Working Memory Capacity, Mental Fatigue, and Human Performance

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Abstract: Errors in aviation can cause death. When the cause of error is not understood, it cannot be mitigated and will repeat. This paper will explore an area of error causality that is not addressed or even identified in aviation training or operations The aviation industry should evaluate their current pilots and establish a hiring baseline for working memory capacity. This is the first step in understanding and mitigating what may be a fundamental cause of many accidents and incidents. First, working memory (WM), working memory capacity (WMC), and mental fatigue (MF) will be defined using current literature. Only one study is operationally based, the rest are experimentally based. In the referenced literature, WMC was evaluated using complex span tests (CST) or automated operational span tests (Aospan). Individuals with low WMC were found to be more likely to be reactive, have slower response times, be more easily affected by interruptions, and have higher error rates. Individuals with high WMC were more proactive, were less affected by interruptions, maintained goal focus, and made fewer errors.

1 INTRODUCTION

Aviation is inherently dangerous. When errors are made, lives are placed in danger. Crew Resource Management (CRM) created a way for crews to communicate more effectively and to include all relevant information in the decision-making process. Not much has changed since that time, and accidents still occur. This discussion will look deeper into the cognitive processes that drive CRM behaviours and may explain many of the recurring failures. The ability of humans to process relevant information resulting in an acceptable outcome, is variable in many ways. Humans are individually unique in cognitive abilities and their expression through decision-making, which is founded on working memory capacity (WMC). There are low-WMC and high-WMC individuals with significant differences in ability. In addition, humans are variable in response to fatigue, specifically mental fatigue (MF), which has a variable impact on low vs high WMC individuals. Studies now show that these variables are identifiable and quantifiable. This may be an open window into understanding how and why CRM fails. More aviation-specific studies are needed that will support this focus on cognitive causality based on WMC and MF variability and influences.

1.1 Error Causality

All airlines spend millions of dollars and thousands of hours on simulator instruction, but one common goal is always present: error elimination. The challenge is tracing error to its expressed behavior, then on to the originating causality. A procedural error in an approach may be identified as a lack of knowledge of the automation capability of the aircraft. What cannot be determined superficially is: why was that knowledge unavailable to the pilot at that time? Foundationally, behavior causality is cognitively based, yet there is no formal process in aviation to evaluate cognitive ability. Instructors assess and evaluate based on observed human performance. As design, maintenance, and automation improved, failure causality was more directly placed on pilots. Studies suggest that between 60% and 80% of accidents have human factor causality (Shappell et al., 2007).

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1.2 CRM Origins

The crash of United Flight 173 from New York to Portland, Oregon, ushered in a new era of crew training designed to eliminate error. The aircraft had experienced a gear malfunction prior to landing. Air traffic control gave the crew airspace to hold and work on the problem. The captain became distracted by the needs of the cabin crew in their preparation for the approach. He ignored the statements about limited fuel made by the cockpit crew during this time. By the time he realized the severity of the situation and turned toward the airport, they were already running out of fuel. Flight 173 crashed in a neighborhood short of the airport due to fuel starvation. Ten people died, and dozens were injured. As a result of the findings of this crash, Crew Resource Management (CRM) was born. The goal of CRM is to ensure that safer decisions will be made with more information and coordination. CRM is an external view of behaviours centered around teamwork, leadership, communication, situational awareness, and decision- making. This approach led to vast improvements in the leadership gradient and overall crew collaboration. Unfortunately, errors continued to occur, and people continued to die. In a high- reliability industry like aviation, one accident is consequential.

2 BACKGROUND

As an instructor/evaluator and teaching Human Factors, I became interested in a series of five near catastrophic events that occurred during the go around phase of flight. A go-around is when the crew or the controller decide that the aircraft must break off the approach and fly a specific procedure instead of landing. This can be directed because the spacing between landing aircraft is too close, wind or weather is now beyond landing limits, an aircraft malfunction, not meeting stable approach criteria, or many other reasons. The five events were evaluated for causality commonality. Was there a training, proficiency, currency, planning, or fatigue issue that could be credited with explaining why the crews flew perfectly good aircraft into an undesired aircraft state (UAS)? The crews were professionally qualified and experienced, had received good training with no deficiencies, and were not physiologically fatigued. The events occurred in different aircraft, at various locations both domestic and international. The intersecting commonality was limited. All UAS events were all at the end of a flight and required the use of a specific procedure engaging both implicit autonomic response and explicit cognitive engagement. All the crews made serious errors including, power application, system control, flight path, communication, and others. In the goal of tracing causality, there seemed to be no common external factors identified that would mitigate the developed UAS. An unidentified influence was likely behind these failed maneuvers.

After doing an informal survey of simulator instructors, a common experience became clear. In training for the requirement of a go-around there is a prescribed procedure that dictates pitch, power, flight path management, and configuration changes. There is also a verbal litany that accompanies the flight path profile with the intent of communicating the steps as they occur. There were pilots who could fly the entire go-around procedure perfectly but could not seem to get the corresponding verbal call outs correctly. Other pilots got every memory call out correctly but could not fly the prescribed procedure profile while doing so. While most pilots seemed to perform to standards, this limited performance group was large enough to be identifiable. While this was completely anecdotal and held no scientific value, it was the assessment of instructors with thousands of hours of observations. The differences in performance behavior could not be explained through error analysis of CRM, or any other training application. Boksem and Tops research identify attentional control decrements due to the impact of mental fatigue (2008). Further research, presented here, exposed attentional control decrements as a shared impact of low-WMC and MF on cognitive performance. This paper explores the limitations of WMC variability and the combined impact of MF. There are several questions that should be answered. First, can variations in WMC among non-mentally fatigued individuals impact their performance under high workloads? Next, could that explain why some pilots who met application and interview criteria seem to underperform? Drews and Musters (2015) warn that individuals who are functioning at their maximum WMC are likely to have increase error rates and less effective strategies for task completion. Finally, what impact, if any, does MF have on the performance of those with low-WMC vs high-WMC. These questions must be explored to fully understand the potential for performance decrements in high workload environments.

Moreover, if having a specific WMC score has an impact on human performance, measuring this prior to employment may provide a benefit to error reduction and safety.

Understanding the interaction and integrated impacts Working Memory Capacity and Mental Fatigue have on Human Performance must start with definitions. By providing clarity through definitions, the nature of the interactions and potential performance variability can be described with more specifics.

3 DEFINITIONS

3.1 Working Memory

Working memory (WM), as defined by Unsworth and Engle (2008), combines the recall, use, and management of information relevant to the task at hand. It has been further defined by including the ability to keep behaviorally focused on the relevant information despite distractions (Jarrold & Towse, 2006). Baddeley (2001) considered executive attentional control as an important agent for maintaining WM focus. In early research into WM, the concept of accessing information from long-term memory (LTM) was developed by Ericsson & Kintsch, (1995). They differentiate the durability of long-term working memory (LT-WM) and short-term working memory (ST-WM) in WM. They suggest that LT-WM is dependent on attentional controls, and once available, it must be kept active, or it is lost. This concept is critical when considering task interruption and reengagement.

3.2 Working Memory Capacity

Working memory capacity is a newer concept that explains the personal differences in functionality, fixed storage, and ability to focus attention (Shipstead et al., 2016). In earlier work by Unsworth & Engle (2008, p. 616), the idea of “active manipulation” is offered as a defining component for moving WM to WMC. This is the process of bringing relevant long- term memories forward for integration. There are strong positive correlations between WMC and fluid intelligence, offering an avenue for assessment (Shipstead et al., 2016). Fluid intelligence is demonstrated by novel problem-solving methods. Strong capabilities in fluid intelligence access relevant information from LT-WM and apply it to the current environment in creative ways that provide solutions. A significant aspect of fluid intelligence is the propensity to identify and activate disparate stored information that, when integrated, adds to the developed solution (Shipstead et al., 2016). Jastrzębski, et al. (2018) suggest that the efficiency of WM is strongly supported by an individual’s fluid intelligence. Their work specifically identifies that WMC, and fluid intelligence are insulated from strategy use and show interdependence (Jastrzębski, et al., 2018). With such strong correlations to WMC, future studies of pilot cognitive abilities should incorporate fluid intelligence assessments. WMC is the ability to take in current stimulus held in ST-WM, use executive control to identify relevant LT-WM information, and apply attentional controls to keep all the information available. All this is accomplished while determining the appropriate response during the engagement of implicit, automaticity-based behavior.

WMC Assessment. WMC variation can be measured and evaluated using complex span tasks (CST) (Redick et al., 2012). An automated operation span test (Aospan) has also been used successfully and is associated with fluid cognition (Unsworth et al., 2005). The common research employment is to assess WMC, then invite those in the top and bottom quartiles for quantitative testing. This process provides a clear division in capabilities and performance variations in WMC among the individuals evaluated (Bafna & Hansen, 2021). Then, during task loading testing, performance is related to the WMC scores. Osaka et al. (2021) have identified brain activity differences between high-WMC and low-WMC individuals. Their work indicates that low-WMC individuals appear to engage more areas of the brain to accomplish certain tasks than those with high-WMC. High-WMC individuals showed much higher engagement in the anterior cingulate cortex (ACC). This may indicate a need to recruit more areas of the brain in low-WMC individuals for the same task. The ACC is thought to have a significant impact on attentional control and inhibition. Inhibition, in this case, is helpful in maintaining goal-oriented behavior by inhibiting nonrelevant stimuli from becoming significant. In addition, Quaedflieg et al. (2019) show reduced capabilities in those with low WMC when under stress. Ahmed and Fockert (2012) use visual flanker trials in their study of WMC and working memory load (WML). Consistent with other studies, they found that “high-WMC individuals were indeed better able to adjust their attentional window to task-relevant information compared to low-WMC individuals” (Ahmed & Fockert, 2012, p. 9). This visual response study is relevant to the visual distractions that can occur in the cockpit. Variations in both high-WMC and low-WMC individuals have proven to impact performance. What happens when they are impacted further by high levels of task loading?

USAF WMC Assessment. In 1980, while attending USAF pilot training, I was exposed to a process that evaluated WMC from an operational performance perspective without having the scientific definitions or studies to support it. Everyone was ranked by the end of pilot training. The ranking was for the purpose of identifying those with the highest skill sets. The ranking was from highest to lowest: fighter/instructor qualified, fighter qualified, and multicrew qualified. How did they manage to develop the ranking without the science of WMC? A pilot candidate had to be exceptionally skilled at flying to rise above the multicrew ranking to become fighter-qualified. Next, those with the fighter-qualified ranking still had to prove their ability to be instructors as well. The technique the USAF used was to create a high-task-loaded environment during challenging flying engagements. They did this by engaging the student in distracting conversations while flying a challenging formation rejoin maneuver or any other challenging flying task. If the student could still fly the jet well with no performance loss while engaged in conversation and other distractions, they were fighter/instructor qualified. This was an important evaluation, as many new pilots were brought back and trained as pilot training instructors. Most of the fighter/instructor-qualified pilots were selected for F-15, F-16, or other single-seat high- performance aircraft. The USAF also required forward air controllers to be fighter/instructor qualified. Their job was to fly the OV-10, a single pilot twin engine turboprop, at low altitude while talking on three different radios, marking targets on maps, and recording fighter information. Then the pilot developed attack headings and providing final attack clearance, a very task intensive job. The USAF circa 1980 ranking system was experientially developed and offered pilots a way to compete for the best assignments. More importantly, it created a margin of performance capability and safety for the USAF. The result was a ranking system based on a pilot's ability to maintain attentional focus and keep relevant information a priority. Military pilot training is intentionally a culling process with high washout rates. The candidates had to prove their capabilities if they wanted to get their wings.

Airline Assessment. Commercial flying is a multicrew-based operation with international and federal regulations as well as corporate rules and guidance. Pilots must meet minimum experience requirements to be invited to an interview. Pilots prove their qualifications when they pass the interview. The training is designed to be the most efficient in the least amount of time to produce a safe pilot. The interview process does not necessarily identify capabilities under stress or high task loading. The ability of the pilot to operate under stress is assumed. This assumption is a mistake and exposes a gap in capability assessment. As aviation moves into higher levels of complex airspace management and aircraft automation, this gap should be eliminated. The importance of eliminating this gap in assessment becomes stark when the impact of mental fatigue is considered.

3.3 Mental Fatigue

Mental fatigue is differentiated from both physical fatigue and sleep-loss fatigue. While both conditions may contribute to mental fatigue, it does not require their presence. Task loading induced mental fatigue can be categorized as acute mental fatigue. Other forms of mental fatigue can be injury or illness induced (Bafna & Hansen, 2021). Here, the term mental fatigue (MF) will refer to acute task-loaded mental fatigue. MF can be identified by many different cognitive test variations that identify deviations correlated to task level increases. MF can develop during short periods of high task loading and does not require prolonged periods of work (Boksem & Tops, 2008). MF is further defined based on physiology and energy use. The biochemical activity of energy use in the brain under high demand can produce sleep regulatory substances, including adenosine, which shut down that part of the brain. This inhibitory effect may be contributory to MF decrements (Kumar et al., 2013).

The ACC (anterior cingulate cortex) is an area of the brain where the impact of excess adenosine may directly impact WMC and information processing. Darnai et al. (2023) identify that as MF rises, activity in the ACC and other non-task-specific areas decreases. High-WMC individuals have increased activity in the ACC as compared to low-WMC individuals during complex-span tasks (Osaka et al., 2021). This may result in improved executive function and goal-directed behavior by high-WMC individuals. In addition, Osaka et al. (2021) identify the importance of the ACC in central executive functions, a key component of WMC. Moreover, elevated levels of adenosine may directly affect effort-based decision-making (Martin et al., 2018). Proper decision-making requires all components of WMC, including drawing explicit memories from long-term memory. Anything that degrades motivation or allows irrelevant information into the processing process can disrupt this process. This is an effortful activity engaging in goal-centered processing, which is an executive function required to ensure proper response inhibition. The brain engages in filtering processes that inhibit inappropriate or irrelevant responses. Chen, et al. (2021) produced an electroencephalographic study engaging participants in task interruption trials. To induce mental fatigue, they used the AX continuous performance task. A negative effect of interruption on WM was identified in non-MF participants. They also noted that: "In the current study we found that high WMC individuals were indeed better able to adjust their attentional window to task relevant information compared to low WMC individuals…" (Chen et al., 2021, p. 9). This finding is consistent with other forms of testing that have identified the importance of attentional control associated with WMC (Ahmed & Fockert, 2012; Baddley, 2001; Engle, 2002; Kane and Engle, 2002). Guo et al. (2018) support this and determined that in addition to degraded and delayed response inhibition, there also appeared to be a reduction in the allocation of attentional resources. When referring to the definition of WM above, the impact of attentional focus and control on relevant information is identified as essential for WM maintenance and function. WMC, then, must have those components available to effectively engage in the active environment. Adenosine buildup from high cognitive activity and task loading-induced MF may have a negative impact on the functionality of WMC through various channels. This impact is associated with the ability to accurately process the information required for an effective response. Loss of executive attentional control, an effect of MF, appears to allow irrelevant information to drive inappropriate reactions or delayed responses. In addition, MF has been shown to create resistance toward increasing effort during task accomplishment (Lorist et al., 2000). This is consistent with the concept that MF results in reduced motivation and effort for task completion (Boksem & Tops, 2008). Lorist et al. (2000) show how mentally fatigued subjects move toward stimulus-based reactions and away from WMC-based responses. This may be due to the loss of the capability of executive control to exclude irrelevant stimulus. This loss of executive control through MF has been shown to affect the allocation of information resources of WM through electroencephalogram testing (Yang, et al., 2021).

Goal-directed behavior is a key component of executive control, where inhibition of irrelevant information maintains goal focus. Reduced executive control resulting from MF actions is driven more by "…situational or external cues, even when this is inappropriate" (van der Linden et al., 2003, p. 47). This can be translated behaviorally as reactions rather than responses. Reactions tend to be explicit in nature, rapid, and without effortful thought. A response takes time and includes explicit memory recall and cognitive processing. The former may or may not produce a positive outcome; the latter is an attempt to produce a desired outcome. When a response becomes too effortful and irrelevant stimuli are present, an erroneous reaction can occur. The data shows that there are limits to WMC. When increased task loading develops into MF, information processing declines, resulting in degraded decision- making. While heuristics are not assessed here, they are less effortful processes in decision-making and often inaccurate, based on previous experience or framing. The influence of MF on perseverance may also show up as confirmation bias: not making the effort to explore all the data before committing to inclusion.

4 DISCUSSION

Proactive and reactive control are defined by Wiemers and Redick (2018). They describe proactive control as using available information to infuse or prepare for a response before a reaction is needed, resulting in faster response times and greater accuracy. Alternatively, they explain reactive control as not engaging relevant information until a critical stimulus appears, then trying to retrieve the information and select an appropriate response, which can lead to slower response times and less accurate responses. In addition to other influences, Wiemers and Redick (2018) identify WMC as an influence in the use of proactive or reactive control. An important concept they present warns that just because low- WMC individuals are less likely to use proactive control, it does not mean that they are incapable of using it. More practice or time on-task training may improve their use (Wiemers & Redick, 2018).

Möckel et al. (2015) also identified how task loading can lead to WM, action control, and attention deficits. They further add that MF may add to the difficulty of staying focused on the relevant information (Möckel et al., 2015). Looking at this another way, irrelevant information or stimulus may become engaged in the process of human performance and degrade available WMC throughput. Considering WMC limits, if additional irrelevant data is added to the processing requirement, it seems likely that there will be an increase in errors. Interruptions have been associated with error causality. Aviation is fraught with interruptions. Drews and Musters (2015) conclude that higher WMC reduces the impact of interruptions. Interruptions increase cognitive demand and can create capacity interference. Key to their findings is that it is the irrelevant information in an interruption that creates cognitive overload. This ties the impact of MF to the degraded inhibition of irrelevant information. Kane and Engle (2002) promote a strong executive attention component in WMC. They define executive attention as:

"a capability whereby memory representations are maintained in a highly active state in the presence of interference, and these representations may reflect action plans, goal states, or task-relevant stimuli in the environment" (p. 638).

Kane and Engle support their position and further claim that active maintenance and distractor blocking function as the core of WMC through the activity of executive attention (2002). Recall that MF can degrade executive attention and allow non-relevant stimulus considerations to increase perceived task loading. This perception influences the effort projection and can reduce motivation for perseverance. Kane and Engle (2002) suggest that active maintenance of information is most critical when interference and distractions are present. This brings focus to the concept that high-WMC individuals perform better during distractions due to stronger executive control inhibiting nonrelevant stimuli.

Unsworth and Robison (2020) explored WMC during extended vigilance tests. This is suggestive of a pilot's requirement to monitor aircraft systems for hours during cruise. They found that while the results for both low and high WMC individuals were similar early on, as time went on the low-WMC individuals experienced a greater performance loss over the high- WMC individuals (Unsworth & Robison, 2020). Studies indicate performance decrements in low- WMC individuals in both short term, high task loading, and long term, time-on-task events.

Research must provide solutions that will function in future proposed cognitive environments. Tools are now available that can identify high-WMC candidates for task-challenged positions like piloting. By eliminating those who will commit more errors based on their limited WMC, aviation organizations will improve safety margins. Individual variations in WMC must be managed by creating a working environment that minimizes distraction potential, a key error contributor. There may also be ways to train more efficient strategies for low-WMC individuals and reduce reaction-based decision-making (Drews & Musters, 2015).

Westbrook et al. (2018) looked at emergency department physicians. They shadowed thirty-six physicians over 120 hours. While this is a small study, it has immense potential to guide future studies in aviation. They assessed the physicians WMC levels using OSPAN, with error rates correlated to interruptions and multitasking. They identified prescribing errors and clinical errors. Prescribing errors increased in association with multitasking; interruptions, however, during this task, failed to have an effect. When trying to accomplish multiple tasks simultaneously during administrative prescribing duties, error rates were high. It was discovered that for every one-point increase in the OSPAN WMC score, the decrease in error rate was 2%. A higher WMC produced fewer errors (Westbrook et al., 2018).

Westbrook et al. found that clinical errors, however, significantly increased with interruptions. While error rates also increased with physician age, they were inversely proportionate to physician seniority. WMC was also associated with clinical errors. A 19% reduction in error rate was observed for each ten-point increase in the OSPAN WMC score (2018). Westbrook et al. (2018) indicate that their study showed a direct connection between error rates and WMC, where those with low WMC made more errors.

This is one of very few operational assessments of WMC, specifically in a high-task-loaded environment comparable to aviation. The correlation is significant. In their conclusion, Westbrook et al. make several points worth considering. They point out that accepted practices of interruptions and multitasking had a negative impact and should raise questions about those traditional strategies (2018). This is also good guidance for aviation. Next, they demonstrated that high-WMC individuals are better at operating in this high-task-loaded environment (Westbrook et al., 2018). Pilots and physicians have been compared many times based on personality types and the stress and task load of their jobs. Tests are available to determine WMC variance. The evidence suggests high-WMC individuals are less error prone. Testing pilots could be a powerful tool for error, incident, and accident prevention.

Human performance in aviation is subject to many influences and variables. The environment is ever- changing, with variations in weather conditions, maintenance restrictions, and changes to NOTAMs (Notices to Airmen), routes, approaches, and personnel. Often, crews meet for the first time an hour before a flight that can take them halfway around the world through many challenges. Regulations and procedures are designed to structuralize behavior as much as possible. CRM and Threat and Error Management are tools and performance aids designed to minimize error-producing behaviors. What if the ultimate error-producing causality is currently invisible to our system of analysis? After an error has occurred, cognitive evaluation is not historical and provides little value to an investigation. During interviews pilots are eyewitness, and eyewitnesses have been shown to be the least reliable source in investigations. The information gathered event by event will be unique to the individual with no way to associate that to the general pilot population. Identifying individual WMC in advance, provides added value to a Safety Management System. Testing on a broad-based level will produce data that will reflect the general population of pilots and allow for system-wide responses.

5 CONCLUSIONS

As aviation moves to higher levels of automation with increased specificity of cognitive focus, matching capabilities to requirements becomes a safety issue. Low-WMC individuals are identified as having higher error rates and longer response times. Their ACC activation levels are lower, and they are more susceptible to distraction and irrelevant stimuli, especially after high task loading and MF onset. High-WMC individuals demonstrate higher levels of perseverance and increased goal-oriented focus despite distractions and irrelevant stimuli. Their response times are faster, and they have fewer errors. Additionally, studies have shown a strong correlation between WMC and fluid intelligence.

Before there can be procedural development or performance filtering, there must be more direct studies involving active pilots from major airlines as well as air traffic controllers. Using available CST and Aospan testing, the WMC and fluid intelligence of the current employees can be ascertained. If validated, training studies should be developed to explore the effectiveness of providing low-WMC individuals with alternative strategies that will prevent reactive behaviors. Alternately, based on the data results, it may be effective to develop a screening process for high-WMC, high-fluid-intelligence candidates. A WMC score scale included in the interview process would bias the selection to those who are more capable of operating in a high-task- loaded, high-interruption profession with reduced error potential. The benefits, projected forward, may allow reduced training times, more complex operations, reduced errors, and improved safety.

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