Research Directions for Future Simulation-Based Training Design in Defence

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ABSTRACT

New technologies provide potential increases in operational capability through improved survivability, mobility, and lethality. For technologies with a human in-the-loop, however, this potential is only translated to actual combat power through the expertise of the human controllers. This places training on the critical path for maximising the return on investment for technologies of this type.

Modern systems also support distributed command and control through increased connectivity. To exploit this technology and seize the operational initiative, commanders must have the mental agility to respond as the situation changes and new information becomes available. This includes creating novel solutions when faced with unexpected situations. This places an emphasis on training to support greater personal adaptability.

This paper discusses collaborative research by Rheinmetall Simulation Australia and the Australian Defence Science and Technology Organisation Land Division to investigate the impact of these issues on future training needs analysis and simulation-based training design in Defence. It discusses training as the selected sampling of the environment to provide the experience and feedback opportunities required for the accelerated development of expertise. Using this model, it evaluates the requirements for future Defence training, compares this with current approaches, and identifies a series of future research questions/"roadblocks" for supporting the goal of more efficient, effective, and responsive simulation-based training. The discussion is intended to share Australian research with the international audience.

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INTRODUCTION

The Defence Science and Technology Organisation (DSTO) is the main government group for providing scientific support to the Australian Defence Organisation (ADO). It is divided into specialised divisions supporting specific aspects of Defence. The DSTO Land Division (LD) provides support to Army, the Australian Defence Materiel Office (DMO), and Special Forces Command (SOCOMD).

Rheinmetall Simulation Australia Pty Ltd (RSA) is an Adelaide-based company that develops simulators and computer-based training (CBT) systems. It was formed when Rheinmetall Defence purchased the Defence arm of Sydac Pty Ltd in early 2013. Rheinmetall is the sixth largest global Defence simulation provider and the second largest provider in Europe.

Since 2009, personnel from DSTO LD and the now Rheinmetall Simulation Australia have collaborated to provide scientific support to the ADO in the area of simulation and training. Particular attention has been given to the diverse training requirements for LAND 121, which is an Australian Defence Force (ADF) project to replace the existing Army transport and logistics vehicle fleet with over 7,000 modern, networked vehicles, many of which will be protected.

An important focus for this collaboration has been the future requirements for training needs analysis (TNA) and training design in simulated environments. For Defence systems with humans-in-the-loop, personnel must actually be able to capitalise on the technical means at their disposal. The increased connectivity of the LAND 121 vehicles, for example, provides an operational potential. This is only converted to actual combat power by the expertise of the crew. This places training on the critical path in ensuring the maximum benefit and return on investment for new Defence technologies.

This paper provides a high level summary of some of the research output from the DSTO-RSA collaboration in this area. It begins by outlining a utilitarian model of training in which the objective of the training system is to ensure that trainees gain the ability to achieve specific ends within the Defence environment. For simulation-based training, the challenge is to find and simulate the set of experiences and feedback opportunities required to construct this ability.

Using this model, this paper outlines a series of goals for this form of training. These goals are compared with historic task-based approaches to training and training needs analysis and evaluated against current trends in the Defence environment, including increasing complexity and uncertainty.

These issues emphasise the importance of cognitive adaptability. Building from foundational skills, personnel must be able to manage variable, uncertain situations by reacting on a just-in-time basis as threats and opportunities emerge and new information becomes available.

These issues require improved approaches for training needs analysis and training design. This paper reviews some of the issues encountered with current approaches in complex environments and outlines a series of research questions for further investigation. These questions are framed as roadblocks to be countered in moving towards the goal outlined in this paper for more efficient (less time and cost), effective, and responsive training.

In responding to these roadblocks, it is important to move towards cognitive models that better explain how personnel are able to learn, adapt and decide in complex environments. Explanatory knowledge of this type is important for optimising training and maintaining mission assurance. To improve a design approach and have confidence that it will succeed, it is important to understand how and why it actually works. This paper notes the recent increased research focus on the computational basis of cognition (for example, the European and US "Human Brain Projects"). This type of mindset is useful in seeking to understand how humans as systems respond to novel situations requiring adaptation. Such knowledge in-turn aids the design of improved training solutions.

The meaning of the term "training" varies across cultures and contexts. In some Defence environments, it is distinguished from "education" as only focusing on routine tasks and "teaching people what to think, rather than how to think". This is in conflict with the increasingly cognitive nature of even basic Defence tasks (e.g. operating a vehicle with a multimode "glass cockpit"). It also conflicts with the common use of the term when discussing decidedly cognitive activities based on reasoning and deduction (e.g. "medical training", "chess training", "decision-making training" etc). In this use, "training" refers more to task or role-specific learning, as opposed to the general learning that is associated with education. This paper uses "training" in this broader sense. It focuses on preparing individuals for specific roles and holds that while routine capabilities are the foundation for expertise, non-routine tasks and knowing "how to think" are essential for all contemporary Defence personnel.

GOALS FOR SIMULATION-BASED TRAINING IN DEFENCE

Pragmatically, Defence expertise is associated with exerting will over a situation, given sufficient means. It is a capability to achieve preferred futures, rather than being swept along without control to a future that is not preferred. To be viewed as an "expert" in a particular environment or field, an individual should need to reliably display a capability for shaping the future to their will, compared either to the relative capability of other individuals or an agreed standard.

A capacity for exerting will cannot be directly transferred from one person to another. It can only be *constructed* by experiencing specific scenarios within the work environment and extracting insights for improving future performance. Beginning with limited initial capacity, personnel encounter events, attempt to manage the situation, observe the outcomes, and build capacity through learning. Over time, the range of events and the degree of control ideally increases to the defined "expert" level.

Training could be viewed as a planned process to build this capacity. Ideally, a training design should selectively sample from the environment to provide the experiences, feedback and learning opportunities to improve with maximum efficiency. This supports a process of "accelerated expertise", in which personnel gain experience with situations that they might otherwise only naturally encounter over many years. Events should be deliberately planned as practice opportunities for eradicating existing performance weaknesses (Ericsson, 1993). These events should be presented in an order and environment in which, personnel are able to manage each situation, and sequentially progress to a higher level of capability. Events are challenging without being impossible. By contrast, events in normal work can occur without any concern for learning or the capabilities of personnel.

From this perspective, experts are personnel who have taken the right lessons from the right experiences to be able to extract the maximum from the opportunities and means available to reliably exert will over the environment. This agrees with the theory of naturalistic decision making (NDM), in which experts leverage past experience to recognise familiar cues and automatically recall goals, actions and expectancies for how the situation will develop. From a variety of experiments (see Klein, 2008; Simpson, 2001), this process is believed to account for up to 95% of expert decisions in real-time operations (Kaempf et al., 1996; Endsley, 2001). The stored experience of experts is usually sufficient for them to react without even being consciously aware of having made a decision (Klein et al., 1986; Klein, 1989). Experts instead experience a "flow" in which they have the sense of constantly knowing what to do.

After undertaking training, it is expected that trainees will be able to achieve ends in the environment that were previously beyond their capability. For standardisation and assuredness, personnel in modern Defence Forces are assigned to "jobs"/"roles" defined by specific expected capacities. Through a formal TNA, training is usually expected to provide the basic capability for the role. While this capability will be enriched over time through experience, personal reflection, and further formal and informal learning, training provides the foundation for this development and at minimum allows personnel to operate safely and effectively. In this sense, the initial TNA is supposed to be a guard against sending personnel into operations unprepared.

Stakeholders expect personnel to be able to adapt and deliver the ends required for successfully achieving mission objectives. Training designers are expected to provide the sequence of training activities and opportunities for feedback and deliberate practice required to reach this point. Simulator and computer-based training developers are expected to provide the materiel and training technologies to support this effort. In Defence, the focus is operational capability. All training systems and technologies are a means to this end.

These issues have provided the framework for the training-based research completed as part of the DSTO-RSA collaboration.

- Training has been viewed as a scenario-based process to provide the right experiences and feedback for learning. For each trainee, the challenge is to find the limited set of situations and inputs amongst the infinite possibilities that will make the greatest contribution within the available finite training time. These situations must be sequenced to build toward a required level of capability. Each step in the sequence must be difficult for the trainee without being impossible.

- Simulation and computer-based training have been viewed as the technical means to provide this experience and feedback within a holistic curriculum. The challenge is to provide cognitively and physically “authentic” systems that allow trainees to learn the cues, expectancies, goals and actions associated with expert performance (see Harris-Thompson et al., 2006) within the time, resource, assuredness and logistic requirements of Defence.

- Using a pragmatic perspective, expertise has been viewed as an ability to achieve ends. This links with the Defence focus on operational capability and combat power. The challenge is to unpack the requirements for these ends through the TNA to understand how this capacity can be built from experience and feedback provided in training.

In combination, these requirements create the further challenge to design a training system that is:

- *Efficient*: It is preferable to gain the required capacity using less time and resources than more.

- *Effective*: Training is pointless if trainees are learning the *wrong things* or if they are unable to apply the learnt capabilities when needed. Similarly, in the unforgiving Defence environment, personnel do not get the option of exiting the situations they encounter simply because they are unfamiliar or unexpected. Safety and mission success can depend on solving a problem that has never been seen before. To manage this threat, training must support personnel in adapting to novel situations on the basis of finite knowledge and preparation.

- *Responsive*: The Defence environment is subject to emerging threats, technological change, and sudden shifts. Training must detect new requirements and be prioritised to support rapid mobilisation. Equally, training should respond to the requirements of individual learners.

THE HISTORIC TRAINING SITUATION

Long established processes exist for meeting these training requirements in routine and predictable environments. By being able to predict and step through the specific situations that will encountered, a role can be deconstructed into successively smaller tasks and sub-tasks. These can be identified in entirety and trained against measurable standards (see USAF, 2002). In combination, they can provide the complete capacity for the role.

More recently, the focus has shifted from tasks to “competencies”, which can be viewed as the individual abilities that collectively allow for the achievement of the ends required for the role. In completing the TNA, these competencies are divided into simpler “elements of competency”, which are in-turn divided into supporting "knowledge", "skills" and "attitudes". A hierarchical, reductionist perspective is assumed where difficulty can be managed by subdividing a system into successively smaller and simpler pieces. Capability is understood as being able to "know things" (knowledge), "do things" (skills), and work within a particular mindset (attitudes). This framework is currently mandated in the ADF as part of the Defence Training Model (DTM) (Australian Defence Headquarters, 2007). The DTM is in-turn derived from the competency-based system used in the Australian civilian Vocational Education and Training (VET) sector.

In the modern interconnected Defence environment, individual personnel have greater responsibilities than ever before, as reflected by the phenomenon of the "Strategic Corporal". They can be globally deployed to situations that were never anticipated with the expectation that they will find a solution when they arrive nonetheless. This is compounded by technological advances, the increased potential of modern weapon systems, and improvised and unconventional enemy tactics.

These factors place far greater emphasis on the ability to adaptively recombine foundational skills to respond to unfamiliar situations. These skills can be viewed as "capability elements" that can be combined on a just-in-time basis to form a wide range of *emergent* behaviours (i.e. complete novel work procedures) that vary with the environmental conditions. In this sense, the term "elements" has been used to invoke the analogy of chemical elements and chemistry, as opposed to the linear output that can be associated with the more familiar term of capability "bricks".

With an ability to combine the capability elements, a large number of solutions can be created from a smaller collection of basic capabilities. If a situation is encountered without a known solution, the elements can be combined to "synthesise" a new response. This provides the theoretical means for managing a vast range of situations on the basis of finite knowledge and training time.

From this perspective, military expertise is built upon basic knowledge, skills, procedures and standards. To free cognitive resources for higher decision making, these capability elements must be trained until they can be completed automatically with high reliability. Personnel cannot efficiently adapt or display more advanced capability without this sound foundation.

Adaptability is essential to distributed command and control and network centric warfare. The process of providing personnel with additional real-time information presupposes that they are actually able to use it to adaptively keep pace with the changing situation and continue finding actions that move towards the Commander's Intent. In unfamiliar situations, non-adaptive personnel could easily be overtaken by events or unable to find a suitable response, even with greater information and freedom of action. It is the human element that bridges the gap between the potential of networked distributed command and control and actual combat power. The technical means alone have no operational effect without adaptive personnel to exploit them.

Similarly, by being able to recombine basic capabilities to create new solutions, personnel are able to extend the range of situations they are able to control. Conversely, for a given range of situations, personnel can rely on learning a smaller set of capability elements and the means to adaptively combine them, as opposed to having to learn the rote response for each situation. In addition to increasing efficiency, this also allows personnel to robustly adapt around problems if the rote response fails. These factors provide a better and lower cost training solution. As the situations become more unpredictable or exceed the available training time, this approach becomes essential for mission assuredness.

DSTO-RSA RESEARCH

These issues have been investigated through a series of RSA technical reports written for DSTO between 2009 and the present. Much of this work has been completed in the context of LAND 121. The research methodology has followed a qualitative "theory building" approach. This has involved reviewing the international literature and numerous Defence training case studies to build a model for the type of adaptive, simulation-based training and education required. The reports have focused on providing practical guidance to DSTO and Army, including the Army personnel responsible for designing and providing LAND 121 training. In the longer term, this input might be converted to formal training and simulation design guidelines to supplement the existing competency-based ADF DTM.

An important issue has been to understand the limits of existing task and competency-based TNA and training design *methodologies* for supporting greater adaptability. The literature notes numerous issues, including difficulties assessing unobservable "cognitive tasks" (Stanton et al., 2004; Wei & Salvendy, 2004; Harris-Thompson et al., 2006) and an inability to manage unexpected, potentially safety critical situations that cannot be predicted and unpacked in advance (Vicente, 1999; Vicente, 2000; Naikar et al. 2005). Beyond basic skills and routine activities, fixed tasks in general are vulnerable in the face of a thinking enemy attempting to create confusion and counter the planned course of action (Luttwak 1987).

The impact of these issues from the perspective of training designers and simulation developers has not been extensively discussed in the literature. To respond to this shortfall, a technical report was completed reviewing the literature and assessing the issues that would be encountered in completing a TNA for LAND 121, particularly given the cognitive adaptability required to exploit the new networked Battle Management Systems installed in the vehicles. Based on these issues and practical experience completing TNAs at RSA, four main difficulties could be summarised:

- Through emergence and complexity, highly variable and adaptive behaviour can be generated from far simpler underling processes interacting with each other and the environment. This ability to generate complexity from simplicity is the power of the capability elements concept. As a consequence, however, it is also extremely difficult to reason in reverse to identify the underling capability elements from the observed emergent behaviour. This does not mean that the elements do not exist. It simply means that they are difficult to find given the holistic and situated information available for analysis. TNAs can become massive documents unable to find a simpler description than the observed complex behaviour. Alternatively, with an inability to identify the capability elements more precisely, the TNA can become an expensive and uninformative exercise in defining vague, generically-stated "competencies" for "decision-making", "managing difficulties", "responding to contingencies", "displaying leadership" etc.

- Without a model of how people learn complex skills as a dynamic combination of existing basic capabilities, it is difficult to know how to structure the training tasks to support optimal learning. While it is known that personnel can adapt from basic capability elements given sufficient feedback and opportunity to practice, it is unclear *how* this actually works. Improved knowledge in this area could increase training efficiency and reduce training time and costs.

- High level expertise is characteristically non-verbal. It is well documented that experts are able to display high performance within a domain without being able to explain how (e.g. most people find it easier to drive an actual car, for example, than to try and verbalise the processes involved). This suggests that there are fundamental limits in trying to describe "knowledge", "skills" and "attitudes" in a written paper-based TNA (Guthrie, 2009). This can result in uninformative TNA line items that fail to adequately describe expertise within the domain (e.g. "use workplace technology", or "apply planning and organising skills to own work activities").

- Modern work often requires significant knowledge and skill. The sheer volume of information can be underestimated prior to analysis. This "knowledge bottleneck" was a significant roadblock in attempting to capture expert knowledge within artificial intelligence "expert systems" in the 1980s. With the time and resources available for a typical TNA, analysts can again be forced to use surface level descriptions that fail to properly describe expertise within the work domain.

In effect, as the environment becomes too large and/or complex to predict in advance, the demand shifts from predefined declarative procedures and abilities to the recombination of a finite set of potentially non-verbal capability elements on a just-in-time basis. This dynamic, situated process of building a novel solution is also not easily captured in a written, static, decontextualised TNA, especially without a model describing the mechanics of the adaptive process.

In this and subsequent technical reports, a series of research questions/"roadblocks" were identified for finding a solution to these issues. This has provided a direction for further research. The roadblocks include:

Inert Knowledge and Capability Elements

The capability elements concept potentially allows personnel to dynamically assemble just-in-time solutions as the situation is encountered and more information becomes available. Being able to access and utilise this extra information offers a potentially critical decision-making advantage. This can be compared with the lack of information associated with trying to anticipate and plan for unseen hypothetical situations in advance.

For the capability elements concept to succeed, personnel must have a sufficient store of elements to cover the current situation, equivalent to a chef requiring sufficient basic ingredients to cook a particular meal. Equally, the capability elements must be organised to allow the most applicable elements to be recalled and applied on the basis of the available cues from the environment. If these cues are not detected or the access process fails, unworkable or lesser solutions can be pursued while the actual capability required to manage the situation sits in memory as "inert knowledge".

Inert knowledge is a common element in expert decision failures (Endsley, 2001). Reviews will often demonstrate that personnel possessed the capability for success, but either failed in execution or applied the *wrong* knowledge and skill due to misreading the situation.

At present, the basic capability elements are a necessary but not sufficient condition for adaptability. Personnel can have the required capabilities, but still not be able to find a solution, just as possessing the basic ingredients is not the same as having the ability to combine them to cook a gourmet meal. By understanding inert knowledge, training could be designed to ensure personnel gain greater benefit from the basic capability they possess.

Systematically Identifying Training Needs

In complex environments, training needs analysis is a process to identify the basic capability elements. It involves identifying a limited amount of capability that will nonetheless allow personnel to safely complete the mission, even though all situations cannot be specifically identified in advance.

While excellent methodologies are available for collecting input about the cues, expectancies, goals and actions used by experts within the domain (e.g. cognitive task analysis, critical decision method interviews), this assessment mostly relies on specific scenarios of note recalled or presented to subject matter experts (SMEs). Additional processes are required to systematically assess the entire role to ensure that important capability elements are not overlooked. Crucially, these processes must be workable with the time, resource and SME limitations encountered with typical TNAs. As roles become more complex, analysis must counter information bottlenecks by better understanding the adaptive process and the core capability elements. It is not sufficient to simply create larger and increasingly unusable TNA documents.

A TNA is similar to requirements analysis in engineering. In both cases, a higher level goal is deconstructed into simpler components (i.e. learnable competencies, designable sub-systems). These are built (i.e. though training and manufacture respectively) and integrated to achieve the original performance specification. Significant research has been invested in requirements analysis to avoid missing or incorrectly describing system requirements. This has included the development of numerous methodologies and software support systems. Further TNA research should be completed to leverage this development.

Knowledge Elucidation and Storage

Better processes are also required to store the outputs of the TNA. Current solutions still mostly result in large written documents with inherently limited descriptive power. Advanced research in this area is actually being completed more in engineering and the biosciences (see, for example, Schmidt, 2006; Warwick & Norris, 2010; Qu et al., 2010; An & Christley, 2011). In response to rapid increases in domain knowledge and the increased complexity of contemporary projects, research in these fields has focused on capturing and representing information using simulation and functional computer models. This offers numerous advantages over written documents. Extending these concepts to training needs analysis and training design could improve training efficiency and increase the opportunities for organisational knowledge management and transfer.

These issues also extend to procedural learning. As the complexity of the work environment increases, the volume of data makes rote learning fixed procedures inefficient outside of the most common or safety critical cases. Future training systems and designers must focus on compressing these procedures to simpler rules, motifs and sub-routines that will robustly generate the full procedures when combined and applied to the environment. This process of finding a simpler set of rules to describe/generate a larger body of information is common in information science. Concepts from this field could be applied to improve the efficiency of training.

Providing Feedback

Feedback is crucial in assisting trainees to extract the right lessons from experience. With limited domain knowledge, novices often lack the background to properly assess their own performance or separate important environmental feedback from meaningless background noise (Kirschner et al., 2006). Similarly, the mental effort required to manage an unfamiliar scenario can leave reduced capacity for further reflection and analysis (Paas, 2003; Kirschner et al., 2006). Instructors are left with the difficult challenge of providing the right type and amount of feedback and support/“scaffolding” for different individuals, while also trying to maintain trainees in their “zone of proximal development” where training is neither too straightforward nor difficult.

Paas et al. (2003) frame these issues from the perspective of cognitive workload. Under this model, training can be assessed in terms of the “intrinsic” load required to complete the task, the “germane” load required for learning, and the “extrinsic” load required in dealing with outside factors in the environment and the training program itself (e.g. reading course materials, navigating the user interface of a CBT etc). While the extrinsic load should be minimised to free capacity for learning, at any moment for any individual the training program must ensure that the combined intrinsic and germane load does not exceed available cognitive capacity. If this capacity is exceed, training will be too difficult and the process will fail. Conversely, if this load falls far below capacity, training will be too simple and un-engaging. If trainees are operating with excess free resources, this also suggests that the efficiency of the program could be improved. This workload model of learning provides a more concrete theory for dealing with the abstract “zone of proximal development”.

Crucially, as personnel gain experience with a particular task, there is a definite progression from initially conscious and deliberate knowledge-based behaviour (KBB) to unconscious skill-based behaviour (SBB) where the task can be completed automatically with minimal cognitive effort (Rasmussen, 1983). This concept provides an additional insight for identifying suitable levels of support. At all times, the training program should ideally keep the combined intrinsic and germane load close to cognitive limits. As competency is gained and processing for the current tasks moves from KBB to SBB, the level of cognitive load will be reduced. At this point, the training program needs to move forward at a suitable rate of difficultly to return the load closer to the cognitive limit. From this perspective, scaffolding is a control mechanism that takes the current form of processing and the intrinsic and germane loads as inputs to constantly maintain the overall cognitive load near but below the cognitive limits of the trainee.

With further research, it is plausible that biometric measures could be used to track cognitive load and enable CBT systems that automatically adapted to an individual learner’s zone of proximal development. At present, however, the total training requirements are usually passively deconstructed into simpler modules according to the judgement of SMEs and the training designers. The use of performance data and biometric measures to optimise the training program for a specific individual is an on-going area of interest at DSTO.

CONCLUSION

This paper has framed training as a targeted process for equipping personnel with the capability to achieve operational ends. This capability is constructed through experience and feedback provided by specifically selected scenarios and learning opportunities. In a Defence environment, this input is provided through physical exercises and/or the technical means of simulation and computer-based training.

Defence expertise is built on a foundation of basic skills, tactics, techniques, procedures and standards. To maintain robustness under the stress of operations and free cognitive resources for higher level reasoning, these "capability elements" must be trained until they are automatic. Existing task-based training approaches provide a proven solution for this requirement.

In the modern Defence environment, personnel must also be able to combine these elements to adapt on a just-in-time basis as situations are encountered and more information becomes available. This is essential in managing uncertainty, responding to emerging threats, and exploiting opportunities to seize the initiative.

The ability to combine these elements should not be assumed. Personnel can have the basic ability for success, but be unable to bring the pieces together to find a solution. In this sense, greater adaptability is important in allowing personnel to operate closer to their existing potential, in addition to being better able to manage unexpected and unfamiliar situations.

Adaptability is also essential for achieving greater efficiency in training. If personnel are able to successfully combine simpler basic capabilities to solve novel problems, the total space of situations that can be managed is greatly increased. This involves far less cost, time, and trainee effort than attempting to rote learn solutions for each individual situation, assuming these situations can even be identified in advance at all. As such, while adaptability is essential for managing uncertainty, it is also essential for managing large training tasks, particularly when even minor disturbances can potentially cause rote solutions to fail.

This paper has presented a framework for considering these issues. It discusses the strengths and weaknesses of existing training approaches and presents a series of research directions/"roadblocks" to be countered in supporting more efficient, effective, and responsive training. Further international research in these areas would be highly beneficial.

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