Simulation-based Military Training: An Engineering Approach to Better Addressing Competing Environmental, Fiscal, and Security Concerns

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Abstract

Governments and militaries have long recognized that armed forces must engage in training in order to develop and maintain the proficiency necessary to effectually carry out those legitimate duties with which they are entrusted by their nations. This is made particularly salient by the increasing demands placed on individual members of the Armed Forces because of reduced staffing and increased task complexity. Yet training comes at a significant financial cost: roughly one third of the total defense budget in fiscal year 2012 is devoted to training. Moreover, military operations directly impact the environments in which they are carried out, while also burning significant quantities of fossil fuels. Broad societal, government-wide, and Department of Defense commitments to improved environmental management together with fiscal austerity measures enacted in response to the financial crisis will increasingly bound the scope of training operations, potentially limiting their utility. Often the challenges these bounds bring are approached only as a zero-sum problem of balancing interests, as exemplified by the 2008 Supreme Court trial over sonar training by the U.S. Navy. However, scientific advances have improved the understanding of physical phenomena and, together with innovations in modeling techniques and advances in computational power, this has enabled simulation-based training to augment live-action training for many military applications. In this paper, sonar training serves as an example through which to illustrate in broad overview the scientific and technological advances that have enabled enhanced capabilities for simulation-based training. It also provides a framework through which to examine how these technologies should be best developed to address the unique demands imposed by environmental, fiscal, and security concerns. Beyond enhanced knowledge of the ocean environment, improved models of sound propagation and scattering within that environment, and new algorithms for real-time computation, effective simulation-based training also requires an understanding of how the learning process is mediated by the fidelity of the simulation. This, in turn, impacts the efficacy of simulation-based training and the cost of developing a training system. Such considerations are a necessary part of any system-engineering process if it is to ensure that a training technology satisfies the diverse demands imposed on it.

Introduction

THE ARMED FORCES are the institutional embodiment of the responsibility legitimate governments have to protect their political communities from foreign acts of aggression that endanger life and property. Right exercise of this responsibility requires that governments ensure that armed forces are capable of effectually responding to aggression and that their response will conform to the laws of war. Both requirements are realized through military training. Readiness requires that militaries develop and maintain equipment and personnel capable of rapid and efficacious response to threats. Proficiency requires that militaries develop and maintain within their personnel skills necessary for combat. Long-term trends toward increasing task complexity and reduced staffing complicate fulfilling these demands, by placing greater demands on training to convey larger amounts of complex information in shorter periods of time.

Thus, training is a necessary and essential component of maintaining a standing military. But it is not without significant cost and consequence. The time, materials, and infrastructure necessary to conduct training all have substantial economic costs, as do wear and tear to military systems that result from training. In fiscal year 2012, roughly one third of the total defense budget is devoted to training – a figure that only partially reflects the full financial costs [1].

Training operations also can have both immediate and long-range environmental effects. Direct environmental disturbances that result in immediate effects include acoustic and thermal emissions together with impact on air and water quality from byproducts of combustion. Over a longer timescale, use of munitions in test ranges presents possible risks for soil, water, and groundwater contamination from unrecovered munitions and a direct risk to human and animal life from unexploded ordnance. At still longer timescales, military training operations impact climate change through use of fossil fuels.

Moreover, members of the Armed Forces participating in training operations – particularly live-fire exercises – face significant physical risks including loss of life [2]. Just as it is imperative for the military to minimize total casualties during active operations, so is it imperative for them to do so during the preparation for such operations.

Because there are compelling reasons for both conducting and limiting training, the situation seems to present a problem of balancing two competing obligations: an obligation to conduct training sufficient in scope to maintain the readiness and proficiency of a standing military, and an obligation to limit training in order to better steward fiscal, environmental, and human resources. Arriving at a compromise between these obligations may be possible [3], though there is substantial disagreement over the proper balance [4, 5].

The present approach to resolving the competing obligations, particularly as it has been decided within the U.S. courts, relies on assessing the "balance of interests" between two parties within government or between government and another party. This reasoning, which decides based upon which party has a more compelling interest, is exemplified by the 2008 Supreme Court decision on the case between defendant Secretary of the Navy Donald C. Winter and plaintiff Natural Resources Defense Council, Inc. (NRDC). Writing for the majority, Chief Justice Roberts summarized in the opinion the court's assessment of the balance of interests:[6]

> We do not discount the importance of the plaintiff's ecological, scientific, and recreational interests in marine mammals. Those interests, however, are plainly outweighed by the Navy's need to conduct realistic training exercises to ensure that it is able to neutralize the threat posed by enemy submarines.
>
> Military interests do not always trump other considerations... In this case, however, the proper determination of where the public interest lies does not strike us as a close question.

While the opinion in this case rejected a limit on military training, two prevailing trends suggest that the frequency and scope of training will decrease in the future. The first is a series of fiscal austerity measures enacted in response to the financial crisis, which will likely extend across all elements of the Department of Defense (DoD). The second is a broad growth in societal commitments to improved environmental management that are increasingly finding regulatory embodiment in laws and policies. The risk posed by limiting training operations is that smaller scale operations may trade utility for other gains so that, ultimately, they are less cost effective.

Simulation-Based Training

Simulation-based training provides a technological alternative that resolves the tension between obligations by effectively mitigating the competition between their demands. Rather than conducting training in the conventional manner, simulation-based training uses computer-generated virtual environments to augment or replace portions of the real environment. By doing so, it can often reduce or limit risks to the participants and the environment while reducing overall costs. Provided that, in so doing, it can also ensure proficiency and readiness are achieved, simulation-based training can better jointly meet the broad scope of obligations faced by training operations.

There is a long history of use of simulation technology for training operations [7]. Today simulation technology employed by the military spans a broad range including desktop flight trainers derived from commercial products, immersive virtual-reality training environments, and complex tactical team trainers comprising multiple sites each replicating the physical environment of one or more military platforms.

The recently developed primer on modeling and simulation from the National Training and Simulation Association defines modeling as "the representation of an object or phenomena," which "may be mathematical, physical, or logical representations of a system, entity, phenomenon, or process" [7]. Simulation, in turn, is defined as "a representation of the functioning of a system or process," comprising the collective functioning of one or more interconnected models that together predict the time evolution of a system [7].

Systems for simulation-based training, as depicted schematically in Figure 1, comprise simulation, with various constituent models; environmental and other databases, which serve as input for models; and rendering algorithms, which enable presentation of simulated data to users.

As depicted in Figure 2, simulation-based training exists on a continuum, ranging from augmentation of the real environment with simulated, virtual entities to fully simulated, purely virtual environments.

Likewise, rendering takes various forms depending on the mode by which those being trained interact with the output of the simulation. These include (1) first-person presentation, as in immersive virtual reality; (2) third-person screen-based presentation, as in video games; and (3) technology-mediated presentation, as in radar or sonar training for which simulation output replaces real-world input to standard technological interfaces.

In the first case, simulation output is rendered to sensory transducers (such as display goggles and headphones). In the second case, simulation output is similarly rendered to sensory transducers (such as display screens), but from a third-person perspective. In the third case, simulation output is rendered as the output of data from one or more sensors that are modeled within the virtual environment.

The distinction between the first and second modes of rendering is quite fluid, as demonstrated by video games that adopt a first-person perspective. Such a distinction relies upon assumptions about the ontological status that trainees assign to simulation. However, the ontological status afforded to simulation – the subjective sense of whether something is "like real life" – cannot be described meaningfully in such simple terms. An alternate approach, discussed later in this paper, grounds this subjective assessment in biology, giving an objective basis for understanding the full spectrum over which simulation can be perceived "as real."

Nonetheless, the type of rendering constrains the type of simulation and the constituent models it uses. Rendering bounds the physical and temporal scale and limits over which simulation is carried out. Likewise, distinct display modalities make distinct demands on the physics that a simulation must incorporate. This is particularly well illustrated by the case of simulation-based sonar training.

Simulation-Based Sonar Training

In recent years concern over the risk posed by quiet submarines operating in littoral waters has motivated the Navy to increase their use of active sonar to detect these threats [8]. Though computational algorithms assist human operators, detection and classification of submarines using active sonar is an "incredibly complex" task that requires substantial amounts of training in realistic environments for operators to achieve proficiency [9]. However, some evidence suggests that active sonar may adversely affect marine mammals, in particular, certain species of whale [10-13].

The Navy has used simulation-based sonar training in various forms for more than fifty years [14-15], largely due to the pedagogical, logistic, and cost advantages it offers. Peter W. Singer reports that "the Navy estimates that its use of gaming at bases, in lieu of doing the same exercises at sea, saves it some 4,000 barrels of fuel a year" [16]. Therefore, despite legal decisions that allow for ongoing live training, the Navy has supported development of new simulation-based training. This has included support for the Surface ASW Synthetic Training (SAST) program, which developed simulation-based training for the SQQ-89A(V)15 sonar system that was the subject of Winter v. NRDC [17].

Sonar provides operators with a technologically mediated connection to the physical world; a trait it shares with other military sensing technologies such as radar. More than simply enhancing existing sensory modalities of operators, these technologies categorically extend the human capacity for sensing by enabling distinct new ways of observing the world but displaying the sensing data to operators so they can be perceived.

Of particular interest here is active sonar, in which a sonar transducer emits acoustic signals and uses the returns scattered back from the environment to detect, classify, and localize targets of interest.

Active-sonar systems typically present information to operators through visual displays, auditory displays, and the output of automation algorithms. Each display effectively selects and highlights particular aspects of the data and the underlying physical processes by which it was generated. For example, a conventional A-scan display (a plot of amplitude versus time) for the time series associated with a particular spatial beam provides little or no useful information about the Doppler shifts associated with each return. Neither does a GEOSIT display in which B-scan displays (displays of amplitude mapped to intensity plotted as a function of time) are mapped to range and bearing. However, the equivalent spatial auditory display [18] conveys some Doppler information and a specialized spectral display might convey even more.

Because sonar mediates the connection of operators to the physical world, simulation for sonar can take two distinct approaches. In the first, simulation models the phenomena of the displays themselves and renders the simulation results directly to the displays. Alternately, in the second, simulation models the phenomena of the physical environment and renders the simulation results in the form of virtual sensor output. This virtual data then replaces the data generated by the real world.

The latter approach, termed simulated stimulation (sim-stim), is more computationally demanding and requires greater knowledge of the physics of the environment. However, simulation at the environment level offers significant advantages over simulation at the display level.

Display-level simulation is tied to the particular display and sensor system for which it is developed, making upgrading or repurposing of simulation components potentially costly and time consuming. Moreover, it relies (at least implicitly) on a form of reduced-dimension latent-variables model, which is inherently susceptible to errors if the display data used to develop the models are not truly representative.

A number of recent advancements have enabled broader application of sim-stim simulation-based sonar training. First, advances in computational power via multicore CPU and many-core GPU processors, together with algorithms able to utilize these new architectures to their best advantages, allow real-time computation for scales of problem that were previously intractable. Many numerical techniques in underwater acoustics are amenable to parallelization (see, *e.g.*, [19]), though work is ongoing. Second, there have been significant advances in understanding the physics of underwater acoustics in shallow water. Development of modern high-resolution broadband sonar systems had, until recently, outpaced growth in knowledge of fundamental physical mechanisms of sound propagation and scattering in the ocean, particularly in shallow-water regions for which boundary interactions are significant.

Efforts over the last fifteen years have specifically sought to improve the knowledge of the physical processes underlying scattering from the air/water [20] and water/sediment interfaces [21], which has recently led to development of new computational models.

Similarly, fundamental research efforts have been directed toward the physical mechanisms responsible for spurious target-like echoes (termed “clutter”) [22]. This has recently resulted in new models for scattering from target-like objects in the environment [23] and new models that explain how scattering from boundaries can lead to target-like clutter [24].

While new developments make simulation-based training for active sonar more viable and realistic, it remains necessary to determine how to best utilize new models within a simulation system. Likewise, the level to which simulation is carried out must be determined. Ultimately, all simulation relies on a set of assumed phenomenological models and archival databases to serve as inputs to physics-based models. Simulation-based sonar training must, for example, determine whether the physical properties of the ocean environment will be based on archival databases and heuristic models or computed by coupled ocean/acoustic models [25].

In order to assess the answers to such questions, it is necessary to consider the relationship of simulation fidelity to training efficacy.

Simulation Fidelity and Training Efficacy

Simulation-based training must, when properly employed, result in the desired results of proficiency and readiness. If not, untrained or improperly trained combatants may hinder, impede, or prevent the Armed Forces from performing its functions. Failures of efficacy for training technologies belong to one of three types. First is *omission*, which occurs when knowledge and skills are not taught or fail to transfer from the training environment to the real world. Second is *negative transfer*, which occurs when exposure to training technology results in slowed learning in the real world. Third is *negative training*, which occurs when training results in acquisition of incorrect knowledge, skills, or behaviors. Avoiding these failures requires careful consideration of fidelity and how it is allocated.

In the field of modeling and simulation, *fidelity* describes "the degree to which the representation within a simulation is similar to a real-world object, feature, or condition in a measurable or perceived manner" [26]. Thus, while fidelity is intrinsically measurable, there is no single scale on which it is measured and no convenient means of comparing fidelity. Typically fidelity is expressed in terms that suggest some topological knowledge about relationships (higher or lower, nearer or farther) without knowledge of a metric.

Beyond modeling the physical environment with an appropriate degree of veracity, fidelity requires representation of appropriate complexity in scene, scenario, and tasks. It also requires that joint behaviors such as relations between stimuli and the response environment be represented with an appropriate degree of faithfulness to reality [26-27].

In many cases, efficacy of simulation-based training is governed by the fidelity of the virtual environment. Simulation fidelity is generally thought to enhance the transfer of training from virtual environments to the real world. Moreover, failure to replicate real-life scenarios with sufficient fidelity can produce absent, false, or distorted cues, the consequences of which can be negative transfer and negative training.

For this reason, allocation of fidelity within a simulation is critical. The fidelity with which task-related information, such as perceptual cues, is presented has a direct bearing on the efficacy of the training experience.

The fidelity with which distractors and other elements of the environment that complicate task performance are presented is likewise critical.

However, in other cases, fidelity requirements can often be relaxed. In doing so, suppressing artifacts associated with lower fidelity – and thereby avoiding creation of false or distorted cues – is generally more important than reproducing phenomena that are not task related.

Yet, it is also necessary to reject the "naïve but persistent theory" that fidelity alone is sufficient to ensure efficacious training [28]. Simulation alone is not training, but serves the purposes of a broader training program [29]. Therefore failures of omission can result from the training design in which simulation is employed. To avoid omission it is also necessary that simulation fidelity be matched to the training design. This is not trivial because the critical relationships between user, task, and environment may not be known a priori. Moreover, theories of attention and working memory suggest that providing excess fidelity not directly tied to training goals may be harmful [29-32].

Even if relationships between user, task, and environment are replicated, ontological distinctions cause stress, motivation, and consequences to differ between real and simulated environments. The result of this is reduced transfer of training [29, 33]. Efficacy of training depends on the relationships between affective, cognitive, and physical states in the real and simulated environments [34]. For example, to effectively train for performance in stressful environments, task learning and stress exposure must be integrated [35].

These same issues animate consideration of negative transfer and negative training. Designers of simulation-based training must respect the complexity inherent in the process of acquiring new knowledge and skills. In so doing, they will be required to consider the relationships between user, task, and environment, rather than unilaterally "solve" issues through an undifferentiated technological approach.

Unfortunately, in practice, development of simulation-based training often fails to adhere to these principles. Equating high levels of physical fidelity with training efficacy has a long history and remains commonplace [30].

Presence

The belief that improvement of simulation fidelity necessarily will result in enhancement of transfer of skills and learning from a virtual environment to the real world is generally grounded in the notion that fidelity enhances the "sense of being there" – termed "presence" – and that learning that occurs in virtual environments that are experienced "as though it is real" is more likely to have real-world impact.

Presence, being a subjective measure typically evaluated through questionnaires, is rather imprecise and of limited use in developing a simulation-based training system. Thus more recent work has sought to ground the concept in biology.

Functionally, a simulation can be said to have achieved presence if users respond to the synthetically generated proximal cues of the virtual environment as though they correspond to distal stimuli in the real world. This phenomenon, which has also been termed "place illusion" [36], results from virtual environments that are veridical in terms of their congruence with the empirically derived and ecologically adapted cognitive models and methods used for interpreting reality. That is, they reproduce with appropriate fidelity the complex relationships between user, task, and environment.

Mel Slater has described an analogous "plausibility illusion" which he defines as the experience "that the scenario being depicted is actually occurring," which "is determined by the extent to which the system can produce events that directly relate to the participant, the overall credibility of the scenario being depicted in comparison with expectations" [36]. Provided that both illusions are present, Slater argues that "participants will respond realistically."

A related but distinct theoretical framework has been developed by Slater *et al*. [37]. In this framework presence and plausibility, illusions are a response to stimuli that satisfy three requirements: (1) a low-latency sensorimotor loop between sensory data and proprioception (*i.e*., the internal perception of one's own volitional motion), (2) statistical plausibility of sensory data in relation to the empirical probability distribution over environments in the real world, and (3) appropriate correlations between egocentric behaviors and the response of the environment, on both local and global scales. While Slater focused on virtual-reality systems in which humans interact directly with the virtual environment, much simulation-based training is for systems in which connection to the physical world is technologically mediated. Because this interface is unchanged between virtual training and the real world, the notion of presence that is constrained by the "sensorimotor contingencies afforded by the virtual reality system," is problematical or irrelevant. The primary question is whether the simulation can sustain the plausibility illusion, "the illusion that what is apparently happening is really happening (even though you know for sure that it is not)." Requirements (2) and (3) are related to the plausibility illusion largely through reaction of the virtual world and entities in it to egocentric actions, *i.e.,* "correlations between external events not directly caused by the participant and his/her own sensations (both exteroceptive and interoceptive)." Examples include both shadows and echoes that behave in response to the actions of the participant.

The requirements, and particularly the last two, are naturally interpreted within the framework of ecological psychology in general and Brunswig's probabilistic functionalism in particular [38]. From this perspective, presence requires the virtual environment to correspond to empirically derived probabilistic notions about real-world ecology. Requirement (2) reflects the expectation that stimuli will conform to empirical estimates of the probability distributions describing ecological models of the real world. This requirement extends across temporal and spatial scales, including not only naïve physics and cause-and-effect relationships, but also expectations about the narrative structure of scenes [39].

Though it has not been shown, it is likely that this reasoning applies not just to the response of the environment to egocentric behaviors, but also to the naïve physics of task/goal oriented behaviors by other entities or elements in the environment. For example, if the task were to be pursuing an individual in a complex environment, accurately simulating the acoustic response of the environment to the footsteps of the individual being pursued would be important for ensuring users respond to the simulation as though real in the same manner that simulating egocentric responses of the environment have been shown to be in other cases. Task-relatedness, rather than, or together with egocentricity, is likely to be what determines the importance of fidelity [40].

While the functional definition of presence does alter the meaning of the term in some sense, it also removes one of the major failings in application of the term. The conventional view holds that presence, in the sense that a virtual environment is "interpreted as being real" is necessary for transfer of training to the real world [41]. But the universality of this requirement has been generally refuted by a growing body of recent work following the seminal findings of Green *et al*. [42]. This work has shown that perceptual and cognitive skills gained by playing conventional action video games transfers and generalizes to real-world tasks. Yet, these games do not produce a sense of presence in the conventional sense.

This difficulty is largely resolved by the functional definition of presence. While conventional video games typically do not produce a sense of "being there," they do produce neurological and physiological responses that are the same as responses to the real world with respect to those aspects that transfer. For example, Green *et al*. [42] found that training from first-person shooter games enabled players to make decisions more rapidly and accurately in real-world scenarios – a cognitive process for which playing such games evokes the same neurological and physiological processes as real-world experiences.

Likewise, this functional understanding of presence and its effect on transfer of learning accounts for prior findings that simulations that provide a sense of "being there" are required for the acquisition of complex behaviors in virtual environments and the transfer of these experiences to the real world [41, 43], while allowing that simulations that are not immersive, but produce identification with avatars can result in changes in behavior [44].

Presence (as functionally defined) ensures that a virtual training environment is actually training users for a real-world task by ensuring that the simulation engages users in the same physiological and neurological processes they are being trained to perform in the real world. Thus, it is simply a restatement of the anecdotal finding that simulation-based training should ensure appropriate fidelity in representation of task-critical elements of the virtual environment.

Within this framework, the purpose of allocating fidelity to task-related aspects of the simulation is understood as ensuring that the same neurological and physiological processes are used. In the same way, allocating fidelity to components of the environment that complicate the task ensures that the training experience replicates all aspects of cognitive function including load and attentional effects that result from distractors.

Simulation-Based Sonar Training

Determining the level and allocation of fidelity needed for simulation-based sim-stim sonar training requires understanding the display phenomena operators make use of during task performance and how these phenomena map to physical processes. Figure 3 is an example of a taxonomy of phenomena for one particular mode of display, illustrating one particular branch. Additionally, it is necessary to understand the mapping from phenomena observed by operators to models of physical phenomena, as shown schematically in Figure 4. Such taxonomies and mappings provide a basis for selecting the constituent models of a simulation.

Significantly, the understanding of the relationship between fidelity and training efficacy presented previously suggests that not only is the fidelity of simulated target entities important, but also the fidelity of clutter, noise, and reverberation that distract from, or otherwise complicate, the task of sonar operators.

The cognitive processes involved in detection and classification cannot be reduced to pattern recognition alone. They also involve discriminating between similar distractors and are modified by the complexity of the task the environment presents. Likewise, simulation of clutter, noise, and reverberation is important to ensure proper training on the use of automation; such signals can trigger false alarms, which further complicate the task of operators.

Discussion: Cost-Effective Design for Simulation-Based Training Systems

Taken collectively, the new possibilities offered by simulation-based training can enable governments and militaries to provide necessary training for their armed forces able to develop and maintain the proficiency at or above current levels while, at the same time, more fully addressing fiscal, environmental, and safety concerns.

Virtuality also introduces unique benefits. Training can be conducted more frequently because of the enhanced availability virtual technologies allow. Training can also be more flexible, incorporating elements that would be difficult or impossible in live training. For example, virtual training can depict potential threats that cannot be present during live training. Both of these benefits have pedagogical advantages.

However, such gains are neither automatic nor guaranteed. Simulation-based training systems able to fulfill the promise of the technology must be developed in such a way that fidelity is allocated to best achieve efficacy while accounting for inherent limitations and concerns of cost.

Moreover, the tacit assumption that simulation-based training is cost effective is not always accurate. Initial development costs for such systems are high; the technology ages rapidly, which increases the effective lifetime costs; and other alternatives may provide similar performance with lower initial and lifetime costs. Thus, it is only in those situations where the risks associated with live training are high that cost effectiveness is reasonably assured [29].

This relationship can be depicted graphically, as shown in Figure 5. Prudential ethical decisions bound the allowable risk and cost of live-action training in the real world. Training scenarios that exceed these limits on risk and cost must be conducted virtually, if at all. Scenarios within these limits can be conducted as live-action training, but the range of particular combinations of cost and risk for which live training is appropriate are constrained to fall within the area under a curve that is determined by the lifetime cost of effectual simulation-based training. This dependence on costs leads to a family of curves. As new technologies enable effectual training at lower cost, the effective cost limit associated with live-action training is reduced, the risk threshold remains fixed, and the total area under the curve decreases. In practice, the curves associated with effectual simulation-based training are specific to particular training environments and, in some cases, cannot be drawn because simulation-based training is not yet effectual.

Transfer of learning from simulation-based training to the real world cannot be assured through "brute engineering force" that attempts to achieve very high levels of fidelity [29]. Generally, if task and training environment are identical, perfect transfer is expected. This explains the drive for physical fidelity in virtual environments, particularly for technologically mediated weapons systems such as radar, sonar, and unmanned vehicles in which the interface remains consistent between training and real life. But stewardship concerns must balance the goal of ensuring efficacy by achieving high levels of fidelity.

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Figure 1. A high-level schematic of a notional simulation-based training system illustrating the general components and flow of information. While rendering only receives simulation data, the nature of the rendering determines the nature of the simulation (a concept that is depicted here by a dotted arrow). The responses of trainees both alter the rendering (*e.g.*, in response to head motion) and require changes in the simulation (*e.g.*, in response to a change in the signal being transmitted).

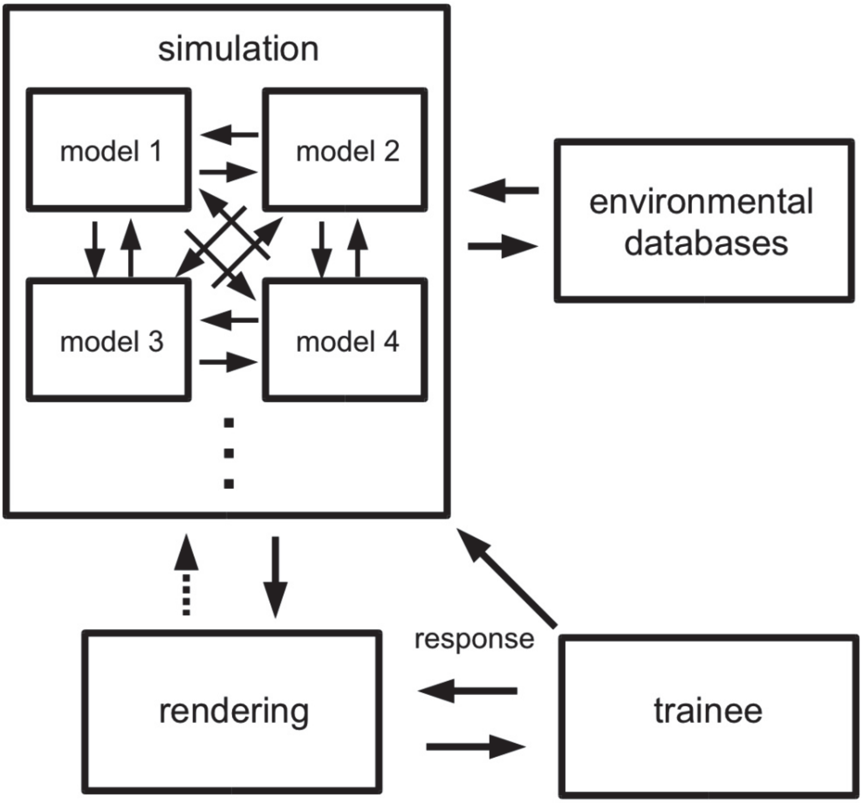


Figure 2. As depicted here, training exists on a continuum between live training, which occurs in the real environment, and virtual training, which occurs in the virtual environment. Between these poles, constructive training uses mixed reality to augment the real or virtual environment.

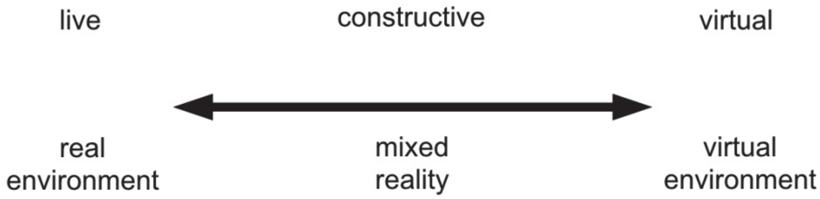


Figure 3. A graphical depiction of a taxonomy of phenomena for active sonar. One branch of the taxonomy is shown for clutter echoes that are discrete, and persistent, such as the echo from a scatterer on the seafloor or a large biological entity.

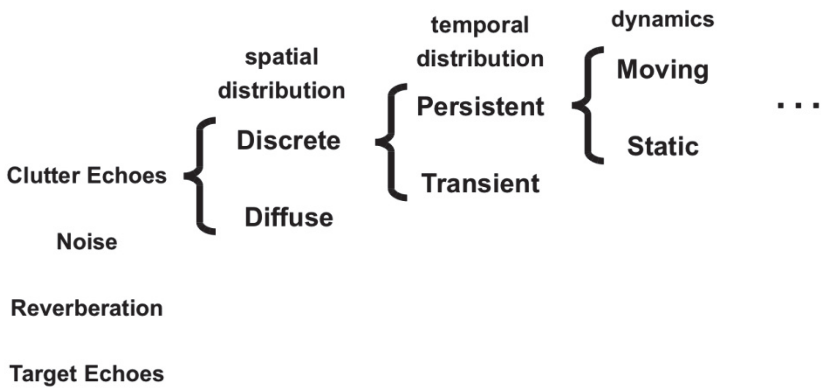


Figure 4. A schematic graphical depiction of the translation from phenomena observed by active-sonar operators, to physical phenomena, to physical mechanism, to mathematical and computational models. The circles show the item under consideration for each category.

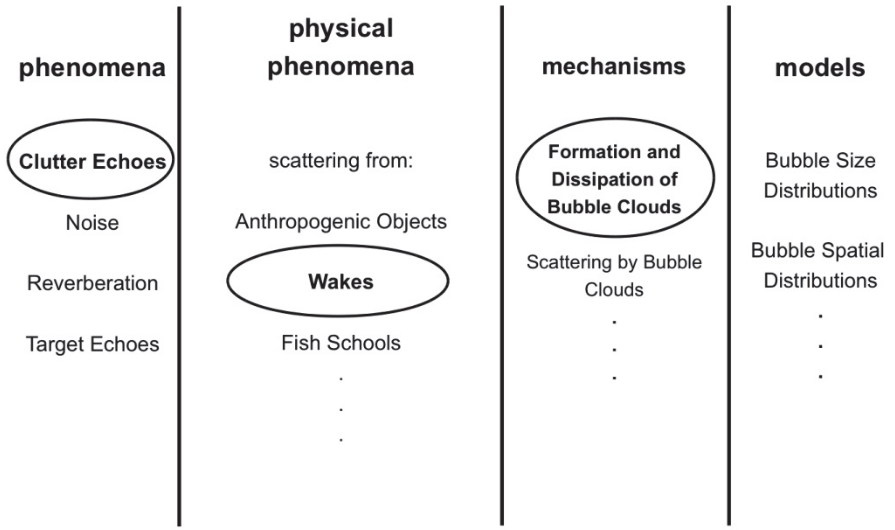
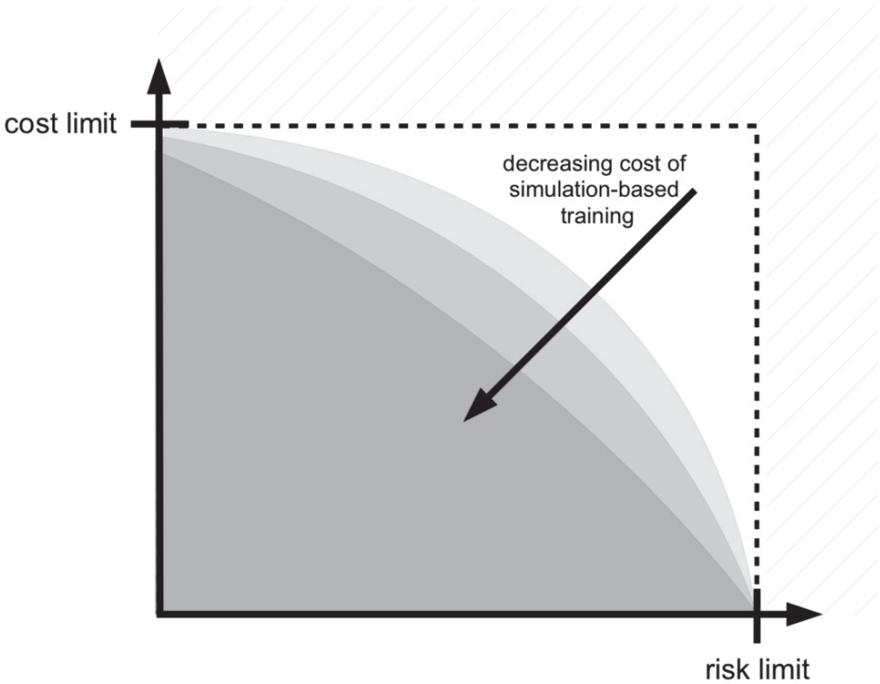


Figure 5. A notional depiction of the cost-risk constraints on the viability of live versus virtual training: only the area bounded by the cost and risk limits allows for live training; in the cross-hatched region training must be virtual, if it is possible at all. The three curves depict varying levels of cost effectiveness of simulation-based training, with the shaded areas under the curves representing the reduced region for which live training is appropriate.



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