (Salas and Cannon-Bowers 2001). However, an increasing body of literature suggests that full learner control may not be advantageous. Instead, careful scaffolding (Aleven and Koedinger 2001) or 'adaptive guidance' (Bell and Kozlowski 2002) is recommended to guide learners. Such mechanisms have been implemented in operational training systems.

Given such challenges, the use of VE systems for training must be empowered by a full understanding of the range of instructional techniques available and how various interventions map to different knowledge, skill and ability domains. As discussed above, only exposing trainees to complex performance/learning environments (such as high-fidelity VE systems) may be counterproductive. Anderson *et al.* (2000) make this point by drawing analogies to other complex performance domains. For example, these authors point out that a student who wishes to play a violin in an orchestra would have a hard time making progress if all practice was conducted in a full orchestra context. Similarly, high-level sports team training often involves a large percentage of practice time that is spent on individual skill-building drills. Other researchers have pointed out that using 'virtual worlds' to learn basic facts may be highly inefficient and possibly counter-productive (Winn 2002). Thus, the use of high-fidelity, VE-based exercises must be placed in a curriculum-like context, via careful sequencing and choices of instructional interventions.

The mandate to engage in careful instructional strategy design is made difficult by the fact that despite 50 plus years of research, we fundamentally do not know the best way(s) to give feedback in dynamic performance and decision-making environments. Multiple studies have shown that various types of feedback (e.g. evaluation, outcome) are not necessarily effective in such environments (e.g. Gonzalez 2005). Moreover, the absence of a generally accepted taxonomy of training interventions in the applied psychology literature is striking, particularly in light of technological advances to deliver interventions. (The reader's attention is drawn, however, to a recent effort to develop just such a training intervention taxonomy (Van Buskirk *et al.* 2005.)

One way to array possible interventions, within VE- and simulation-based environments, would be a three-stage framework: preparation; practice; and feedback. This stems in part from previous work conducted in the learning and instructional design literature that takes a sequential 'events of instruction' approach to learning (Gagne and Briggs 1979). Various techniques, technologies, interactive methods and media must be decided upon at each stage and trainees might enter training at any of the three stages, depending on their level of development with regard to desired learning objectives. For example, completely new knowledge and skills may require starting with a lecture or manual to outline basic concepts, followed by practice opportunities and reinforcement. In contrast, trainees that already have the necessary declarative knowledge may jump right into practice.

While such approaches are discussed in the literature, and practitioners often adopt such approaches on an *ad hoc* basis, further work on a general framework to guide intervention choice and sequencing, especially in the context of VE- and simulation-based systems, is needed. Such models must incorporate sequences of instructional techniques within interventions (e.g. preparation, practice, feedback) and across interventions (e.g. a 'crawl, walk, run' model, consisting of low-, moderate-, and high-fidelity exercises) (US Army Research Institute for the Behavioral and Social Sciences 2003). Thus, it may be time to start thinking about instructional strategy development from a 'multilevel' perspective – that is, instructional techniques should be carefully chosen both within and across various training stages or stages of development. Such an approach would fit with a current focus on multilevel models and paradigms in organisational research (Klein and Kozlowski 2000). Development of such instructional strategy models and frameworks must be undertaken with the realisation that the various combinations of instructional strategies and techniques, training content domains and technologies create a large universe of potential choices for training designers. Thus, future training research should focus on practical ways to effectively bound such choices.

Before moving past the discussion of instructional interventions, there are two last issues that the authors would like to raise: unintentional 'instruction'; and underutilised instructional capability in VE training systems. Consider first, a type of learning that may be induced unintentionally in VE systems: implicit learning or the acquisition of tacit knowledge. Instructional research focuses on fostering explicit learning, with an occasional nod to the implicit learning that may have occurred prior to the official instruction, as either something to be leveraged or, more likely, something to be overcome (i.e. naïve preconceptions in science). However, there is a wealth of research that shows that implicit learning does occur in the real world. A commonly used example, from natural language, is the ordering of adjectives in an English sentence such as 'the pretty little red house'. There are over a dozen grammatical rules that determine the appropriate order for a series of adjectives in a sentence. Interestingly, few native speakers can verbally report on even one of those rules. This appears to be a case of tacit knowledge, acquired implicitly, that affects behaviour.

Consider an example that is more relevant to the domains in which VE training systems may be employed – command and control on board a Navy warship. Klein (1999, pp. 35–39) reports on the case of HMS Gloucester, a British destroyer that successfully defended itself against a Silkworm missile attack, before it 'should have' been able to know that it was being attacked. Explicit information about the unknown object provided by the radar system was not sufficient to distinguish the missile from a military plane. However, the officer on watch was immediately sure that the blip on the radar screen was a missile. How did he know? After extensive investigation, it was posited that the officer's experience observing the radar display had supported a type of implicit learning of perceptual patterns to the degree that even a small perceptual anomaly was noticed.

While the existence of implicit learning and tacit knowledge is generally accepted, implicit learning remains an area of research that is in flux and disagreements concerning the mechanisms and the impact of implicit learning abound (Cleeremans and Jiménez 2002). Further, counterexamples of incidents featuring poor decisions made based on incorrect knowledge do exist (e.g. the USS Vincennes, Iranian Airbus incident; Collyer and Makecki 1998). However, because implicit learning touches on the central role of experience in shaping cognitive systems, the study of implicit learning in virtual learning environments may be important. Specifically, the immersiveness of VE systems may lend itself to fostering implicit learning, which, if unintentional, could lead to inappropriate tacit knowledge acquisition. Would a VE training system for the British officer mentioned above have incorporated that minute perceptual difference between military planes and missiles that saved lives on board HMS Gloucester? More importantly, how does one ensure that VEs or other synthetic training environments are not accidentally instantiating a particular pattern recognition that is not valid in the real world? More research is needed on such issues.

Finally, the authors believe that there may be an underutilised and understudied facet of VE interventions – namely, that VEs are a mechanism for augmenting reality in the sense of 'making the invisible visible'. This idea is discussed in the literature in terms of differentiating simulation from 'reification' (Winn 2002). As discussed by Winn (2002), the purpose of a simulation is to create a facsimile of real objects or events, while reification involves making phenomena that cannot be directly perceived available for perception and interaction in a virtual learning environment. More specifically, Winn proposes that reification might be used when objects are too small to see (e.g. atoms), too large to interact with (e.g. solar systems) or natural processes with no perceivable, physical form (e.g. evaporation).

Research has shown that use of such artificial models can facilitate an understanding of concepts, processes and environments (Winn 2002). However, much of this research has occurred with samples of school-age children thus, there are issues of generalisability. Moreover, the power of reification rests on the development of appropriate metaphors and inappropriate generalisations can occur. A good example of this phenomenon is presented by Winn (2002), who describes a global warming simulation in which students oversimplified global warming due to the use of a 'tree' metaphor for green plant mass. Specifically, the students concluded that global warming was not a real problem, because planting more trees remedied the problem completely! Thus, reified metaphors must be chosen carefully. In addition, a social constructivist perspective on learning suggests that one attends to elements of interaction in and around VEs, which may influence how individuals make sense of experiences and metaphors (Wong and Chee 2003).

4.3. *Types of tests/criteria*

Given this review, another critical area for further research is training transfer. As suggested above, the literature on transfer from VE interventions to real-world tasks is mixed. VE-based interventions should theoretically support transfer because of the similarity in 'context' of the artificial and real-world task environments. However, the authors believe that there may be many dimensions of context. As discussed in the literature on fidelity, simulations can vary along overlapping dimensions such as equipment fidelity, environment fidelity and psychological fidelity (Beaubien and Baker 2004).

Understanding how transfer environments map to training environments, in terms of such dimensions, may lead to transfer expectations that are more precise. Viewing transfer in terms of multiple dimensions is in line with training evaluation models that emphasise various types of learning outcomes (e.g. affective, cognitive, behavioural; Kraiger *et al.* 1993).

Over 25 years ago, when it was clear that one-on-one tutoring led to significant gains in learning, Scriven (1975) described individual tutoring as both an instructional imperative and an economic impossibility. If the implementers of VE training systems are to avoid a similar type of terminal conclusion, criteria for effective VE system implementation must go beyond documenting learning gains to include studies of cost/benefits or ROI. While a host of models for cost/benefit and ROI analysis are available (e.g. Phillips 1997), such models are not routinely employed. This may be the case primarily because evaluation itself is so rarely undertaken and ROI is often viewed as a 'follow-on' level of analysis that builds on more basic evaluation steps (Phillips 1997).

General reviews of technology-based instruction do suggest positive cost benefits over conventional instruction. For example, Fletcher (1996) conducted a review in which substantial cost savings, in terms of initial investments, operating and support costs and other cost elements, were achieved via technology-based systems. Notably, the driver for these savings appeared to be the substitution of simulated equipment for real equipment. In addition, when training efficiency is taken into account (thus reflecting 'soft' cost elements), studies indicate that simulations can produce trainee time savings of about 30% (Orlansky *et al.* 1994). However, recent models of cost/benefit and ROI analysis suggest that training interventions should be assessed in light of available alternatives (Bowsher 1998). Thus, the question is whether VE-type interventions yield the same learning gains as other, possibly lower-fidelity or less expensive, interventions comparisons that go beyond contrasting VE systems only with real-world systems.

It should be noted that ROI does not necessarily have to be based on an assessment of the impact on real-world performance. Recall that a VE system may be incorporated as just one component of a larger training pipeline. Thus, the true value of the advanced technology may be in some metric associated with the pipeline itself, such as affording increased throughput or shortening the length of the pipeline.

5. Summary

Hopefully, the current review of the instructional science paradigm and its relation to training in VEs has led readers to conclude that much is the same (front-end analyses are critical; an individual's aptitude or readiness to learn plays a tremendous role; training events should induce engagement and active processing; adaptive training that scaffolds a learner's development is likely to be both effective and efficient; part-task training of component skills contributes to readiness to learn complex whole-task performance; similarity between the learning environment and the testing environment predicts effective application and transfer). Even so, new opportunities for improving research and practice have emerged. Below, the essence of this review is distilled to a few points worthy of further consideration.

- Many of the individual differences that drive learning and performance in complex environments are understood. However, new constructs may emerge as being important and VEs may afford new approaches for measuring individual differences. While the debate over ATIs has not been resolved, technologies such as VEs may add new elements to the discussion.
- Modern approaches to instructional strategy design require attention to guiding learner interactions and control, rather than merely facilitating 'freeplay'. Correspondingly, multilevel models of instructional strategy design are needed that guide the choice of instructional techniques within and across stages of training and development.
- An under-researched aspect of VE usage is 'reification', where VEs are used to augment reality in a manner that 'makes the invisible visible'. This type of intervention requires careful metaphor selection and attention to the whole learning environment, including social facets.
- Effective training evaluation and training transfer requires attending to the multiple facets of 'fidelity', as well as consideration of the multiple types of training outcomes.
- Criteria for effective VE system implementation must incorporate some type of cost/benefit or ROI analysis. Such analyses should consider where a given VE implementation occurs within a training intervention sequence or 'pipeline'.

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It Is Not How Much You Have but How You Use It: Toward a Rational Use of Simulation to Support Aviation Training

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One of the most remarkable changes in aviation training over the past few decades is the use of simulation. The capabilities now offered by simulation have created unlimited opportunities for aviation training. In fact, aviation training is now more realistic, safe, cost-effective, and flexible than ever before. However, we believe that a number of misconceptions—or invalid assumptions—exist in the simulation community that prevent us from fully exploiting and utilizing recent scientific advances in a number of related fields in order to further enhance aviation training. These assumptions relate to the overreliance on high-fidelity simulation and to the misuse of simulation to enhance learning of complex skills. The purpose of this article is to discuss these assumptions in the hope of initiating a dialogue between behavioral scientists and engineers.