A Model-based Approach to Simulator Fidelity and Training Effectiveness

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ABSTRACT

Although there is a commonly held belief that high-fidelity simulators provide a high degree of transfer, some evidence indicates that lower-fidelity simulators can provide benefits without the added expense and complexity of high-fidelity simulators (Wickens & Hollands, 2000). The civilian flight simulator market contains inexpensive systems for training procedures and operations. A plethora of force-cueing devices can augment the lower-fidelity simulators. However, the effect of force-cueing devices on performance and training is a heavily debated topic (e.g., Heintzman, 1997). Furthermore, the available information regarding the impact of fidelity on training effectiveness is documented in a disparate and fragmented literature. The ability to assemble this information in a common location and to establish quantitative, predictive relationships between simulator fidelity and training effectiveness would greatly enhance the value of training programs that utilize simulators to train operators.

In this paper, we will describe the Relating Effective Learning to Attributes of the Training Environment (RELATE) approach, a process designed and applied in the Performance Effects Related to FORce-cueing Manipulation (PERFORM) project. The purpose of the RELATE approach is to establish quantitative, predictive relationships between the attributes of a training environment and training effectiveness. In the PERFORM project, the training attribute of interest is simulator fidelity. The RELATE approach consists of six steps: (1) identifying the relevant dimensions of simulator fidelity, (2) identifying the knowledge and skills (K&S) necessary in the specific domain, (3) determining whether a relationship exists between the fidelity dimensions and the K&S, (4) developing functions that define the relationships between fidelity dimensions and K&S, (5) developing algorithms that predict training effectiveness, and (6) empirically validating the functions and algorithms. We will walk through the steps as they were applied in the PERFORM project, which aimed at determining the level of fidelity required for effective air-to-air combat training in F-16 simulators.

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INTRODUCTION

Today's U.S. military personnel face frequent and lengthy deployments. These deployments reduce the ability of warfighters to train and maintain the skill sets necessary for success in combat. Effective training develops capabilities that can mean the difference between life and death for warfighters. Live training is typically time-consuming and expensive. Simulation is one alternative to supplement live training providing the added benefits of increased safety and decreased costs. However, high-fidelity training simulators, which provide very realistic representations of the environment, come with their own challenges. First, high-fidelity training simulators are prohibitively expensive for fielding on a large scale. Second, high-fidelity training simulators are typically restricted by their size and requirements for infrastructure to a fixed location, necessitating trainee travel to the simulators. Finally, there is little scientific evidence to support the belief that high-fidelity simulators provide greater training effectiveness than lower-fidelity simulators. Although there is a commonly held belief that high-fidelity simulators provide a high degree of transfer, some evidence indicates that lower-fidelity simulators can provide benefits without the added expense and complexity of high-fidelity simulators (Wickens & Hollands, 2000).

The purpose of this paper is to describe the Relating Effective Learning to Attributes of the Training Environment (RELATE) approach—a process designed and applied in the Performance Effects Related to FORce-cueing Manipulation (PERFORM) project. The purpose of the RELATE approach is to establish quantitative, predictive relationships between the attributes of a training environment and training effectiveness. In the PERFORM project, the training attribute of interest is simulator fidelity. We believe that the ability to establish quantitative relationships between simulator fidelity characteristics and training effectiveness will greatly enhance the value of training programs that utilize simulators to train operators.

METHOD

The PERFORM researchers developed a systematic process—the RELATE approach—to establish quantitative, predictive relationships between simulator fidelity and training effectiveness (see Figure 1).

The RELATE approach consists of six steps: (1) identifying the relevant dimensions of simulator fidelity, (2) identifying the required knowledge and skills (K&S) to be trained in the specific domain, (3) determining whether a relationship exists between the fidelity dimensions and the K&S, (4) developing mathematical functions that define the relationships between fidelity dimensions and K&S, (5) developing algorithms that combine these functions and predict training effectiveness, and (6) empirically validating the functions and algorithms. In the remainder of this paper we provide a detailed description of each step. We will walk through the steps as they were applied in the PERFORM project, which aimed at determining the level of fidelity required for effective air-to-air combat training in F-16 simulators.

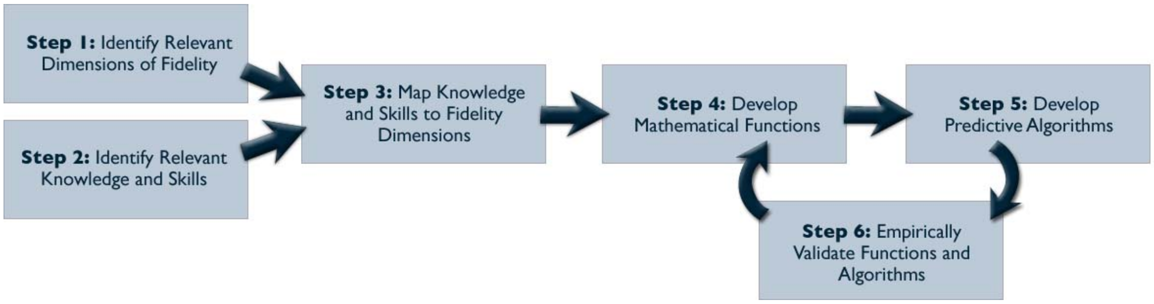


Figure 1. The RELATE approach.

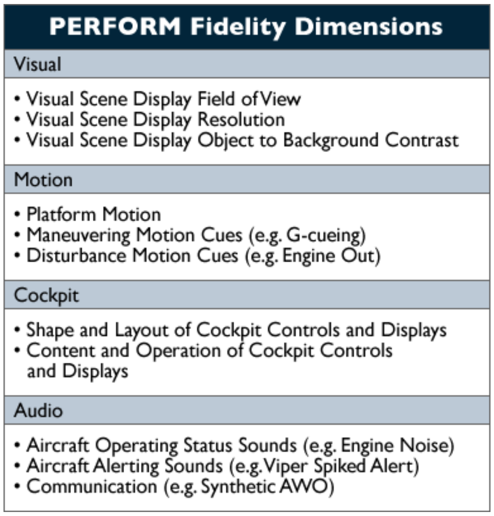
Step 1: Identify Dimensions of Fidelity

The first step in the RELATE approach is to identify the dimensions of simulator fidelity that are relevant to the particular domain of interest. In the PERFORM project, the researchers conducted a review of research articles on the cognitive and perceptual elements related to simulator fidelity to identify the dimensions and levels of simulator fidelity relevant to the air-to-air combat domain.

Substantial research has been conducted over the last few decades on the effects of varying levels of simulator fidelity on performance (Bradley & Abelson, 1995; Cress, McMillan, & Gilkey, 1989; Keirl, Cook, & White, 1995; Winterbottom, Geri, Pierce, & Harris, 2001), training effectiveness (Burki-Cohen, Tiauw, & Longridge, 2001; Chung, Perry, & Bengford, 2001; Lee & Bussolari, 1989; Taylor, Lintern, Hulin, Talleur, Emanuel, & Phillips, 1999), and transfer of training (see Hays, Jacobs, Prince, & Salas, 1992 for a review). The multidimensionality of fidelity has lead to its decomposition along multiple continua to allow for a more manageable approach to the topic. In fact, several different types of fidelity have emerged over the years. Many researchers support the delineation between physical fidelity, functional fidelity, and psychological fidelity (e.g. Allen, Hays, & Buffardi, 1986; Hays & Singer, 1989; Lintern, Roscoe, Koonce, & Segal, 1990). They define physical fidelity as the degree to which the physical simulation resembles the operational environment. Functional fidelity is the degree to which internal mental models correspond to the actual cognitive nature of the task. Psychological fidelity is the degree to which a simulation produces the sensory and cognitive processes within the trainee as experienced in the real world. Researchers have further divided these types of fidelity into distinct dimensions. For example, Lee (2005) decomposed physical fidelity into the dimensions of visual scene simulation, sound effects and communication simulation, whole body motion, and handling qualities and control loading. Furthermore, several researchers have identified specific subcategories within these fidelity dimensions. For example, Heintzman, Middendorf, and Basinger (1999) separated motion cues into maneuver cues and disturbance cues. Maneuver cues result from flight control inputs by the pilots, such as G-cues. Disturbance cues result from changes in the environment or aircraft state outside of the control loop, such as turbulence or loss of an engine.

Utilizing the research and theories from the past four decades on simulator fidelity effects on performance, a representative list of dimensions of fidelity were identified for the PERFORM project. Flight simulation experts assured face validity of these dimensions. Table 1 shows the dimensions of simulator fidelity utilized in the PERFORM project.

Table 1. PERFORM Fidelity Dimensions.



PERFORM Fidelity Dimensions
Visual
• Visual Scene Display Field of View • Visual Scene Display Resolution • Visual Scene Display Object to Background Contrast
Motion
• Platform Motion • Maneuvering Motion Cues (e.g. G-cueing) • Disturbance Motion Cues (e.g. Engine Out)
Cockpit
• Shape and Layout of Cockpit Controls and Displays • Content and Operation of Cockpit Controls and Displays
Audio
• Aircraft Operating Status Sounds (e.g. Engine Noise) • Aircraft Alerting Sounds (e.g. Viper Spiked Alert) • Communication (e.g. Synthetic AWO)

The PERFORM researchers adopted a global approach to defining fidelity in order to (1) develop a framework that will be adaptable to multiple platforms and domains, and (2) to avoid excluding fidelity dimensions that would potentially impact the performance outcomes. For example, F-16 subject matter experts (SMEs) from U.S. Air Force Research Lab in Mesa, Arizona (AFRL/Mesa) identified the dimension of "aircraft alerting sounds" as important to performance on several air-to-air skill elements. They explained that the alerting sounds provide redundant information to that provided by their cockpit displays and that pilot behavior in the simulator would be different given a lack of alerts. For example, visual scan patterns of pilots may be different in the simulator without aircraft alerting sounds because pilots would need to spend more time looking at displays versus looking outside of the aircraft.

This global approach to the review of the literature allowed us to identify trends across the literature and identify relevant theories and research that have held up over time and across domains. As a result, we believe that the PERFORM framework is suited for reuse with different platforms (e.g. F-15, Joint Strike Fighter (JSF)), types of training (e.g. procedural training, mission training), missions (e.g. air-to-ground combat, emergency procedures), and domains (e.g. commercial aviation).

Step 2: Identify Relevant Knowledge and Skills

The second step in the RELATE approach is to identify the relevant K&S for the specific domain. To accomplish this, the PERFORM researchers leveraged the air-to-air Mission Essential Competencies (MECs^{SM}). The air-to-air MECs^{SM} are the competencies, knowledge, and skills that have been identified as necessary for F-16 pilots to acquire to be considered mission-ready for air-to-air combat (Colegrove & Alliger, 2002). Furthermore, the MEC^{SM} K&S elements have been linked to the objective and subjective performance measures collected in the Distributed Mission Operations (DMO) Training Research Test-bed at AFRL/Mesa.

The DMO test bed is used to conduct training research with a variety of platforms (e.g. F-16 pilots in air-to-air combat). The training research consists of a weeklong exposure to competency-based scenarios that focus on developing the MEC^{SM} K&S elements. Researchers at AFRL/Mesa assess the effectiveness of the DMO training research syllabi by examining the pilots' performance on comparable "benchmark" mission scenarios presented on the first and the last day of training research. The difference in performance from the beginning to the end of the training research week is determined by comparing both the objective and subjective performance data (Symons, France, Bell, and Bennett, 2003).

The PERFORM project leveraged air-to-air K&S elements, and related objective and subjective performance measures, as a means for assessing training effectiveness following the current AFRL/Mesa method. However, it seemed unlikely that all of the measures currently collected in the DMO environment would be sensitive to fidelity manipulations. As a result, we developed hypotheses about which measures would be sensitive to fidelity manipulations, and we will collect these measures during the experimental validation in Step 6.

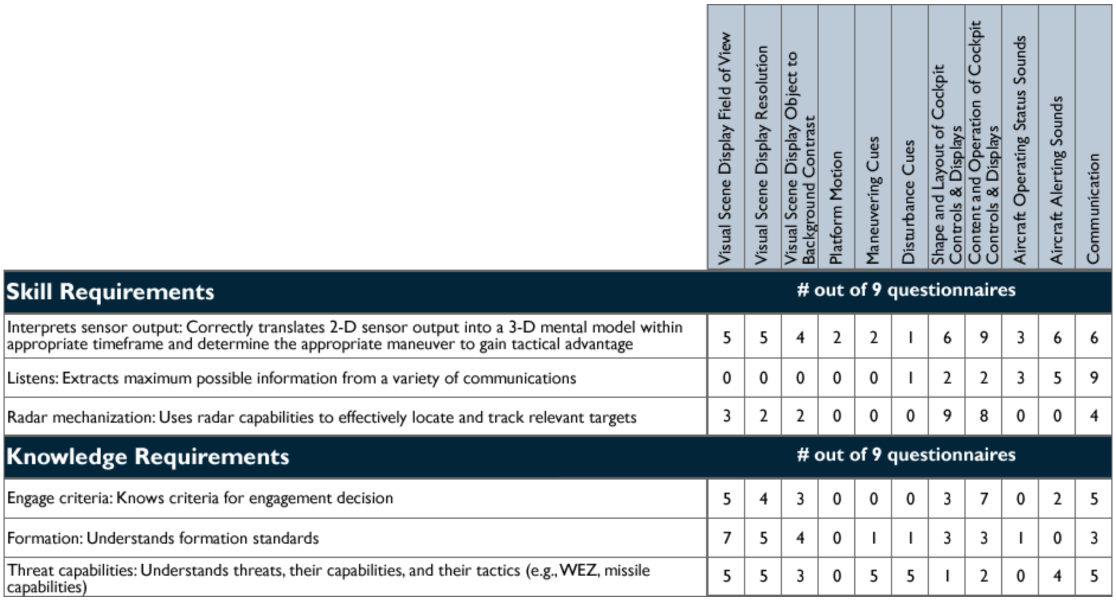
Step 3: Relating Fidelity Dimensions to K&S

The third step in the RELATE approach is to identify if a relationship exists between the fidelity dimensions established in Step 1 and the K&S identified in Step 2. In order to identify if a relationship exists between the fidelity dimensions and the air-to-air K&S elements, the PERFORM researchers developed and distributed a questionnaire that asked the respondents to identify if they would expect performance on a particular air-to-air K&S element to be affected by changes in fidelity within each dimension.

Five F-16 SMEs from AFRL served as initial respondents to the questionnaire. In addition, four PERFORM researchers—with expertise in training, cognition/perception, and performance measurement—also completed the questionnaire. The researchers drew upon their related expertise and the relevant theory and research found during the literature reviews. For example, one of the PERFORM researchers previously examined the effects of field of view (FOV) on pilot performance (Alexander, Wickens, & Hardy, 2005), and was able to utilize those findings in hypothesizing the relationship between FOV and the air-to-air K&S elements.

The results from the questionnaire identified which subsystem changes in fidelity are hypothesized to have an effect on the air-to-air K&S elements. For example, nine of the survey respondents—100 percent—identified that changes in communication fidelity would have an impact on performance related to the air-to-air skill "listens." Table 2 provides an excerpt from the results of the K&S-to-Fidelity Questionnaire with the frequency of responses out of nine questionnaires received.

Table 2. Excerpt from the K&S-to-fidelity dimension matrix.



	Visual Scene Display Field of View	Visual Scene Display Resolution	Visual Scene Display Object to Background Contrast	Platform Motion	Maneuvering Cues	Disturbance Cues	Shape and Layout of Cockpit Controls & Displays	Content and Operation of Cockpit Controls & Displays	Aircraft Operating Status Sounds	Aircraft Alerting Sounds	Communication
Skill Requirements	**# out of 9 questionnaires**										
Interprets sensor output: Correctly translates 2-D sensor output into a 3-D mental model within appropriate timeframe and determine the appropriate maneuver to gain tactical advantage	5	5	4	2	2	1	6	9	3	6	6
Listens: Extracts maximum possible information from a variety of communications	0	0	0	0	0	1	2	2	3	5	9
Radar mechanization: Uses radar capabilities to effectively locate and track relevant targets	3	2	2	0	0	0	9	8	0	0	4
Knowledge Requirements	**# out of 9 questionnaires**										
Engage criteria: Knows criteria for engagement decision	5	4	3	0	0	0	3	7	0	2	5
Formation: Understands formation standards	7	5	4	0	1	1	3	3	1	0	3
Threat capabilities: Understands threats, their capabilities, and their tactics (e.g., WEZ, missile capabilities)	5	5	3	0	5	5	1	2	0	4	5

During Step 3, the PERFORM researchers identified variables that affect the relationship between simulator fidelity and training effectiveness. For example, several researchers cite trainee related variables (e.g. trainee's experience level) as factors that potentially affect the relationship between simulator fidelity and training effectiveness (Baum, Smith, Klein, Hirshfeld, Sweezey, & Hays, 1982; Hays, 1981; Hays & Singer, 1989). In addition, several researchers cite task-related variables that potentially affect the relationship between simulator fidelity and training effectiveness, such as the specific K&S required by the task (Advisory Group for Aerospace Research and Development (AGARD), 1980; Baum et. al., 1982; Hays, 1981; Hays & Singer, 1989). The predictive algorithms captured and accounted for these variables effects in Step 5.

Step 4: Develop Mathematical Functions

The fourth step in the RELATE approach is to translate the K&S-to-fidelity dimension relationships into mathematical functions that describe the direction and strength of these relationships. Mathematical functions define the relationships between air-to-air K&S elements and the fidelity dimensions. Data from the K&S-to-Fidelity Questionnaire facilitated the identification of whether a relationship exists between the air-to-air K&S element and the fidelity dimension. Next, F-16 SMEs participated in a focus group to identify the direction and strength of these relationships as they relate to air-to-air combat training within the F-16 simulators. For example, the F-16 SMEs explained that training pilots to use their radar to locate and track relevant targets effectively in air-to-air combat (i.e. the air-to-air skill of "radar mechanization") would require high-fidelity cockpit controls and displays in the simulator. The focus group also pointed out fidelity needs that are specific to the F-16 platform. For example, the maneuvering motion cues are less noticeable in the F-16 aircraft due to the leading edge slats. Alternatively, in a fighter aircraft without leading edge slats (e.g. F-15), maneuvering motion cues (e.g. buffeting of the aircraft) inform pilots that they are pulling high G-forces. Because the maneuvering motion cues are not provided in the F-16 aircraft, the SMEs identified the fidelity dimension of maneuvering motion cues as less important in the F-16 training simulators.

In addition, the PERFORM researchers also consulted published research/theories to identify the strength and direction of these relationships. For example, experimental data indicated what type of function and graphical shape best describes the change in the training effectiveness (e.g. a simulator's effectiveness at training a pilot to extract the maximum possible information from a variety of communication sources) given a change in a specific fidelity dimension (e.g. communication fidelity).

The results of the focus group meeting and the literature review aided in the definition of the mathematical functions that describe the relationship between the air-to-air K&S and the fidelity dimensions as they apply to the F-16. Figure 2 shows the mathematical function that represents the relationship between the air-to-air skill "interprets sensor output" and fidelity dimension of visual scene display FOV.

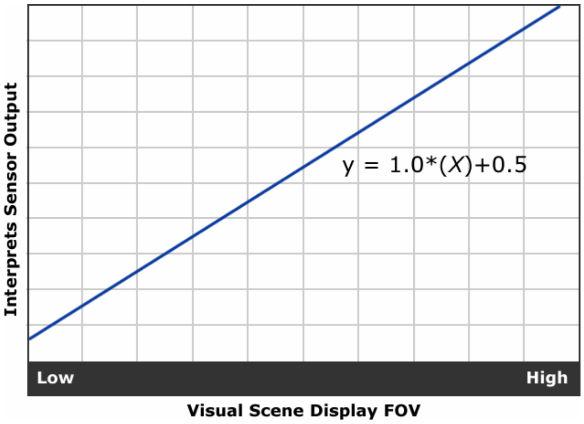


Figure 2. Relationship between Interprets Sensor Output and Visual Scene Display Field of View.

Step 5: Develop Predictive Algorithms

The fifth step in the RELATE approach is to piece the individual functions together to develop an algorithm that will predict the effectiveness of a given training simulator. The PERFORM researchers developed initial predictive algorithms—one for each of the air-to-air K&S elements—that incorporate the values for the dimensions of fidelity, and the relationship functions between the air-to-air K&S elements and the fidelity dimensions. Specifically, the functions translate the variance in fidelity within the dimensions into a composite value for each K&S element. That composite value is compared to the maximum possible composite value to get the predicted training effectiveness score. This score represents the predicted effectiveness of the given simulator for training a specific K&S element. Figure 3 shows a notional predictive algorithm for the air-to-air skill element "interprets sensor output."

In this example, the values for the dimensions of fidelity appear in the blue boxes (e.g. visual scene display FOV = 10, visual scene display resolution = 5, etc.). The functions that were defined based on theory, research, and F-16 SME input are shown in the blue text (e.g. $y = 1.0(x) + 0.5$, $y = 0.5(x) + 0.5$, etc.). These functions define the relationship between the dimension of fidelity and the air-to-air skill element "interprets sensor output." The PERFORM model runs each fidelity dimension value through its relevant function and adds these values to determine the composite "interprets sensor output" value. This composite value is compared to the maximum possible composite value to determine the hypothesized "interprets sensor output" training effectiveness score.

The areas that are grayed out (Figure 3) are related to a small sample of the many pilot and scenario factors that impact the relationship between fidelity and training effectiveness. These areas are gray because the researchers did not incorporate these factors into the algorithm during the initial phase of the PERFORM effort. However, future versions of PERFORM will model these and additional factors to make the algorithms more robust. For example, weighting factors for each K&S element based on its relevance to a particular scenario of interest may be implemented. Each DMO training scenario exercises the air-to-air K&S elements related to the air-to-air Mission Essential Competencies (MECs^{SM}) at varying levels. Symons, France, Bell, & Bennett (2003) developed rating criteria to capture the relevance of a scenario to evaluating or exercising the air-to-air K&S elements. The PERFORM researchers will consider translating relevancy ratings into weighing factors for the various training scenarios. Weights derived from the relevancy ratings for each scenario may be useful in the predictive algorithms.

Other areas of exploration that may increase the robustness of the predictive algorithms include the interactions between dimensions of fidelity. For example, the relationship between FOV and motion has been acknowledged in the literature (Heintzman, 1997). Borah, Young, & Curry (1977) concluded that peripheral rather than central visual fields must be simulated to create visually-induced motion, suggesting the use of a wide FOV. Studies have demonstrated that FOVs larger than 180 degrees create effective visually-induced motion sensations in flight simulators, thereby reducing the need for platform motion (AGARD, 1980). The PERFORM researchers plan to explore the motion/FOV and other fidelity dimension interactions to determine the impact on the aggregation of functions within the PERFORM algorithms.

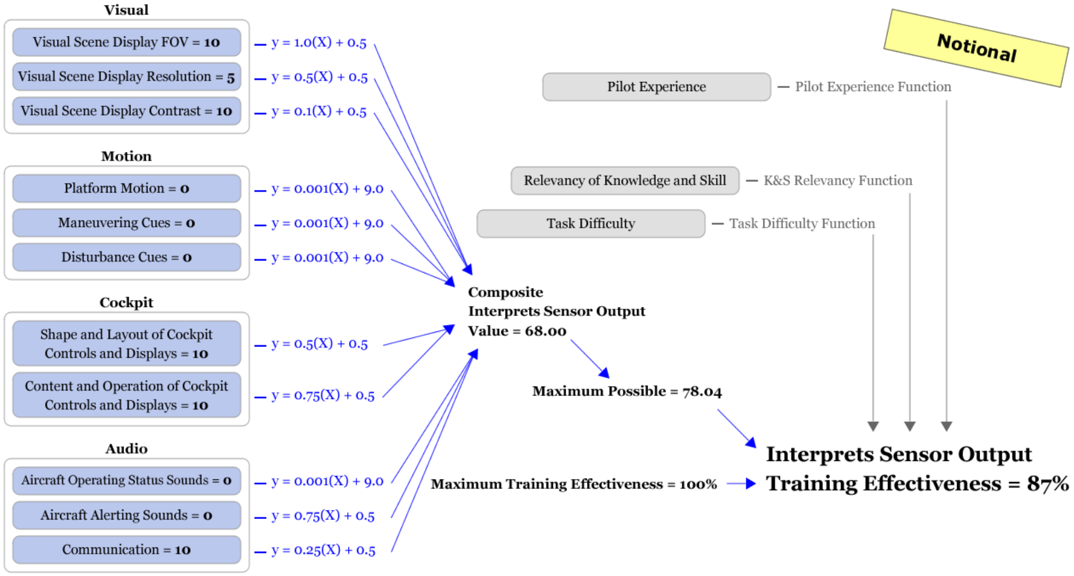


Figure 3. Notional PERFORM Predictive Algorithm for "Interprets Sensor Output."

Step 6: Validate Functions and Algorithms

The sixth and final step in the RELATE approach is to conduct experiments to validate the hypothesized functions and algorithms. The hypothesized functions and algorithms developed during Step 4 and Step 5 of the PERFORM project were based on broad theories and research related to the impact of simulator fidelity on performance. In fact, there is very little training "effectiveness" research looking at the impact of simulator fidelity, so performance data were not available to utilize when developing the functions and algorithms. Future tests will provide performance data in a training effectiveness study that will be conducted at AFRL/Mesa in Spring 2007 to compare pre- and post-training performance between two simulators of differing levels of fidelity.

DISCUSSION

In this effort, the PERFORM researchers designed and applied the RELATE approach to bring together the last several decades of research concerning simulator fidelity effects on performance and establish quantitative, predictive relationships between simulator fidelity and training effectiveness. We believe that the ability to establish quantitative relationships between simulator fidelity characteristics and training effectiveness will greatly enhance the value of training programs that utilize simulators to train operators. For example, predictive models can provide training designers with the ability to conduct comparative assessment of the impact of various levels of simulator fidelity on training effectiveness prior to investing in any new technology. Alternatively, if simulators are highly integrated within an established training program, predictive models can assist in determining what K&S can best be trained in that particular simulator configuration. In this situation, models can assist with the prioritization of technology enhancements and/or the development or selection of training scenarios to improve the training effectiveness of existing simulators.

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