Dynamically coupled 3D visualization and real-time simulation as an aid to developing mental models of sonar

Jason E. Summers, Daniel T. Redmond, and Charles F. Gaumond
Applied Research in Acoustics LLC (ARiA)
Washington, DC / Culpeper, VA
jes@ariacoustics.com, dtr@ariacoutics.com, cfg@ariacoustics.com

ABSTRACT

Training sonar operators for Anti-Submarine Warfare (ASW) in complex environments is challenging. Performance deficiencies are the product of errors in both analysis and employment. Experts use mental models to interpret displays and reason about the underlying scenario in order to perform analysis under uncertain conditions and achieve more optimal tactical-system employment. To accelerate the development of this expertise and improve the retention of proficiency, ARiA is developing the Environment for Surface ASW Interactive Learning (E-SAIL™). E-SAIL™ enables operators to visualize the environmental and tactical scenario that resulted in the received sonar signals while allowing them to directly manipulate that scenario and observe the outcome of the manipulation. Here we discuss the theoretical basis for the E-SAIL™ learning approach and overview development of the visualization environment and graphical user interface that deploys on tactical hardware and interfaces with tactical displays, tactical decision aids, embedded simulation-based training (SBT), and environmental databases through a high-performance asynchronous messaging library and software-independent interface specification.

ABOUT THE AUTHORS

Jason E. Summers is Chief Scientist of ARiA and principal investigator (PI) for E-SAIL™. He received the A.B. in Physics from Kenyon College in 1998 and M.S. in Physics and Ph.D. in Engineering Science (Acoustics) from Rensselaer Polytechnic Institute (RPI) in 2000 and 2003, respectively. He currently serves as the PI for multiple projects in ASW and mine-counter measures (MCM) signal processing and modeling and simulation (M&S) for training. Prior to founding ARiA in 2010, Dr. Summers served as Technical Lead for NAVSEA's Surface ASW Synthetic Trainer (SAST). As a Research Physicist with Naval Research Laboratory, Washington, DC (NRL-DC), Dr. Summers developed perception/physics-based classification algorithms for broadband active sonar. As a Postdoctoral Researcher with NRL-DC he conducted physical investigations of scattering from rough elastic seafloors. His current interests include machine learning for classification and simulation-based training.

Daniel T. Redmond is a Software Engineer with ARiA and software lead for E-SAIL™. He received the B.A. in Computer & Information Sciences from Berea College in 2013. Redmond's current work focuses on server-based networks, ontological databases, and computational modeling. In addition to E-SAIL™, Redmond developed the Synthetic ASW Generation Engine (SAGE™), contributing his experience with semantic-web principles to creation of training ontologies and their data manipulation through the use of the SPARQL query language. Redmond has also assisted in development of ARiA's educational video game, WaveQuest. His prior work included the creation of large databases for both Academic and Commercial sectors.

Charles F. Gaumond is a Senior Scientist with ARiA. He received the B.S. in Physics (with distinction) from Clarkson University in 1972 and M.A. and Ph.D. in Physics from University of Rochester in 1975 and 1979, respectively. Previously Dr. Gaumond was Section Head of a signal-processing group at NRL-DC developing compressive sensing for beamforming array data, a new paradigm for human-mimetic classification of broadband sonar echoes, and Broadband Operator Decomposition for Time Reversal (BBDORT). While detailed at the OPNAV ASW Office, he assisted in technical assessment, managing a JASON study of the time budget in the performance of ASW. He has performed program management at the Office of Naval Research in the area of passive sonar signal processing. Dr. Gaumond also developed estimates of target strength for use by other Navy organizations using analytic, numerical, and physical models.

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INTRODUCTION

Among the greatest challenges of training Navy sonar operators to become proficient and ultimately attain expertise in the complex task of sonar analysis and employment is, first, helping them understand and internalize the relationships between phenomena observed on the sonar tactical displays and the corresponding phenomena and environmental conditions in the physical world (viz., mental models of that transformation) and, second, helping them understand how this knowledge of the mapping between the two domains—encoded as mental models—can be utilized to improve tactical-sensor employment. The role of mental models in facilitating expert performance in analysis and employment of surface-ship tactical sonar systems for ASW is depicted graphically in Figure 1.

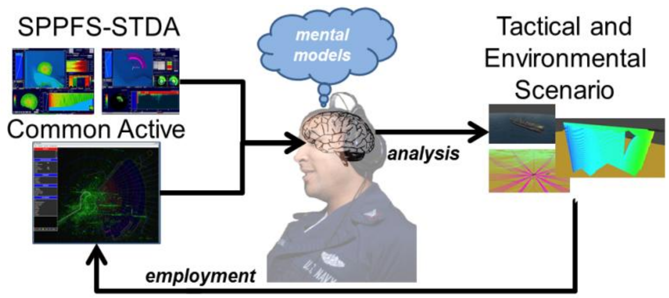

Figure 1. Graphical Depiction of the Conceptual Basis for the Training Approach Developed in E-SAIL.

ASW watch-standing performance deficiencies are the product both of errors in signal interpretation (analysis) and equipment-mode selection (employment). Errors in signal interpretation are well characterized by standard sonar-performance metrics and constitute a failure to correctly perceive, interpret or act on information. In contrast, errors in equipment-mode selection can actually prevent information from being conveyed. An incorrect display setting or failure to consider a particular display mode may result in latent information being overlooked or imperceptible, while a poor choice of operating mode may so restrict the information content of the signal that detection or classification is impossible (Gaumond, Soukup, Baer, & Summers, 2008). Figure 1 illustrates information available to operators: the tactical active-sonar display (in this example the "Common Active" display) and performance-prediction tactical decision aids (in this example the "SPPFS-STDA" tactical decision aid). As illustrated, operators must first employ mental models to parse and interpret this uncertain information to develop an understanding of the tactical and environmental scenario. Operators can then employ mental models and mental simulations together with external tactical decision aids (TDAs) to optimize employment of the system.

Current training products for individual and team sonar-technician (ST) training—both for classroom and on-board use—use actual or simulated tactical displays and software driven by recorded or simulated sonar data for operational training and also for employment training. This approach has the advantage of ensuring fidelity to the actual tactical experience, but has weaknesses as a pedagogical approach in that it inadequately supports trainees learning complex concepts—particularly those mental models and mental-simulation capabilities (Trickett & Trafton, 2007; Christensen & Schunn, 2008) experts use to interpret tactical displays and reason about the underlying tactical scenario in uncertain situations. To address this challenge, ARiA is developing E-SAIL™, the Environment for Surface ASW Interactive Learning. E-SAIL™ enables operators to visualize the environmental and tactical scenario that resulted in the received sonar signals while allowing them to directly manipulate that scenario and observe the outcome of the manipulation.

THE NATURE OF EXPERTISE

Characterization of ASW performance deficiencies as analysis and employment and the employment limitations predicted by the signal-processing model developed by Gaumond, Soukup, Baer, & Summers (2008) are borne out in the empirical studies of passive-sonar analysis and employment by expert submarine STs (STSs) conducted by Kirschenbaum & Gray (2000). In these studies the chief difference observed in the behavior of expert STSs relative to journeyman STSs was the time spent investigating noisy or otherwise uninformative data before taking steps to obtain better quality data. In this schema-directed problem solving, journeymen and experts follow the same steps, but the more extensive and robust cognitive frameworks of the experts (viz., schemata) provide better guidance regarding how to follow through the indeterminate number of steps that adaptively address shallow subgoals (Kirschenbaum & Gray, 2000). Thus, experts may have a better developed strategy (Chi, Glaser, & Farr, 1988) or better employ a common strategy. In the work of Kirschenbaum & Gray (2000), expert operators understood the source of limitations in the data and how to employ the tactical system in order to enhance the information present in that data. Both this rapid analysis and ability to make decisions to enhance received data through more optimal employment require the ability to translate between the display domain and the tactical and environmental scenario.

Anti-Submarine Warfare: A Complex Task

Tasks are complex when they involve reasoning about outcomes that are affected by multiple interacting factors or continuous variables through dynamic and nonlinear processes described by stochastic mappings that need not be one-to-one or onto [see, e.g., (Feltovich, Spiro, & Coulsen, 1993)]. Interpreting (i.e., for ASW analysis) and exploiting (i.e., for ASW tactical employment) the mapping between the real-world environmental and tactical scenario and the technology-mediated presentation on the sonar tactical display is exemplary of such a complex task. Other examples include interpretation of medical images (Lesgold et al., 1988; Feltovich, Spiro, & Coulsen, 1993; Meadows, Wulfeck, & Wetzel-Smith, 2009).

Following the taxonomy of Meadows, Wulfeck, & Wetzel-Smith (2009), ASW analysis and employment is complex because the mapping between world and display domains is *abstract*: all of the relevant phenomena and many of the causes [e.g., sound-speed profiles (SSPs)] cannot be directly observed. It is also extremely *multivariate* with complex correlations between variables.

The mapping is inherently *nonlinear*, in the sense that functional (viz., *causal*) relationships between input parameters—like wind speed, bottom loss, and SSP—and display outputs—like reverberation time/range envelope, clutter location and level, and target signal excess—cannot be described by simple linear functions. Moreover, the physics of underwater sound propagation and scattering is strongly *conditional*: the observable properties are highly dependent on the environment and the sonar-system settings (roughly speaking, boundary conditions and initial conditions).

Sonar reveals to the operator phenomena that are both *simultaneous* and *causal*. Some observable parameters on the display change together reflecting an (unobserved) underlying phenomenon (e.g., an internal wave perturbs the SSP, altering multiple observable aspects of the active display at the same time) while other observable display parameters are (indirectly) caused by observable changes in other parameters (e.g., a surface ship moving in or out of a convergence zone). This has significant implications for learning causal models (Sloman, 2005).

The ability of experts to reason about complex tasks such as sonar analysis and employment that involve dynamic, nonlinear, and uncertain mappings between high-dimensional spaces is predicated on multilayered schemata and causal mental models that enable mental simulation. In ASW analysis and employment, the internal models used by experts allow them to simulate the mapping from the domain of environmental and tactical scenarios to the range of tactical display configurations. ASW is a complex task in part because the mapping between domains need not be one-to-one or onto (i.e., injective, surjective and, thus, uniquely invertible).

Schemata and Mental Models

Experts achieve high levels of performance through use of cognitive representations of domain knowledge: *schemata* and *mental models*. Schemata are conceptual structures for representing, storing, organizing, and using knowledge in a domain. They represent objects and their relationships to other objects, situations, events, and sequences of events. They contain information about categories of objects in general (e.g., submarines) and specific information about objects that are members of a category (e.g., Kilo class submarines). Schemata affect the way knowledge is received and interpreted. Through schemata experts represent the problems they encounter at a deeper, more principled level than novices (Chi, Glaser, & Farr, 1988; Lesgold et al., 1988), which enables more efficient use of short- and long-term memory. The same schemata that enable deep reasoning also enable experts to better recognize targets given noise or variations in how the targets present (e.g., multipath time-spread/smearing and aspect-dependent target strength).

Mental models are essential tools by which humans interpret (i.e., segment and understand) reality (Zacks & Tversky, 2001; Zacks, 2004; Sloman, 2005). Like schemata they embed knowledge about object and actions, but they also implicitly encode causal structure by describing physical quantities such as position or speed in terms of ordinal or relative relationships (Trickett & Trafton, 2007; Christensen & Schunn, 2008). This enables mental "what if…?" simulation of outcomes—even where there is no prior experience of the exact input or output conditions. For this reason, mental simulations are run under situations of uncertainty to turn that uncertainty into approximate answers by generating possible mappings (Christensen & Schunn, 2008).

To achieve expertise in analysis and employment, STs must develop facility in inferring from multiple observable properties the unseen cause of phenomena and predicting the results of changing one or more of those variables. Mental models and mental simulation enable STs interpreting and analyzing information presented by the tactical displays and their ability to more optimally employ the tactical system to obtain better or more-complete information (Kirschenbaum & Gray, 2000).

Learning Schemata and Mental Models

Schemata used by experts in complex tasks are deep, multilayered structures that better represent the problem space and can be more readily tuned to the specific attributes of the problem (Lesgold et al., 1988). Learning such deep and highly layered structures requires that learners be exposed to *conflict situations* that contradict existing schemata in order to "promote formation of higher-order structures" (Leith, 1968). This concept of cognitive change in response to anomalous data that challenges existing schemata has been more fully developed in the framework of inquiry learning (IL) (Collins & Stevens, 1982a, 1982b; Collins, 1985).

Modern developments of IL [see, e.g., (Hmelo-Silver, Duncan, & Chinn, 2007)] focus on methods of structured and guided inquiry that provide appropriate scaffolding for the learning process (viz., management of working memory) as learners progress through the sequence of steps that culminates in development of new or deeper schemata. However, early development by Collins et al. (Collins & Stevens, 1982a, 1982b; Collins, 1985) conceived of IL dialogue meant to help learners understand causal relations. That is to say, Collins et al. thought of IL as a tool for acquiring mental models by deriving new theories in a particular domain from examples. Specifically, to help a learner acquire a complex model, Collins et al. argued that training should select scenarios that (1) exist at extremal points of the variables, (2) have parameters that span the non-injective/surjective parameter combinations, or (3) provide counterexamples to faulty models by highlighting factors that are insufficient, unnecessary, or irrelevant, in the domain of the mapping(s) for which the learner should acquire models. Similarly, training should propose hypothetical "what if...?" scenarios that provide similar counterexamples. Beyond this, training should provide opportunities for learners to formally articulate hypotheses (viz., mental models) and evaluate those hypotheses by making testable predictions.

This relates to more recent theories of causal learning that contrast learning by *observation* with learning by *intervention* (Steyvers, Tenenbaum, Wagenmakers, & Blum, 2003, Lagnado & Sloman, 2004; Hagmayer, Sloman, Lagnado, & Waldmann, 2007). Intervention (i.e., observer-directed manipulation of the world such that outcomes can be directly observed and causal linkages inferred) has distinct advantages for learning causal relations enabling some causal structures not distinguishable by observation alone to be disentangled, focusing learner attention on specific parameters, and accelerating the learning process.

However, learning by intervention is not without risk; learners probe only those causal relationships they are able to manipulate (Sloman, 2005). Thus, to be effective, a system must expose all of the relevant factors to manipulation. Moreover, for a complex task such as sonar analysis and employment, the manipulation itself must be appropriately scaffolded to ensure that learners understand which parameters they are manipulating and are exposed to relevant parameters. For example, this necessitates provision of semantic labeling for multivariate parametric inputs such as SSP, which have a causal linkage to propagation paths *in aggregate* according to semantic categories that label certain classes/patterns of SSP data (e.g., *surface duct*). Those guidelines developed by Collins et al. for IL serve as a baseline for designing scaffolded processes of learning causal mental models by intervention.

THE ENVIRONMENT FOR SURFACE ASW INTERACTIVE LEARNING (E-SAIL™)

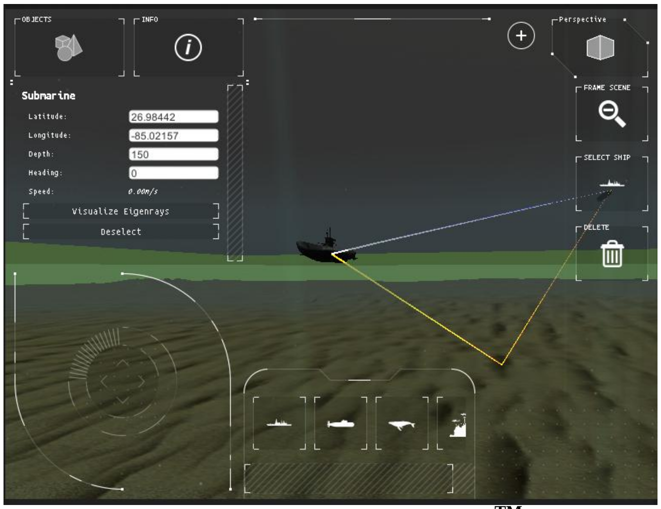

Figure 2. A Perspective View of a Submarine Target from an E-SAIL™ Screen Capture Showing Integrated Display of Eigenray Data for that Target.

E-SAIL™, as shown in the example screen capture in Figure 2, is a unique learning tool for interactive replay and control of data from simulated and reconstructed tape exercises and simulation-based ASW training that supports schoolhouse and onboard training and after-action reviews (AARs). It enhances the ASW knowledge and skill learning and retention of STs by enabling them to visualize the environmental and tactical scenario that resulted in the received sonar signals they observe on tactical displays while enabling them to directly manipulate that environmental and tactical scenario through an intuitive interface and observe the outcome of that manipulation on the tactical displays. This capability for contextualized "what if…?" analysis facilitates training methods, tools, and protocols (individual, team, and game-based) through which STs actively learn and internalize through a guided and scaffolded inquiry process (Hmelo-Silver, Duncan, & Chinn, 2007; Edelson, Gordin, & Pea, 1999) the mental models and mental-simulation capabilities (Trickett & Trafton 2007; Christensen & Schunn, 2008) experts use to interpret tactical displays and reason about the underlying tactical scenario in uncertain situations to achieve more optimal tactical-system employment.

Though use of coupled, interactive simulation (whether TDA overlays or interactive control of SBT capabilities) and intuitive, scaffolded, three-dimensional visualizations of the ground-truth tactical situation and environmental data, E-SAIL™ enables instructors to reveal complex environmental effects and decompose the environment and enables learners to explore and intervene in the environment. By coupling the tactical display with a 3D rendering of the ground truth from the scenario controller of an SBT or reconstructed tape data, E-SAIL™ provides for users a graphical solution to the inverse problem of reconstructing the physical domain from the display domain.

E-SAIL™ provides an interface to external models and simulations (whether performance prediction from TDAs or explicit simulation by a SBT) that replicates the function of internal mental models and simulations. Such external models and simulations serve different purposes for learners and experts. Learners use simulations to gain understanding about the basic concepts that are embodied in models (i.e., to acquire internal mental representations of those models) while experts use external simulations in much the same way as internal simulations: to consider the implications of an already known model for new sets of parameters.

Models and Interfaces of E-SAIL

As shown in Figure 3, E-SAIL™ is a visualization environment and direct-manipulation graphical interface built within a commercial video-game engine that deploys on tactical hardware through the Unity3D platform-agnostic build environment and interfaces with tactical displays, TDAs, embedded SBTs, and environmental databases by sharing data through a platform-agnostic high-performance asynchronous messaging library (ZeroMQ) and a set of platform- and software-independent interface specification (Google Protocol Buffers).

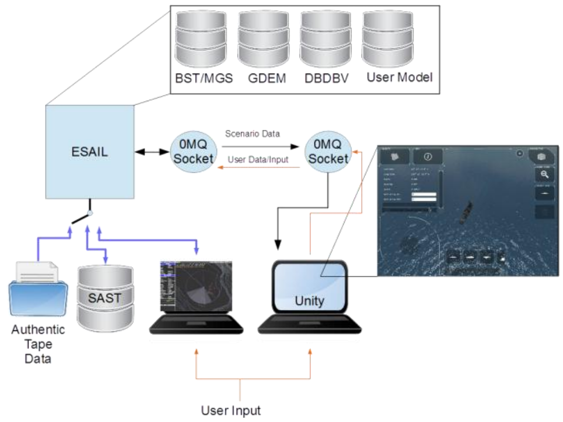

Figure 3. Overall structure of E-SAIL™ for the surface ASW use case shown in Figure 1, emphasizing input/output, standalone software components, and interfaces between them.

The network interfaces and data structures we have developed, built, and tested during this phase of E-SAIL™ prototype development enable:

- users to view real-time motion of entities in the virtual environment based upon scenario data provided by the SBT scenario controller or by the metadata of reconstructed tape data, and
- users to manipulate (e.g., translate and rotate) entities in the virtual environment or manipulate the environment (e.g., wind speed, SSP, bathymetry, bottom type) and have this data passed to the scenario controller such that the simulated sonar data generated by SBT dynamically reflect these changes.

For users of E-SAIL™ to learn and internalize mental models of the mapping between real-world environmental scenarios and the tactical display, E-SAIL™ must accurately visualize those environmental data used in the generation of the sonar data (in the case the display is driven by an SBT) or present when the data were collected (as in the case of reconstructed tape data). This is accomplished in E-SAIL™ by dynamically ingesting and rendering environmental data from archival databases, forecasts/nowcasts, and in-situ measurements including bathymetry, sediment type/bottom province, sea-surface wind speed (mapped to sea state/wave height), and (range-dependent) SSP.

Likewise, to assist operators in forming an understanding of complex environmental and tactical scenarios and the mapping from those scenarios to display phenomena, the models that underlie the simulation of the physical world in the E-SAIL™ virtual environment (e.g., the motion of fish schools or the shape of the surface wake) must provide appropriate fidelity (Summers, 2012a) relative to the physics that generated tape data (to the extent such physics is invertible) and be aligned with the models that drive the acoustic simulation when simulated data from an SBT is used as an input to E-SAIL™ (Summers, 2012b). Thus, E-SAIL™ includes physics-based models for the physical motion of the environment—such as wave height and motion—and clutter entities—such as surface-ship wakes, fish schools (Redmond, Meyer, & Summers 2014), and marine mammals. Motion of targets, ownship, and sensors (viz., towed-array motion and shape) are modeled by the internal algorithms of the scenario controller and those data provided to E-SAIL™ through the asynchronous messaging interface.

Finally, E-SAIL renders within the 3D visual environment and scaffolds (Summers, 2012a) the output of acoustical models and sonar performance-prediction models (viz., TDAs) because displays of physical quantities, such as transmission loss (TL), and derived quantities, such as signal excess (SE), are intermediate structures in the causal models used by experts to reason about the mapping between the physical world and the tactical scenario (e.g., “that surface ship will not be visible on the tactical display because the TL to and/or from its location is too great given the propagation environment”). Similarly, models such as ray-tracing and eigenray plots that serve as graphical aids to interpreting acoustical phenomena are also rendered in the virtual environment. Figure 2 shows an example of eigenrays rendered for a submerged target. Figure 4 shows an example of a full-field TL plot along a bearing of interest.

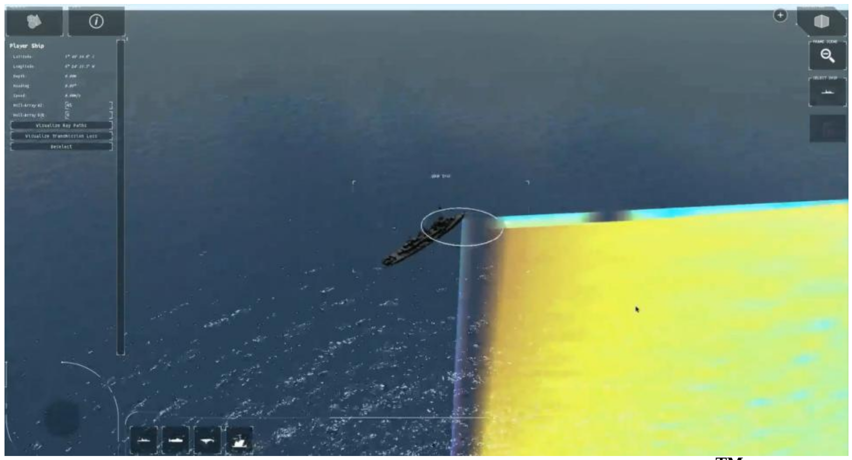

Figure 4. A Perspective View of a Full-Field Transmission-Loss from an E-SAIL™ Screen Capture.

Pedagogy of E-SAIL

E-SAIL™ supports the acquisition of mental models and schemata by providing an extrinsic source of information (i.e., a dynamic 3D visualization) that clearly illustrates for STs what specific environmental and tactical scenario led to the specific configuration on the tactical displays. That is to say, E-SAIL makes explicit the mapping from the domain of environmental and tactical scenarios (i.e., what is happening in the real world) to the domain of tactical display configurations (i.e., what is seen on the display).

While visualization coupled with interactive M&S has had a long and significant role in science and engineering education [see, e.g., (Edelson, Gordin, & Pea, 1999)], the efficacy of these learning tools depends strongly on their ability to scaffold the learning process and appropriately manage cognitive load for the trainees, who may lack perceptual expertise or key declarative knowledge necessary to learn schemata and mental models from the visualization. In E-SAIL™ the presentation of and interface to visualizations and the underlying M&S is adapted to the proficiency of trainees (Summers, 2012a), ensuring effective learning experiences for all operators. Likewise, users are implicitly and explicitly scaffolded through use of embedded models to perform “what if…?” interventions used for causal learning and development of mental models.

To convey information visually, E-SAIL™ borrows from the work of Barton et al. the concept of “gisting” (Barton, Rowland, & Encarnação, 2000). Models and schemata developed by expert sonar operators over years of experience are encapsulated in “information icons” that describe the environment and enable novice and journeymen operators to navigate through “new information space” presented by the tactical displays. Consistent with Schneiderman’s Visual Information Seeking Mantra, “overview first, focus and zoom, details on demand” (Schneiderman, 1996), these “information icons” describe the essential data (i.e., the *gist*). Now familiar as interface elements from uses such as weather icons on mobile-phone and tablet displays, information icons conceal low-priority information and thereby reduce the visual search space, providing an “experience multiplier.”

Learners given control of the deployment of animation sequences obtain a better understanding as compared to those learners without flexible control of animation viewing (Harris, 2012). For this reason, E-SAIL™ tempers use of explicit adaptivity of the display, preferring implicit adaptivity through affordances that enable adaptation to individual users or teams. Novice learners more frequently use bottom-up processing of animation elements (Harris, 2012), which E-SAIL™ supports through user-accessible scaffolding (information icons, textual and visual aids).

Acquisition of Mental Models by Intervention

The central capability to the pedagogical approach of E-SAIL™ is provision for "what if…?" interventions by instructors and learners, together with intrinsic and extrinsic scaffolding of the process through intuitive direct manipulation of the environment, semantic classification and labeling of manipulable parameters, semantic information embedded in visualizations (viz., lexical drill-down capabilities), and integrated modeling tools (e.g., ability to graphically relate echo delay to range in terms of multipath structure). Such "what if…?" interventions can be effected in E-SAIL™ either through manipulation of the scenario controller of the SBT used to generate synthetic data or through selection of archived tape data with desired properties.

Because all display outputs in the set of possible display outputs result from actual scenarios in the physical world, the mapping is always subjunctive, but it is not always injective. This is the reason E-SAIL™ cannot allow an operator to directly modify the tactical display and observe (the set of) possible physical scenarios that might have caused it: in addition to multiple physical scenarios that might lead to the same tactical display (a non-injective mapping) there are some states of the tactical display that, while possible to imagine or draw, have no corresponding physical scenario that could produce them. This likely has little or no disadvantage for learning of mental models because temporal order (Sloman, 2005) is a strong clue to causal structure and environment precedes sonar response.

Semantic Classification and Labeling

Manipulation of the environmental scenario is performed in current SBTs through selection of the time and location of the scenario with limited capability for direct manipulation of environmental parameters. The same holds for archived tape data: a user must locate a tape that was recorded when the ship was in such a location at such a time that the desired environmental scenario parameters were present. In contrast, E-SAIL™ allows for a more intuitive and semantically meaningful interface for manipulation of the environment through parameterization and scaffolded interfaces.

The first key attribute that enables intuitive control of the environmental scenario is semantically meaningful, low-dimensional *parameterization* of environmental data. Some environmental properties such as surface loss and surface backscattering strength can be parameterized by a single semantically meaningful parameter such as sea state (viz., significant wave height) or wind speed (assuming fully developed seas). In other cases, such as SSPs, the environmental data is inherently high-dimensional and not amenable to parametric manipulation in its native format. In such cases it is necessary to develop lower-dimensional parameterizations that are linked to physically and semantically meaningful attributes.

For example, this parameterization is achieved for SSPs in E-SAIL™ using machine classification of a linearized representation according to semantic categories. SSPs are decomposed into (semantic) components that results in particular phenomena and (numerical or ordinal) parameters of those components. In this interface paradigm, the underlying M&S (e.g., the SAST SBT) naturally constrains the range and type of possible actions, which provides some measure of implicit scaffolding (Podolefsky, Perkins, & Adams, 2010).

Scaffolding the display via "information icons" (as described in the previous subjection) requires automated classification of extracted environmental data according to meaningful semantic categories. For example, an expert visualizing a field of sound-speed profiles (SSPs) extracted from GDEM-V as an orthographic projection can interpret the SSPs in terms of the resulting propagation behaviors that will be observed in the environment. Using internal models, an expert understands that certain aspects of the SSP will correspond with semantically meaningful propagation categories such as "surface duct," "deep sound channel," or "convergence zone" and can further identify attributes of those propagation channels such as "channel depth," or "cycle distance." In contrast, a novice does not yet have the underlying mental models needed to interpret SSPs in terms of tactically meaningful phenomenology. The same is true for a scaffolded "what if…?" interface to learning by intervention. The interface must present the user with semantic information that is sufficiently abstracted from the raw SSP data such that the desired mental model can be learned, which requires classification and labeling of the SSP.

In the example case of SSPs, E-SAIL™ performs automated machine classification and semantic labeling of environmental data extracted from GDEM-V and stores this information for the entire GDEM-V database in an ontological OWL database that supports semantic query, i.e., searching for SSP by meaningful attributes such as "has a surface duct." We have automated classification of SSPs using a simplified linear parametrization of the SSPs coupled with a rule-based classifier for the overlapping categories (i.e., an SSP can belong to one or more classes with restrictions on membership expressed in terms of first-order logic). Additional numeric parameters are extracted for SSPs belonging to certain classes (e.g., depth of the surface duct or cycle distance). The semantic class-membership properties and numeric parameters of all GDEM-V SSPs are stored in an ontological database. Using this semantically indexed database, SSPs can be searched using natural language terms and intuitive logical/semantic relations. For example, it is possible to request a SSP with a deep-sound channel and a surface duct that has sufficient depth excess to support a CZ.

This system, termed SSPro™, is critical to the ability of E-SAIL™ to help learners acquire mental models through intervention because it collapses multivariate input parameters into lower-dimensional semantic labels. This achieves scaffolding by directing the inquiry process and guiding inquiry toward meaningful sets of input parameters. SSPro™ has also enabled us to demonstrate a number of other unique capabilities within E-SAIL. For example, using the interface shown in Figure 4, a user may design an SSP graphically as a means to search the GDEM-V database for an SSP having the desired attributes. Using a real-time GUI a user can "draw" an SSP that has certain attributes (e.g., a surface duct, or a deep sound channel with a particular channel-axis depth). The automatic classifier then classifies the "drawn" SSP and uses the search terms to semantically query SSPro™ and return a matching set of SSP profiles with the desired attributes.

Semantically meaningful intuitive search tools such as this have not previously been used for Navy environmental databases and enable trainers and learners using E-SAIL™ to make optimal use of both archived tape data and SBT generation of synthetic data.

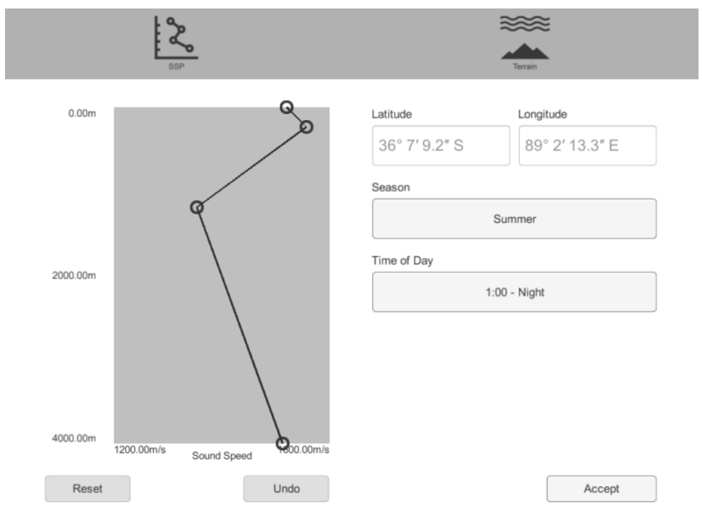

Figure 4. A View Of The Graphical SSP Query Interface Showing How A User Can "Draw" An SSP Using Control Points Or Select A Season/Time Of Day (Viz., Day/Night) As A Means Of Specifying A Desired SSP Type From Which To Choose Tape Data Or Generate A SAST AIC Scenario.

User-Driven Intervention as Extrinsic Feedback

E-SAIL™ is a source of extrinsic information (i.e., feedback) otherwise unavailable to STs during the normal performance of ASW tasks: it is precisely those unknown elements of the tactical scenario displayed by E-SAIL™ (viz., the location of submarines or information about what environmental element corresponds to a particular feature on the tactical display) that STs are seeking to determine during the normal performance of ASW tasks.

The content and valence of E-SAIL™ feedback are modulated by scenario and user actions. The modality is primarily graphical, but augmented by semantically meaningful text labels, icons, and opportunities for drill-down interrogation. This means that the amount of feedback, in terms of level of detail, naturally adapts to user needs through the multilevel interface. Timing of feedback remains the critical variable for consideration. Fortunately, the role of feedback timing in SBT has been investigated in a number of recent studies [see, e.g., (Atwood, 2009) for a review of recent work]. In general, immediate feedback, provided during task performance, enhances acquisition of proficiency but harms retention, while delayed feedback, provided after an exercise (e.g., an after-action review), enhances retention but slows the process of acquisition. This suggests that training methods should confine feedback to after-action reviews (AARs)—as it would be in an operational environment—to ensure transfer to authentic ASW tasks. Moreover delayed feedback allows for the development of self-regulatory processes [Atwood (2009)].

However, we envison E-SAIL™ as an opportunity to leverage multiple forms of feedback toward achieving the dual goal of accelerating training and improving retention. By adapting the timing of feedback to the proficiency of learners, feedback can be optimized to speed acquisition of skill when (team) proficiency is low (acquisition phase) then adjusted to optimize retention once a desired level of proficiency is achieved (retention phase).

SUMMARY AND FUTURE WORK

We have described the conceptual basis and basic functionality and structure of E-SAIL, a unique learning tool that integrates game-based visualization of the tactical and environmental situation with real-time modeling and simulation of sonar performance to enable interactive "what if…?" analyses that support acquisition of the causal mental models of underwater acoustics and sonar performance that experts use to achieve (near) optimal performance in analysis and employment of tactical sonar systems. While our development of the E-SAIL™ prototype has been grounded in the current cognitive science of learning and training, the next stages of our work will involve laboratory and field studies using the E-SAIL™ system to investigate the validity of the prior findings and theories for the domain of ASW analysis and employment. Because E-SAIL™ is modular, integrating multiple systems together with the display environment via asynchronous message passing and platform-agnostic message formats, it is well suited for such experimentation in which user models, assessment tools, and adaptation algorithms can be quickly altered, replaced, or removed.

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