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# SHELL Revisited: Cognitive Loading and Effects of Digitized Flight Deck Automation

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# SHELL Revisited: Cognitive Loading and Effects of Digitized Flight Deck Automation

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**Abstract.** Acknowledging the SHELL human factors model, authors examine interfaces among components and assess problems created when the model is aligned with modern digitized flight deck systems. Complacency and over-reliance on automated systems are evaluated, and cognitive load and potential for degraded situational awareness are examined. Authors present a SHELL overlay demonstrating where particular digitized functions and operations present challenges to operators and markedly influence effective SHELL interactions in highly complex flight deck systems. Human factors contributing to the Asiana Flight 214 accident are examined and correlates identified with the SHELL analysis. Implications for advanced crew resource management are presented, and human centered system training applications are proposed for addressing the workload challenges. Implications for working and prospective memory functions are examined, along with accompanying biases. Potential for adaptive automation technology concludes the SHELL overlay analysis with potential for reducing cognitive overload in the digitized flight deck environment.

**Keywords:** SHELL · Digitized flight deck · Human factors · Working memory · Crew resource management

## 1 Introduction

The technological world we live in is currently issuing the next generation of computer power and the aviation industry has been taking full advantage of both computer automation and information in the cockpit in the new millennia. With all these marvelous technologies working together, the industry has improved greatly in terms of safety and efficiency. Pilots can do more in the cockpit with less man power and companies can save money in terms of man power and training. However, as the industry has made giant strides with computer technology, one accident like the 2013 Asiana Airlines Flight 214 crash in San Francisco can be a sobering reminder that even with the best equipment and computers at hand (a Boeing 777), human error can still win the day. Accidents that are investigated by the National Transportation Safety Board (NTSB) like the Asiana Flight 214 crash are thoroughly processed using a meticulous scientific method of elimination to determine safety causation. The vast


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majority of the time the NTSB has no problem narrowing down the culprit to a Probable Cause and then supports that Probable Cause with many human factors causations that contributed to that accident. In the case of the Asiana Flight 214 crash, the NTSB could not come up with one Probable Cause, but instead drew on several different opinions for Probable Causes from a slew of human factors computer automation errors that all contributed to the accident. Why the NTSB had such a difficult time in addressing the Probable Cause of this accident can be analyzed through an older tool of human factors analysis called the SHELL. The SHELL model was developed into a building block structure by Hawkens in 1984 [1] and has been in use since the 1980's to analyze human factors and human error in aviation. By using an updated model of the SHELL in 2017, new light can be shed into the effects of the many editions of the computer on human factors in the cockpit and the many cognitive issues caused by them.

## 2 The SHELL Model Revisited

The SHELL model of human factors analysis that Hawkins presented had the simple block layout of centering the human as represented by the Liveware (L) in the center and surrounding it by four other human factors interfaces: Software (S), Hardware (H), Environment (E) and Liveware (L) as in Fig. 1.

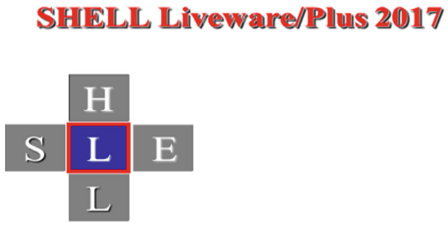


**Fig. 1.** SHELL model updated for 2017 with Liveware/Plus highlighted [1]

There was a time when aircraft had very few, if any, computers in the cockpit for automation and information usage to the pilots represented at the center of the SHELL, but over the last 30 years computers related to automation and information have slowly started to crowd the SHELL model's interfaces as indicated by the red surrounding the center Liveware (L) in Fig. 1. Surprisingly, it is not just the Hardware (H)-Liveware (L) interface where computers have invaded in the form of flight controls to disrupt that direct flow in the ergonomic design of the man-machine interface. In 2017, the computer is now involved in all Liveware interfaces. Multiple computers are now used in all the SHELL interfaces to include the new era of the Electronic Flight Bag (EFB) which has been introduced to aviation cockpits in the last decade. A closer examination of each interface will demonstrate how prolific the computer has become in the cockpit.

### 2.1 The SHELL Model 2017 and the (L)-(H) Interface

The Liveware (L)-Hardware (H) interface shown in Fig. 1. represents all the physical elements of the aircraft and the system including such things as: the wing of the aircraft, the control surfaces along with the entire hydraulic systems, the flight controls in the cockpit. Every part of an aircraft physically falls into this category, but none is a more direct connection than the ergonomic man – machine interface found in the cockpit. It is there where the crew not only utilizes the flight controls, but also continually assesses data in the form of displays to manipulate those controls. The computer has been integrated in the form of automation in the flight controls and the fuel systems to tightly manage the aircrafts control inputs and flight envelope. At the same time the pilots observe the digitalized computer flight information to insure the computer is maintaining the appropriate parameters. This automation and information has formed a well-managed barrier in the Liveware (L)-Hardware (H) interface that is depicted in Fig. 2.

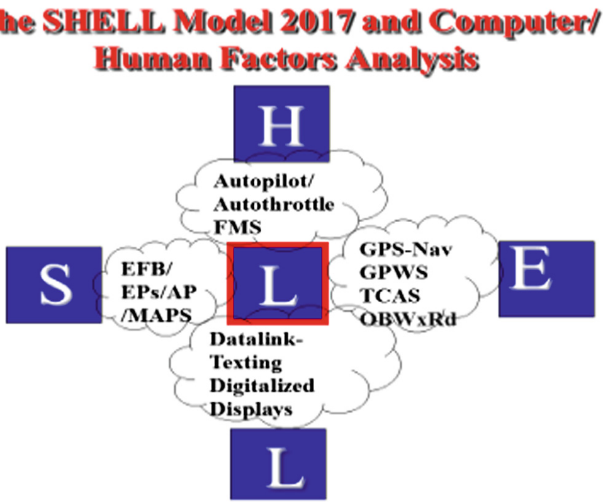


**Fig. 2.** The SHELL model 2017 with computer automation and information displayed by Miller in 2016 [2]

This computer barrier insists that the human work through it to manage the aircraft flight controls indirectly. By doing so the computer is now doing most of the flying thus eliminating a large amount of the direct human interaction. The ergonomic idea behind this is to limit the human's direct control of the aircraft as much as possible to prevent human error and inefficiency. The computer maintains the safe flight envelope and flies the best profile to conserve the most fuel. Here is where the flight management system and auto-throttle join the basic flight computer configuration in the increasing of the controllability of the aircraft. The use of fly by wire controls also has the potential to eliminate the pilot's direct feel for what the aircraft controls are doing and forces the pilot to manage the flight controls by visual reference only. Doing so can make the new

Liveware (L)-Hardware(H) flight control interface optical only. This is flight in the new ergonomically designed human-computer interaction loop by using the optical channel and calls for the pilot to manage the computer to fly the aircraft. The computer is now dominating this interface and it certainly has the potential of flying the aircraft by itself as demonstrated by the many Unmanned Aerial Vehicles (UAV) flying today.

## 2.2 The (L)-(E) Interface

The second interface to be dominated by the computer historically is that of the Liveware (L)-Environment (E) as depicted in Fig. 1. This interface is all about man's relationship to the different types of environment of the flight. This environment includes both inside the aircraft and outside the aircraft and is multifaceted by including such things as: the temperature, cabin pressure, day time, night time, and the weather. The huge growth of the commercial industry internationally after World War II was greatly aided by advent of the Jet age which boasted the safer, efficient and more reliable jet engine, but shifted the causation of most accidents to be human error related. Many of these human errors have been found to be related to the Liveware (L)-Environment (E) interface in four forms: flying the aircraft into terrain, flying the aircraft into another aircraft, flying the aircraft in bad weather and loss of control. To counteract the high numbers of accidents and fatalities, the industry became committed to reducing them by enhancing the Liveware (L)-Environment (E) interface with safety computer technologies in the cockpit in a campaign to reduce human error. This started with the Ground Proximity Warning System (GPWS) to prevent aircraft from Controlled Flight into Terrain (CFIT). With the skies becoming more crowded, the next safety device added was designed to prevent other aircraft from flying into one another and was called Traffic Collision Avoidance System (TCAS). With the all-weather flight capabilities in aircraft and the demand to fly in all types of weather, the industry eventually adopted Airborne Weather Radar to increase safety from the common hazards in the aviation weather environment. Stick shakers were added for Stall Warning. GPWS, TCAS, Airborne Weather Radar and Stall Warning are all tremendous safety devices and they have greatly enhanced aviation safety globally over the last 30 years. At the same time, they are all taking up room in the Liveware (L)-Environment (E) interface as computer generated emergency information to avoid hazards. Adding these with other important computers like the Inertial Navigation System that allow aircraft to navigate from point A to point B in the environment with enhanced computer navigation equipment and the Liveware (L)-Environment (E) interface becomes even more crowded as depicted in Fig. 2. Future Air Traffic Control Systems computers will soon be added to the cockpit in the form of Automatic Dependent Surveillance – Broadcast (ADS-B).

## 2.3 The (L)-(S) Interface

With the Liveware (L)-Hardware (H) interface and the Liveware (L)-Environment (E) interface filled with computers it would seem to be difficult to add more computer power to the Liveware (L)-Software (S) interface. When looking at the original Liveware (L)-Software (S) interface as depicted in Fig. 1, its main purpose was to cover everything that is non-physical used in the aviation system. This is a wide range of materials which includes such things as: procedures, maps, publications, documents, checklists and approach plates. These materials called for a hefty storage space in pilots' flight bags that they would carry with them in the cockpit. The invention of the I-pad would quickly change that allowing everything in those weighty bags to be carried on board electronically by the pilot in what is now called the Electronic Flight Bag (EFB). The Liveware (L)-Software (S) interface was no stranger to computer information, as most modern commercial cockpits produce plenty of computerized information that is digitized in nice LCD screens. However, in the new age of the EFB, all other important flight information that pilots had to carry with them in paper form is now adding more computer information to the Liveware (L)-Software (S) interface as depicted in Fig. 2. This is not only affecting the commercial industry as the EFB is a tremendous step forward for General Aviation (GA) pilots as they are loading everything they can with Jeppesen software into their own EFB's. The advent of pad and smart phone computer technologies taking the form of the EFB have also coincided with the rise of another technology that will offer up what may be the biggest change to come in the SHELL 2017 interfaces related to computers. Surprisingly, this one will be played out in the Liveware (L)–Liveware(L) interface.

### 2.4 The (L)-(L) Interface

The Liveware (L)-Liveware(L) interface accounts for the human interactions that occur in the flight. This can be between the cockpit crew and air traffic control or the cockpit crew and the flight attendants, but most often it focuses in on the heart of flying the aircraft and how the actual flying crew is interacting with one another. The industry has made giant strides in moving from a cockpit paradigm where the Captain was considered god in the cockpit (used up until the 1980s) to a paradigm that focuses on teamwork that is now called Advanced Crew Resource Management (ACRM). The new model focuses on tenants that include: communication, assertiveness, management, task delegation, teamwork, leadership/followership and decision making [3]. Although the computer related safety and efficiency enhancements have had a profound impact on human factors in the cockpit over the last 37 years; it is the non-computer human factors safety program of ACRM that has also had a strong impact to safety and efficiency through the Liveware (L)-Liveware(L) interface. Through this method of teamwork in the cockpit, many of the potential human errors in the Liveware (L)-Liveware(L) interface are being dealt with. However, the strong potential usage of EFB's and ADS-B digitized communication through the computer brings with it a whole new realm of communicating in the cockpit. Instead of communicating with radio, the computer technologies that are now in the cockpit offer a substitute from the radio called digitalized messaging. In terms of NextGen Air Traffic Control technologies this is called "Datalink". This is essentially the same as texting, but is now accomplished from the cockpit. Aircrew are now able to communicate to others outside the cockpit through digital messaging on the computer. Although the industry is at the beginning of implementing this new form of communication, it will be only a matter of time before this new way of communicating through the computer impacts the industry and ACRM. Certainly texting has changed the way people communicate on the ground profoundly. At the same time, it also surprised society by how dangerous it can be if done while driving. How big this computerized communication will become in aviation is something that only time will tell, however its existence and legitimacy as planned in NextGen make it very real. With digitalized communications affecting the Liveware (L)-Liveware (L) interface and the EFB transforming the Liveware (L)-Software (S) interface, the SHELL model has been completely transformed in all interfaces in 2017.

## 3 The SHELL Model 2017 and Asiana Flight 214

The repercussions of this new SHELL model to aviation human factors and human error have been well documented in aviation incidents and accidents over the last two decades and the San Francisco Asiana Flight 214 crash is a great example. The new 2017 SHELL Model in Fig. 2 depicts computer automation and information in all four interfaces of the SHELL and these computer innovations have been responsible for making aviation extremely safe and efficient in the last 20 years. The downside to these technological enhancements are those rare cases where computer/human factors causations line up causing human error from those SHELL interfaces and cause an incident or a rare accident. Some of the most common causes of computer-Liveware (L) error seen the most by the industry are: (1) Complacency in relying on computers, (2) Not understanding the computers, (3) Overly Focused on a computer and distracted from flying, and (4) Optical inside only with little outward scanning. In the Asiana Flight 214 crash, the pilots became complacent in the Liveware (L)-Hardware (H) and relied on their computer system to do the landings instead of being proficient at manual landings while using the computer and auto-throttles to help improve the manual landings [4]. They fell short in the Liveware (L)-Liveware (L) interface where they needed to be able to cross check normal landing checkpoints of altitude and airspeed to correct sooner when too low on glideslope and communicate this through good ACRM. In the Liveware (L) – Environment (E) interface they ignored the GPWS too long as they needed to be able to manually do a missed approach sooner in the landing. In the Liveware (L)-Hardware (H) interface the pilots also had a difficult time understanding the idiosyncrasies of the auto throttle system. By using proper ACRM training techniques like task Management and assertiveness, other members of the crew could have participated and even challenged the wrong auto throttle setting and possibly prevented the accident. In the Liveware (L)-Hardware (H) interface, when the computer technology is not working, the crew must be able to confirm the malfunction and assertively take the proper course of action. Lastly, from the Liveware (L)-Software (S) interface, the Asiana crew had become so reliant on the computer systems to land the aircraft safely that they focused more on their computers inside the cockpit then on basic landing parameters; the most important being the runway glide slope monitor telling them to execute a missed approach sooner. To avoid these errors with computers, pilots still need to aviate, navigate and communicate while scanning outside to use the runway and inside while still flying with the computer automation and information. They need to task delegate with the computers by being more human centered and managing the computer systems to fly the aircraft instead of being computer centered and letting the computer fly them.

## 4 The SHELL 2017 and the Potential Human Factors Cognition Issue

The NTSB recognized many different factors as the Probable cause in this Asiana Flight 214 accident. Usually one or two Probable Causes covers the main cause of NTSB Aviation Accident investigative reports, but the case of Asiana Flight 214 was different. The probable cause of the Asiana Flight 214 accident was determined by the NTSB to be the flight crew's mismanagement of the airplane's descent during the visual approach, the flying pilot's unintended deactivation of automatic airspeed control, the flight crew's inadequate monitoring of the airspeed, and the flight crew's delayed execution of a go-around after they became aware that the airplane was below acceptable glide path and airspeed tolerances [4]. These NTSB Probable Causes are all valid, but when looking at them from the SHELL model in 2017 the underlying cause of human factors cognition also needs to be addressed.

### 4.1 Cognitive Processing

The added interactions among SHELL 2017 components are largely cognitive. This involves considerably more continuous information processing, which suggests the potential for overload at some point. As stated earlier, Liveware activity in the SHELL framework is changing to readouts and text. With this evolution, and the emphasis on optical tasks, it is imperative to keep the pilot scan of the displays and instruments in continual engagement. As shown in Fig. 2, what may have been embedded and non-visualized software now requires more focused pilot attention, optical processing, and cognitive processing to understand the plethora of dynamic information presented. When pilots must look up and through the windscreen, the optical flow changes to actual external cues and associated cognitive processing to comprehend what is happening and the relevance to flight parameters. To some degree, use of head-up display symbology is similar to the screens used, and is consistent with the cognitive processing underway. However, real-world visual cues, particularly in non-standard events quickly overloads the pilot. Synthetic vision can introduce real world and virtual representations in the same display, which will consume far more neural resources in combination. The cognition difficulties inherent in the SHELL 2017 interfaces are both combinatorial and concatenated. These might best be illustrated with Gestalt perception principles [5]. For example, the combinatorial effects are seen with proximity (SHELL clouds approach overlapping), closure (premature conclusions), and primacy (initial optical indication). Concatenation effects are evident in the principle of continuation (current trajectory will continue). Cognitive processing clouds represented in the SHELL 2017 illustrations show these principles and their role in cognitive loading and potential for cognitive error. The SHELL process is essentially linear, and the original model did not initially contemplate simultaneous, multi-dimensional interfaces and interactions among the SHELL components. Consequently, as the optical and cognitive loads have increased with digitization, a concatenation effect can occur where information from one SHELL domain attaches to a second domain, and continues to build until the pilot either becomes confused or may reach a faulty conclusion or determine incorrectly a need for action. This can lead to one of the three forms of cognitive error [6]: faulty synthesis involving flawed processing of available information (with premature closure the most common element), faulty knowledge, and faulty data gathering. To assess the significant involvement of cognitive processing represented in the SHELL 2017 architecture, neural functions are key to understanding the safety implications. Prefrontal cortex connects in some fashion with every level of activity in the brain. In this regard, long-term memories distributed throughout inter-connected neural pathways are subject to disruption or rerouting as a result of excess beta wave activity. If a pilot becomes anxious when overcome with information from the cognitive clouds seen in SHELL 2017, this type of disruption occurs. An associated transmitter, acetylcholine, is highly involved in attentional processes, alpha wave production, and is influential in neural processing flow. When alpha wave activity is deficient, the brain lacks sufficient mental speed to connect perceptions and thoughts [7]. Thus, situations that require escalating optical activities, as SHELL 2017 has illustrated, add to the load placed on the prefrontal areas.

## 4.2 Cognitive Flow

When considering the varying functions and intentions of each SHELL component, the combined effects require synchronous neural processing. To achieve this process, information and associated neural actions must flow freely. This flow, however, is easily disrupted and affects intra-neural communication creating an imbalance in the brain's systems [8]. Flow relies on sustained attention to processing demands and a mental sequencing, or map, of what is required to complete actions with rapid updating of working memory [9]. Bowers et al. [10] demonstrated a strikingly different pattern associated with moving between tasks that would indicate post-workload transition effects might manifest with onset of a high level of workload. This is at the heart of the SHELL process. This is precisely the situation when the pilots must integrate the cognitive content and synthesize flow among the various SHELL components. A workload transition, such as shifting within the SHELL 2017 domains, constitutes a shift in cognitive task difficulty and could likely result in an increase in missed events or significant flight dimensions as described by the hysteresis effect which has been attributed to cognitive resource depletion [11]. Among perceptual tasks with SHELL 2017 is constructing a cognitive map of the operating environment and interacting influences. Recent findings [12] verified that neurons in the brain related to space-mapping react to virtual environments differently from the real world. The hippocampus is recruited when a person develops a cognitive map of the environment, including calculation of distances and space, and is further mediated through the post rhinal and entorhinal cortex. In virtual environments, results showed that as much as half the hippocampal neurons usually involved were actually shut down and the cognitive map was nonexistent. The implications for pilots are profound. This suggests a different region of the brain is involved in the spatial learning tasks and processes, compared with reduced digitalization, and is complicated when perceptual variances become intertwined (one using virtual cues and the other real-world cues). The implications for SHELL 2017 are that the cognitive areas encroaching the component boundaries are increasingly subject to perceptual disparities that consume evermore resources and deplete neural energy rapidly [13]. Combinations of virtual and real world perceptual input among the SHELL 2017 components acts directly upon this hippocampal processing with attendant reductions in comprehension by pilots. Taken together, the optical processing demands, coupled with cognitive processing functions, place a notable load upon the pilot. When combined perceptions and multidimensional interfaces are added, there is a likely potential for cognitive disruption. What becomes sacrificed, then, are cognitive maps and continuity of processing. These introduce the phenomenon of cognitive loading, which is examined next.

## 4.3 Cognitive Loading

The concept of cognitive loading was introduced in 1988 and developed further by Chandler and Sweller [14]. As the term came into use for attention and memory applications, references to information processing became prominent with particular emphasis on perception, memory, and reasoning. The amygdalae are constantly scanning incoming information to determine potentials for safety risks. Increased scanning activity, as with the SHELL 2017 cognitive tasks, has the potential to elevate conscious awareness of perceived threats. As is well known, the amygdalae can dominate the neocortex and obstruct clear thinking when most needed [15]. Related neural function is contained in the concept of continuous partial attention which is a compromised state of focus due to attending many information streams at the same time. This is directly indicated in the growing cognitive task clouds of SHELL 2017, and can lead to infoglut from continuously increasing information contexts. The concept of working memory developed by Baddeley [16] has proven robust and is widely accepted as a useful model for understanding how brief memory operates. As he described it, working memory is the cognitive process that allows moment-to-moment perceptions across time to be integrated, rehearsed, and combined with simultaneous access to stored information about previous experience, actions, or knowledge. As for the encoding aspect of the arriving and cycling information, proteins in the prefrontal cortex are essential to keeping optical tasks and neural processing active. As additional messages are added, the replenishment of synthesized protein is inhibited or diminished, thereby causing loss of some of the cycling elements active in working memory [17], which happens when strings of working memory connected with the SHELL 2017 tasks are compromised and no longer intact. Drawing upon the model developed by Baddeley for working memory, and including recent findings for bandwidth issues and protein cycling limits, it is apparent that pilots operating in the realm of SHELL 2017 cognitive loading can reach saturation of working memory buffering. Pilots in a digitized cockpit often are working with multiple screens and monitors. As would be expected, the visual component of perception is subject to saturation from stimuli and data. Accompanying visual input is the need to interpret the significance or urgency of the information. Perceiving what is critical, what is evolving, and sequences for actions becomes paramount. An element associated with reducing stress is the ability to resolve conflicts as they arise. A resulting uncertainty with regard to conflict resolution can occur between two states such as GPWS alert (L-E interface) and EFB map (L-S interface). While cognitive memory is generally mediated in the anterior hippocampi, affective memory is processed via the amygdalae. Often, amygdala-driven memories can take precedence in neural sequencing. For some pilots, amygdala-level situational appraisal may invite distorted pattern recognition and proneness to false alarms [18]. When considering automation influences between open-loop and closed-loop interactions, issues related to SHELL 2017 cognitive loading become evident. Evidence reported in a study [19] of nearly 2,000 pilots flying aircraft with advanced automation systems showed pilots described differences in "flying through the computer, which required more self-discipline, lags in anticipating aircraft behavior, and increased monitoring of mode annunciations. Each of these conditions increases the vigilance pilots direct to the cognitive tasks in the expanded SHELL 2017 environment. In our examination of SHELL 2017 effects, information being encoded from multiple related sources in an interactive interface can present a delta gap effect which delays correctly understanding the implications of the information received. As the cycling working memory elements from several SHELL domains are attempting to cross-communicate among various neural processing centers, the lag in neural responding and accurate information integration can be profound [20]. Consequently, when cross-neuralization is challenged (as in combined SHELL 2017 cognitive activities) – a delta gap may apply, with signal lag among brain components responding to inquiries from other brain sending locations. Potential for confusion, slowed comprehension, and related cognitive functions increases accordingly. With cognitive shifts from closed loop to open loop processing into the SHELL 2017 architecture, the pilot is likely to be cycling two or more scenarios in working memory, with rehearsal and encoding challenges continually involved to comprehend flight maneuvers and anticipated next steps. Where level of automation is not a significant factor, what has become evident is that although mental resources are not always completely expended for primary tasks, the presence of competing demands from secondary task components can strain the primary functions to the point of saturation [10]. It has been demonstrated that working memory deficits involving increased dopamine levels caused by stress can occur [9]. The obvious implications for SHELL 2017 are that, should pilots become confused or anxious, working memory deficits could manifest. Likewise, calcium sensitive kinases, calcineurin, and dephosphorylation have been shown as detrimental to working memory and are in evidence during high visual task loadings [21]. When neural processing capacities are exceeded, with particular reference to the digitized cockpit environment, degraded situational awareness and various cognitive errors may ensue. Further, this disrupts the prospective memory and remaining ahead of related incoming information from other components of the SHELL interactive process.

### 4.4 Situational Awareness

Research on mental workload, and especially overload, has focused on situational awareness, information processing, and decision making where they are simultaneously present. When too high or too low, cognitive load increases risk of error, more notably when abrupt bursts of a large amount of information must be processed quickly [22]. This would likely occur, for instance, during unanticipated events and rapidly changing information flow in the digitized cockpit environment. Correspondingly, the outcome manifests as a cognitive loading challenge. The researchers found that the nature of a non-linear task environment, like that with SHELL 2017, stimulated operator concerns about future states of the system. The SHELL 2017 domain has advanced the optical interactions significantly. Accompanying the optical loading, interaction effects can be expected. Endsley [23] describes situational awareness (SA) as a working memory bottleneck for pilots in novel situations. For more experienced pilots with skilled performance capabilities, increased recruitment of long term memory augments the SA process and results in fewer gaps or performance decrement. Consequently, the volume of mental processing to sustain high levels of SA require pilot access to embedded mental constructs in long term memory. Such increased and sustained activity would clearly result in a more rapid consumption rate of available brain glucose necessary for effective functioning. Protein that is fueling working and prospective memory is depleted rapidly [21]. A study of pilot decision making [24] affirmed that in low tempo operations extra cognitive resources are available, however, when uncommon or emergency events occur pilot time for reflection is substantially reduced. Consequences result in the need for understanding that the changed situation has compromised the system status. The researchers identified several cognitive breakdowns that occurred: delay in comprehending an event was occurring, fragmented scan of information sources, narrowed assessment, inability to commit to a course of action, and failure to re-check new courses of action to assure implementation as intended. As digital cockpit pilots become loaded near maximum working memory capacity, during especially challenging flight maneuvers or unanticipated procedures, deferring critical actions could be catastrophic. As the SHELL 2017 model illustrates, multiple, simultaneous optical processing tasks must be attended to and integrated with current flight parameters and aircraft systems. When exceeded, neural capacities become strained and, along with incipient cognitive error, mode confusion can result. This has a history, as highlighted in the Australian study of pilots [25] which also confirmed that workarounds highjacked cognitive resources. As optical processing demands have increased, many pilots view the flight management computer as more competent than themselves.

## 5 Conclusions

In summary, the SHELL 2017 representation reflects the combined influences of optical processing demands on pilots, and the related cognitive loading challenges associated with the proliferation of similar cognitive tasks within each SHELL domain. Efforts to contain or reduce cognitive error suggest better training for pilots so they are aware of potential environments that contribute to error. Other efforts are more within the adaptive automation spectrum to recognize potential error and adjust flight computations accordingly. Further assessment of the similarities and differences of cognitive demands within each SHELL domain is indicated to more thoroughly understand how to gain efficiencies and to reduce potential for unintended errors based on cognitive misperceptions.

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