

Layered Fidelity: An Approach to Characterizing Training Environments

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ABSTRACT

Simulator fidelity is commonly considered to be the degree to which the equipment provides an accurate reproduction of the real world (Hays, 2006). Typical fidelity discussions about displays concern things like pixel density, contrast ratios, latency, and field of regard; if they are about motion, the topics of latency, frequency, and degrees of freedom often come up; and for audio, it's common to discuss frequency response and dynamic range. These are good and important subjects; but, there are other important aspects of fidelity.

These other aspects are the motivation behind this paper. They take the form of layers and they can be dichotomized into a framework that looks at the training environment and the human using the training environment. The framework thus includes layers for engineering considerations for designing, building, and using the training environment, as well as, psychological considerations for understanding the effects of fidelity manipulations on the human's experience and on the environment's training effectiveness.

The Training Environment Fidelity layers meet the Human Fidelity layers at the point where displays, motion systems, and physical controls meet the human visual, auditory, and muscular systems. The training environment fidelity layers also include a description of the stimulus- and response-producing systems, the mathematical and computational models that drive them, behavioral models of entities that will be encountered in the environment, and the underlying scenarios. The human layers also include a higher-level perceptual and motor layer that describes object and spatial fidelity, an intuitive layer that describes the degree to which the simulator is suitable for developing highly practiced automatic skills, a cognitive layer that describes the plausibility of more complex situations, a social layer that describes the participant's interactions with other real and synthetic participants, and a pedagogical layer that describes features likely to aid training such as simplification and highlighting for novices.

In this paper we describe the framework and show its successful application to a simulator intended to develop advanced flight skills.

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“*Perfect Sound Forever.*” That is how Philips described the audio Compact Disc (CD) when it was first released in late 1982. According to classic information theory (Shannon, 1948), CD technology’s ability to sample sound at a little over twice the maximum frequency of human hearing should capture all the musical information that humans can hear. Audio would be not just high-fidelity, but perfect-fidelity.

As we now know, the reality of CD fidelity in those days was not perfect. There were many technical explanations, but even if CD reproduction had been perfect, there were other important aspects of the musical experience—other layers—to consider. For example, the quality of the recording, the acoustics of the recording venue, the skills of the musicians, and especially the stories and emotions they convey, all play a major role. Discussion of “perfect” fidelity needs to include layers like those in addition to a discussion of digital sources.

The analogy between CD fidelity and training environment fidelity is strong. For example, discussions of simulator fidelity focus on topics like the pixel density of the display or the latency of the motion system. These play a very important role in simulator fidelity, but, just as in a discussion of audio fidelity, there are other important aspects—or layers—to consider.

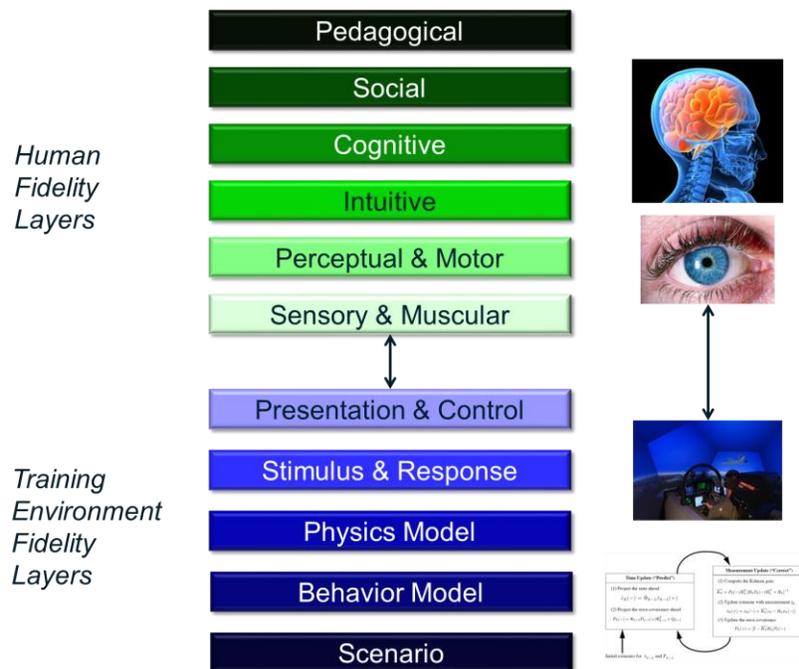


Figure 1. The Layered Fidelity Framework.

In this paper we describe a framework for consideration of fidelity in layers, the *Layered Fidelity Framework (LFF)*, shown in Figure 1. The LFF helps identify the locus of specific fidelity limitations and opportunities that enrich the understanding of the effects of fidelity characteristics of the training environment on training effectiveness. One consequence is that the framework can facilitate interdisciplinary discussions about fidelity. To fully understand the

effects of an upgraded display system, for example, it is important to understand not only the things that are to be displayed on it, but also what impact they have on the pilot's perceptions and cognitions.

The rest of this paper is organized as follows. We first describe the layers in the LFF, their scientific justifications, and ways that layer-specific effects can be measured. Next, we discuss the potential role of the LFF in the larger context of developing effective training. Finally, we describe an ongoing fidelity research effort aimed at improving simulators to provide more effective training for F/A-18 pilots to land on carriers.

A TOUR OF THE LAYERS

The LFF divides the layers into two major groups, one that describes the fidelity engineering of simulator systems, and another that describes the impact of that fidelity engineering on humans. The training environment fidelity layers are organized by their "distance" from the stimulus material available to the human. The top layers are the ones that the humans actually see, hear, touch, and control; the lower layers are the ones responsible for creating the things on those layers and responding to the humans' control signals. The training environment layers thus group together training environment systems (e.g., visuals and motion or aero models and turbulence models) that are sometimes treated separately. Thus, the training environment fidelity layers treat the engineering involved in a unified way, which avoids the stovepiping among visual, motion, audio, and other simulator systems that can sometimes happen. The human fidelity layers provide an integrated view of human input modalities (visual, auditory, proprioceptive, and so on) as well as human output modalities (speech and non-speech motor activities), and are structured with an eye towards distinctions made by modern psychological and neurological science.

The point of separating the human fidelity layers from simulator fidelity layers is simple: human perception and action is not a simple linear function of the stimuli presented to them or acted upon by them. Humans *construct* the world, and though stimuli are an important part of the construction, they are not the only consideration. Chabris and Simon (2009) describe an experiment they performed where subjects were asked to watch a 2-minute video of people playing basketball and to count the number of passes made by certain players. Around the halfway point, a confederate dressed in a gorilla suit entered the scene, pounded its chest, and walked off. Remarkably, only about half of the participants noticed the gorilla. This effect has held up under a number of experimental variations. Humans exhibit certain predictable transformations to stimuli, but they also exhibit a number of other less predictable effects due to attention patterns, situational understanding, background knowledge and expertise.

Referring back to Figure 1, contact between the two groups of layers represents "contact" in the training situation. For example, human eyeballs, described by the Sensory and Muscular layer, see the simulator visuals as they emerge on an actual simulator display, described by the Presentation and Control layer. Underneath the Presentation and Control layer are all the other fidelity engineering activities that lead to that display, and above the Sensory and Muscular layer are characterizations of all the higher-level effects of those engineering activities on the human.

Analysis of the fidelity required for any specific simulator-based training will often focus on just a few simulator and human fidelity layers. For example, for training that results in the kind of perceptual-motor expertise required by F/A-18 pilots as they land their aircraft on a carrier, the Presentation and Control, Stimulus and Response, and Physics Model layers are the important training environment fidelity layers, and the Perceptual and Motor and the Intuitive layers are the important human fidelity layers. On the other hand, training aimed at air maneuvers will emphasize different layers. Interestingly, the LFF can apply to live training, alone or in combination with virtual and constructive training. Though certain aspects of live fidelity are essentially perfect—namely, those associated with the physical aspects of the situation—the Behavior Model layer fidelity of other live, virtual, and constructive entities, the Scenario layer fidelity, and their impacts on the Intuitive, Cognitive, Social, and Pedagogical human layers, can vary, and are worthy of analysis via the LFF. In this sense, the LFF can extend beyond the confines of simulators.

Human Fidelity Layers

Segmentation of human fidelity into layers in the LFF has been guided by current science to the extent possible. For the lower layers, like the Sensory and Muscular and the Perceptual and Motor, neuroscience has begun to help localize the effects. Though there has been great progress in the neuroscience of Intuitive, Cognitive, Social, and Pedagogical phenomena, there are still enough unknowns that the LFF also needs to lean on more traditional

Behavioral Science as well. In some cases it will not be possible, given our current state of knowledge, to be fully confident in assigning a given human fidelity phenomenon to a specific layer; but, assigning it to one of a small set of layers can still be very useful.

The *Sensory and Muscular* layer is the human portion of the contact between the human and simulator. For the visual system, this primarily means the retina, including both foveal and peripheral vision. The kinds of phenomena that this layer deals with range from simple psychophysics—like the mapping between the brightness of a stimulus and its judged intensity—to more complicated phenomena like simultaneous contrast (where the same color seems different depending on the surrounding colors) and the Helmholtz-Kohlraush effect (where the saturation of a color becomes a part of its judged brightness.) Other sensory stimuli—auditory (including speech), proprioceptive, and in some cases even smell—are also a part of this layer. The “output” side of this layer is represented by the muscles used to interact with the world.

The *Perceptual and Motor* layer performs higher-level but still stimulus-related processing of the information provided by the Sensory and Muscular layer. In the visual system, this primarily means the late visual cortex and both the ventral “what” system leading to the inferotemporal cortex and the dorsal “where” system leading to the posterior parietal cortex. As a result, this layer deals with the perception of objects as well as with spatial relationships. For all perceptual modalities, attentional effects, such as missing the gorilla (Chabris & Simon, 2009) reside in this layer. The visual system has been studied extensively, but there are less well-understood analogs for motion perception and auditory perception. On the output side, this layer deals with motor intents, motor plans, and motor “programs,” that is, with sequences of actions that are often performed together. Intuitively, these intents, plans, and programs might be called “muscle memory.” It’s easy to speculate that the premotor cortex would be an important locus in the brain for them.

The *Intuitive* layer is based on a concept that Stanovich and West (2000) discussed, and Kahneman (2011) made popular, “System 1.” System 1 processes are quick, automatic, and effortless. It operates below the level of consciousness, and generates associations, impressions, and enables humans to act quickly. One defining feature is that, unlike System 2 processes (see next paragraph), System 1 processes do not require working memory to operate (Evans, 2003), thus enabling interesting measurement approaches that can determine whether System 1 processes are implicated. For example, System 1 processes will show a minimal effect of distractor tasks or task deadlines, and should in general show reduced cognitive workload relative to System 2 processes (Evans & Stanovich, 2013). Most of the time, the quick decisions it makes are accurate, though it can be fooled (Kahneman, 2011). Kahneman and Klein (2009) cite it as a locus of certain kinds of expertise. The idea is that, with growing expertise, what had previously been a deliberate, effortful, conscious effort becomes quick, easy, and automatic. The fidelity aspect of this discussion is, the degree to which the environment supports Intuitive fidelity outcomes. These could be any quick decision-making training objectives, but an important subset is the development of perceptual-motor expertise.

The *Cognitive* layer deals with higher level thought (i.e., Stanovich and West’s “System 2”, 2000). It involves deliberate, rational thinking using background or situational knowledge. Information presented didactically would fall into this category. Cognitive considerations influence lower layers, including the Perceptual and Motor layer. For example, expert pilots know the implications of the wind reports given to them by the Landing Signal Officer (perhaps supplemented by their careful observation of the ship’s wake), and this knowledge will influence subsequent perceptions and control inputs as they anticipate, say, an unusually difficult burble as they approach the carrier. Fidelity considerations are a kind of mirror of the Scenario layer fidelity considerations except from the human side—is the story believable, does the weather seem like the kind of weather that would occur, does the pattern of activities in the scenario look like a pattern of life, and so on.

There are many skills that are only acquired by interacting with other people, either directly or indirectly, and those are the concern of the *Social* layer. These can range from team, leadership, and organizational skills to combat skills to cultural skills. The effects on this layer are related to these skills, and the human impact fidelity of a training environment describes how effective the environment is for training these kinds of skills.

Finally, the *Pedagogical* layer is concerned with those manipulations of fidelity (beyond the requirement to match the real world) that will result in more effective training. For example, for novices, certain aspects of the controls are simplified; other aspects might be exaggerated and augmented to make sure the trainee notices them. For experts, it

might be important to dial up the challenge by doing the opposite. And, for all trainees, it might be important to provide variations from landing-to-landing in order to avoid rote memorization of the scenario.

Table 1 shows ways in which performance effects on the Human Fidelity Layers can be objectively measured as well as some example performance indicators, and lists some of the fields that contributed to the scientific foundations for each layer. Most of the entries are self-evident, but it is worth elaborating on a couple of entries in the Intuitive layer row. First, the reason that “high performance with few working memory limit effects” is listed is that DeNuys (2006) found that when a task was handled by System 1, there were few if any effects of extra load on working memory; working memory load did have an effect, however, on tasks handled by System 2. Second, Sports Psychology is listed as a foundational field because it is one of the primary places that training of perceptual-motor (intuitive) expertise. Ward *et al.* (2008) and Williams, Ericsson, Ward and Eccles (2008) have written interesting articles on the application of results from that field to Military Psychology, and in particular to training perceptual-cognitive expertise.

Table 1. Performance Assessments and Related Scientific Foundations for the Human Fidelity Layers.

Human Fidelity Layer	Effects Show Up Objectively In	Example Performance Indicators	Scientific Foundation
Pedagogical	Learning curve	Trainee performance remains in challenging range Sequencing of training experiences to match competency dependencies Improved time to training criterion	Training Science
Social	Cultural effects Organizational behavior Team effectiveness Trust	Plausible trainee responses to others in environment Improved interaction skills	Anthropology Sociology Industrial/Organizational Psychology
Cognitive	Problem solving Decision making Situation awareness	Working memory limit effects Improved problem-solving skills	Cognitive Science
Intuitive	Priming effects Automaticity Pilot-in-the-Loop control estimates	Improved ability to predict subsequent events High performance with few working memory limit effects Improved response time Improved accuracy	Dual-Process Theory Sports Psychology
Perceptual & Motor	Object effects Spatial effects Attention patterns Scan patterns Motor intent Motor plans and patterns	Attentional (and inattentional) effects Effects of context on perception Effects of knowledge on perceptions	Cognitive Neuroscience of Attention Perception Motor Control
Sensory & Muscular	Hue/Saturation/Value Frequency/Loudness/Phase Tactile measurements	Psychophysical effects	Psychophysics Signal Detection Theory

Training Environment Layers

The Training Environment Fidelity Layers deal with the fidelity engineering that controls the effects presented to the student by the environment. Many find the descriptions of the layers more straightforward than the Human Fidelity Layers.

The Presentation and Control layer is the “surface” of the training environment: the displays, the physical controls, the motion system, and so on. It is the layer about which it is sensible to talk about the display’s pixel density, motion latency, and frequency response. It is the locus of many discussions about fidelity. The Control aspect has to do with the physical characteristics of the aircraft controls—the shape of the stick and the position of the throttle, for example.

Feeding the Presentation and Control layer is the Stimulus and Response layer. For a simulator’s visuals, this generally corresponds to the Image Generation (IG) system. It is different from the display itself; it’s what determines how things are rendered on the display. It is of course limited by the limits of the Presentation & Control layer—high definition graphics on a standard definition display won’t look better than standard definition graphics, and might look worse. Analogous things are true for motion and audio, though there may not be explicit rendering systems for those stimuli. On the Response side, this layer concerns things like the ease with which the throttle or the stick moves, how well and quickly the gauges respond to button presses, and so on. It’s basically the Control portion of the Presentation and Control layer put in motion.

Feeding the Stimulus and Response layer are various Physics Models—the aerodynamic model of an aircraft, the control dynamics of a vehicle, a physics-based model of turbulence, environmental models, and the like. Generally it is possible to use results from computationally demanding models rather than running the models in real time. But the fidelity of the models can be extremely important for creating realistic effects. The fidelity of the models on the Physics Models layer is limited by the fidelity of the layer above it (the Stimulus and Response layer) because, for example, the fidelity of the wake model will not matter if the rendering system cannot show it accurately.

In many training environments, the behavior of other entities as generated by Behavior Models plays a major role. An important way this is accomplished is through synthetic entities in the environment, which might be completely autonomous or may have a human operator; and, of course, in live environments, the other entities might be fully represented by other humans. In all cases, it is reasonable to ask how the fidelity of the entity’s behavior influences training effectiveness.

Beneath those models lies a Scenario layer, and it contains all the things you would expect: terrain, weather, behaviors of the live, virtual, and constructive participants, and in some cases the Master Scenario Events List (MSEL) or other story line. The fidelity aspect has to do with how true-to-life the scenario aspects are: would that weather occur in that terrain, are the participants behaving realistically, and does the MSEL describe a set of events that could have happened?

USING THE LAYERED FIDELITY FRAMEWORK TO DEVELOP MORE EFFECTIVE TRAINING

The LFF focuses exclusively on fidelity for training. There are other reasonable domains for a fidelity analysis including the development of new tactics, techniques, and procedures, the development of new equipment, and the investigation of the causes of safety mishaps (c.f. Gross, 1999). A focus on training, however, allows an important assumption: fidelity is evaluated by the quality of training it provides rather than by how well it matches the real world. In fact, as we discuss below, to provide effective training, in some cases it will be desirable for a simulator to provide experiences that systematically deviate from those that would come from the real world.

We believe that the use of the LFF to characterize training requirements in a way that can be mapped to the characteristics of the device and the training environment is a strong complement to the Navy’s recent Training Device Certification and Accreditation process (Owen & Meyers, 2012), with its specific emphasis on the mapping between training requirements and device characteristics. An implication is that different training requirements will imply different device and environmental fidelity requirements. Perceptual training will emphasize one kind of

fidelity, procedural training a different kind, and leadership training an even different kind. Even within these broad categories, requirements will differ considerably, though the layers involved may be similar. For example, within perceptual training, the fidelity requirements for learning to quickly identify aircraft will differ from the fidelity requirements for spotting suspicious locations for the implantation of an Improvised Explosive Device (IED).

To characterize these differing training requirements, we separate the description into three parts, each supported by some aspect of the LFF, as shown in Figure 2.

1. A description of the *required training outcomes*. Thoughtful training will have objectives, and the description covers the kinds of the changes that will result from accomplishing those training objectives. The Human Fidelity Layers of the LFF can serve as good organizing principles for the description. For example, training objectives aimed at training sonar operations will have different kinds of outcomes than training objectives aimed at understanding the principles of commanding a battle group. The former is likely to involve perceptual, intuitive, and cognitive skills, and the latter is likely to involve intuitive, cognitive, and social skills.

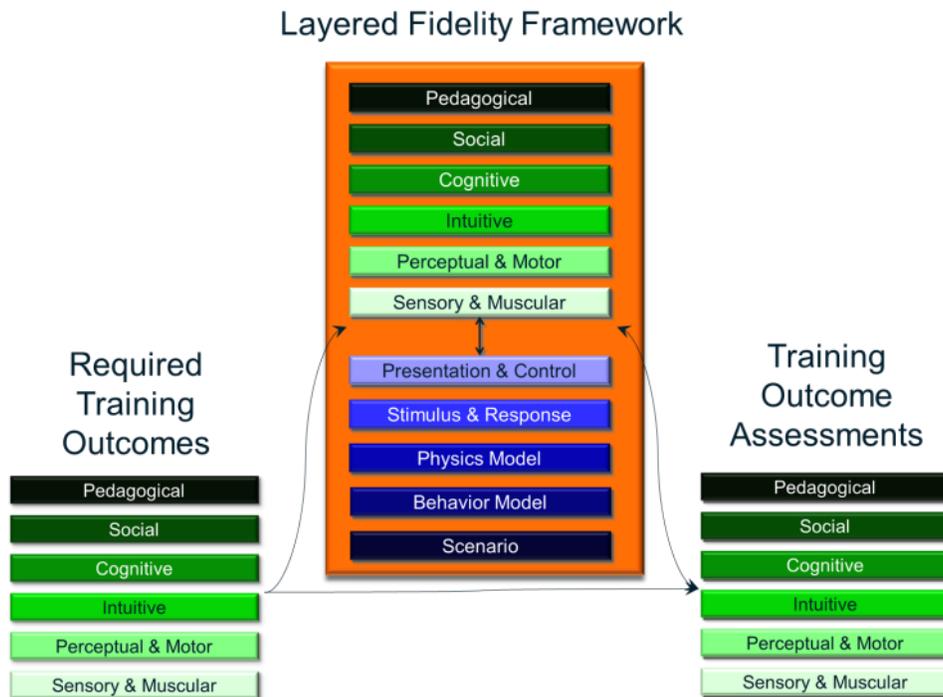


Figure 2. Using the LFF to Characterize the Training Environment

2. A description of methods to *assess how well the student has accomplished the training objectives*. Good assessments will also be based on the kinds of changes that will result from accomplishing those training objectives. As with training outcomes, the Human Fidelity Layers of the LFF can serve as organizing principles for the description. In the examples above, assessments for sonar operations would be drawn from specific measures of perceptual, intuitive, and cognitive skills, while assessments of battle group command skills would be drawn from specific measures of intuitive, cognitive, and social skills.
3. A description of the *fidelity requirements in the training environment*, given the desired training outcomes and assessment methods. The central questions—the answers to which the LFF is intended to organize—are: a) for a given training environment, how good is it for training the desired learning outcomes, and b) how suitable is the environment for measuring those learning outcomes? Sibling questions concern what changes could be made to the training environment to achieve those outcomes and assessments. For this reason, both the Training Environment Fidelity Layers and the Human Fidelity Layers of the LFF will be useful in developing the answers. An analysis of training environment capabilities may find, for example, that the best environment for training sonar operations will be a simulator that will provide strong perceptual, intuitive, and cognitive training, but that the best environment for training battle group command will be a networked live, virtual, and constructive exercise.

The approach espoused here values strong links among characterizations of training outcomes, training assessments, and fidelity capabilities and requirements via the LFF. This is not to say that the layers provide specific answers to these questions; but since each Human Fidelity layer offers both scientific context and exemplars of successful assessments of training effects at that layer, and because the full LFF offers opportunities to understand the links between engineering effects in the training environment and the resulting effect on the human, and because it offers a framework for organizing new results as training science progresses, we believe it can play an important role in developing effective training. Next, we will discuss a case study that demonstrates the LFF's practical and scientific nature.

CASE STUDY: TRAINING CARRIER LANDING IN THE SIMULATOR

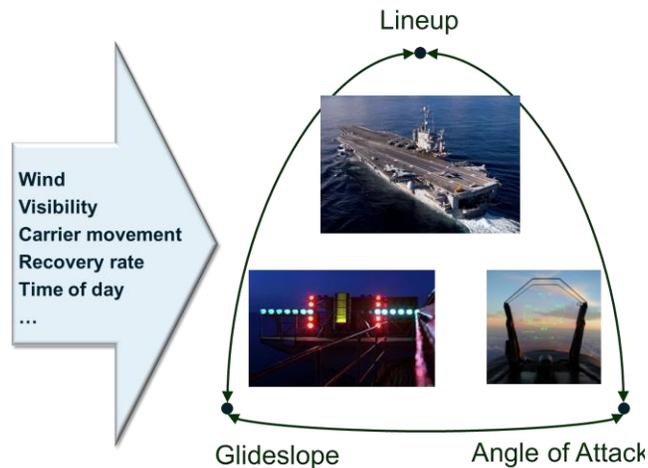


Figure 3. Relations among Three Key Variables for Landing.

which will cause the aircraft to settle to a lower position on the glideslope.

We are involved in an effort to understand how improving simulators can allow them to play a larger role in training F/A-18 pilots to land on a carrier. We are doing this by identifying the cues that pilots use during landing, and by a program of experimentation to discover which cues are critical for effective training.

In the final phase of landing on the carrier, there are three variables that are of primary importance to the pilots: their position on the glideslope, their lineup with the Landing Area on the carrier, and their angle of attack, as shown in Figure 3. A pilot who does well in managing these three variables is deemed to have a good landing. The complication is that correcting for deviations in one of the variables has an effect on the others. For example, banking to correct lineup will cause a loss of lift,

which will cause the aircraft to settle to a lower position on the glideslope. Even though pilots are taught about these relationships in the classroom, inexperienced pilots—fortunately, earlier in their careers than when they are actually trying to land on the carrier—wind up correcting one variable at a time, then correcting the consequences of the correction, then correcting the consequences of that correction, and so on. Experienced pilots, on the other hand, learn to anticipate the effects of correcting a single variable and the result is that they are able to make corrections that account for all three variables at once. They call this proactive flying.

Experience brings even more proactive flying. For example, in the picture of the carrier in Figure 3, the wake is frothy and there are several bow waves. To a very experienced pilot, this means that the carrier is moving fast, meaning that the landing area is receding from them more rapidly than usual, and also meaning that there will be a significant component of the wind that is coming straight down the axis of the carrier instead of down the landing area, and this is a signal that they will need to keep their right wing low in the final phases of landing in order to stay lined up appropriately (FA-18 Subject Matter Expert, Personal Communication, 2013).

Because events move so fast when landing on the carrier, there is no time for the pilot to consciously think through what they intellectually know about the relationships among the variables or what they can deliberately deduce from the wake—they have learned, from experience, how the relationships among the variables intuitively feel and what the wake intuitively means. From a fidelity standpoint, the Intuitive layer is concerned with whether the experience of the relationships among these variables intuitively feels as it should, and the relevant question to be addressed by the LFF is whether the simulator provides a training environment that supports this kind of intuitive learning outcome.

Of course, the Intuitive layer does not stand alone in this analysis. In order to provide an environment with this kind of Intuitive learning outcomes, it is important to provide the pilots with an easily perceived version of all the cues they need, and will come to need as their expertise grows, and this involves the effects that many of the Training Environment Fidelity Layers (Physics Model, Stimulus and Response, Presentation and Control) have on the lower Human Fidelity Layers (Sensory and Muscular, Perceptual and Motor) as well as the Intuitive layer. For example,

there are critical cues for glideslope management that come from a device on the carrier called the Improved Fresnel Lens Optical Landing System (IFLOLS). Proper recreation of these cues involves considerations of the physics of the moving deck, the image generators' ability to reproduce the device, and the pixel density and brightness possible in the display. This can be measured on the Sensory layer with psychophysiological techniques, on the Perceptual layer with contextual manipulations such as scene coherence, and on the Intuitive layer by improved ability to predict later aspects of the landing, among other things. Of course, there may not be resources or time to investigate all these phenomena, but the point is that they could be investigated, in principle.

Another interesting human fidelity layer that plays a role is the Pedagogical layer. Here, the focus is on employing and sequencing the most pedagogically appropriate experiences. For example, there are a number of conditions listed on the left hand side of Figure, all of which matter during landing at some point in a pilot's career. Assuming appropriate fidelity on other layers, the simulator gives an opportunity to control when they happen, thus leaving less of the pilot's training to chance.

Some of those conditions are a simple matter of manipulating the Scenario layer appropriately, say for challenging wind or visibility conditions. Other pedagogical conditions require careful thought about the layers involved. For example, one condition that most pilots face in the real world is to have the sun in their eyes as they land, causing distracting glare. Today's simulator displays, unfortunately, cannot be bright enough to cause the perception of glare; the training environment fidelity at the Presentation and Control cannot cause the appropriate human fidelity at the Sensory and Muscular layer. However, Chladny, Mathia, and Clark (2009) have discovered that simulating human visual glare experience in the IG can work well, thereby reproducing a phenomenon that normally occurs in a human fidelity layer with a stimulus generated in a training environment fidelity layer.

Using the LFF, and based on some preliminary empirical explorations, we have designed a simulator-based experiment to explore several of these issues. The big questions to be answered have to do with whether improved fidelity in several of the training environment layers can provide a suitable environment for learning proactive flying during landings, what level of simulator fidelity (including motion) can provide the most effective cues to the pilot about the effects of throttle changes and about turbulence, and the link between different kinds of visual fidelity and learning effects. In designing this experiment, the LFF provided us with an integrated way to think about the kinds of fidelity variables to manipulate, their potential impact on other fidelity variables, and the kinds of performance measures that will help answer our questions.

CONCLUSION

The LFF provides a mechanism for thinking about both the engineering and the human side of fidelity in training environments. It provides objective measures for the training environment's impact on human performance at multiple salient levels, and provides multiple links to neuroscientific, psychological, and other social sciences as well as links to computer science, physical and behavioral modeling, and mechanical, electrical, and other kinds of engineering involved in training environment construction, and it is positioned to exploit new results in all of those fields as they become available. It provides a unified view of the factors involved in linking simulator fidelity to training effectiveness. It can be used to characterize and recommend training environments. The LFF is currently supporting the planning of a set of fidelity experiments aimed at making simulators even more useful for the Naval Aviation Enterprise. Future work will include application of the LFF to additional domains in the live, virtual, and constructive context, objective human performance measurement suites that provide a fine-grained characterization of response on each human layer, and investigation of mechanisms that predict the effects that manipulations of one layer have on the others. Our intent is that it provide both a principled scientific basis and a useful and practical context for characterizing the effectiveness of experiential training environments.

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