The Extreme Environment of High Altitude Gas Ballooning: Lessons Learned in Assessing Cognition

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Extreme environments often profoundly impact one's cognition and subsequently the ability to make accurate and correct decisions. Although we are beginning to understand how these environments impact individual and team cognition, more specific work conducted in *real* extreme environments is needed to further understand this relationship. In this paper, we present data collected in the extreme environment of gas ballooning. Recently, the Two Eagles gas ballooning project set two absolute world records: longest duration in a gas balloon and longest distance in a gas balloon. During this project, our research team was able to collect cognitive abilities data and data on the effects of multiple stressors in the environment. We present the overall project along with some insights from the data. We also highlight lessons learned from attempting to collect data in an extreme environment.

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On January 24, 2015 a gas balloon referred to as "Two Eagles" launched from Saga, Japan heading over the Pacific Ocean carrying US pilot, Troy Bradley, and Russian pilot, Leonid Tiukhtyaev. Bradley and Tiukhtyaev were confined to an unpressurized box the size of a king-size bed flying at very high altitudes. Six and ¾ days later on January 30, 2015, Two Eagles landed in the water about four miles offshore near La Poza Grande in Baja, California. The mission was a great success, setting new world records for gas ballooning distance (6,646 miles) and duration (160.5 hours), beating the old records by 27% and 17% respectively (Hawatmeh, 2015).

The Two Eagles mission provided a unique opportunity to assess cognitive readiness in an extreme environment. The purpose of the assessment was twofold: 1) to collect data on the relation between cognitive function and the environmental stressors, and 2) to monitor the cognitive health of the pilots in real-time (or near real-time) to identify periods in which decision making should be turned over to mission control on the ground. However, collecting data in an extreme environment can be challenging and in this article we highlight specific lessons learned during the process. We first describe the Two Eagles mission as an example of an extreme environment.

THE EXTREME ENVIRONMENT OF THE TWO EAGLES

Extreme environments are "*settings that possess extraordinary physical, psychological, and interpersonal demands that require significant human adaptation for survival and performance*." (Manzey & Lorenz, 1998, cited in Orasanu & Lieberman, 2011, pg. 4). Even though these environments are considered *extreme*, many people routinely work in them. Medical practitioners (Harnett, Doarn, Rosen, Hannaford, & Broderick, 2008), firefighters (Aisbett, Wolkow, Sprajcer, & Ferguson, 2012), police officers (Maguen et al., 2009), space explorers (Salas et al., 2015), and many others work and make difficult critical decisions in these contexts. Further, extreme environments with high stress, increased time pressure, ill-defined work-information-goals, changing contexts, emotional distress, extreme ambient conditions, and increased mental and physical workload can greatly strain cognition (Lowe et al., 2007; Maruff, Snyder, McStephen, Collie, & Darby, 2006). Most research on cognition in extreme environments is simulation-based (Kaplan, Connor, Ferranti, Homes, & Spencer, 2012; McNeese, Mancuso, McNeese, Endsley, & Forster, 2014). The Two Eagles provided a chance to examine cognitive function in a *real* extreme environment.

Historical Context of Gas Ballooning

The history of gas ballooning dates back to the 18th century. Gas balloons were one of the first aircraft to fly in 1783, accomplishing the first extended flight in 1784. Gas balloons or Lighter-Than-Air (LTA) aircraft differ from hot air balloons, which obtain buoyancy by heating the air inside of the balloon. LTAs are inflated with a gas of lower molecular weight than that of ambient temperature. The Two Eagles Mission extends from a lineage of record-breaking gas balloon missions- the Double Eagle V in 1981- 5,208 miles (record for distance) and the Double Eagle II in 1978- 137 hours (record for duration). The process of planning the current Two Eagles mission spanned over a decade.

The Two Eagles Team

The Two Eagles mission utilized two extremely accomplished pilots and a mission control team consisting of world-renowned experts. Two Eagles pilot, Troy Bradley, came to the mission with over 6,200 hours of experience and 60 world records in ballooning. In addition, Two Eagles pilot, Leonid Tiukhtyaev was, at the time of the project, the President of Balloon Federation of Russia, leader of the "Russian Records Factory" ballooning project, and had previously set eight world records (see Figure 1). The mission control team was led by Dr. Steven Shope, a pilot himself who has extensively studied high-altitude gas flights and who had served as an event director for five international ballooning competitions. Other members of the crew included a retired Air Force flight surgeon, the world's premier meteorologist for long distance and duration balloon flights, a retired Naval flight officer, a flight scientist, a flight director, a recovery crew coordinator, a flight tracker, and several other critical support members and technical advisors. The mission control team was distributed across many nations with the launch crew in Japan, weather operations out of the Middle East, the recovery team in Mexico, and the mission control site in New Mexico.

Figure 1. Two Eagles Pilots- Troy Bradley and Leonid Tiukhtyaev

The Two Eagles Environment

The balloon system itself consisted of a capsule and an envelope. The 7 ft. long, 5 ft. high, and 5 ft. wide capsule was made from Kevlar/carbon-fiber composite, allowing it to be both very strong and lightweight (approximately 220 lbs.). The capsule was designed to provide shelter from harsh conditions and to survive a rough landing. The interior of the capsule housed an array of navigation and communications equipment, as well as a high altitude heater. The custom-made 350,000-ft^3 envelope weighed 1,475 lbs. and could carry a ballast weight of 11,500 lbs. Helium gas was used because it has a lower molecular weight than the ambient atmosphere.

Several aspects of the Two Eagles mission were unique. First, the Two Eagles balloon was custom-made and had never flown prior to the mission. Second, the 350,000-ft^3 balloon was considerably larger and thus more difficult to fly than most sport gas balloons that are 35,000 ft^3. Third, the unpressurized capsule required the pilots to wear oxygen masks at altitudes of 12,000 ft. and above (altitudes this high can result in temperatures as low as -10 degrees Fahrenheit). Many times throughout the mission, the pilots would have to climb outside of the capsule while at a high altitude to drop ballast bags to adjust the balloon's altitude (Figure 2). Finally, the pilots had no experience (other than training) piloting and flying together prior to the actual mission.

Figure 2. Outside the cabin at a high altitude.

Several additional factors also contributed to the complexity of the mission. The Trans-Pacific flight required a worldwide team to coordinate and work together despite time differences, different air traffic control standards across the globe, and many constant changes during the flight. Pilot health and fatigue were of concern due to the extreme physical environment of the mission and the significant cognitive resources required for nearly seven days. The mission control team also faced great fatigue as they continuously monitored and helped the pilots make critical decisions during the flight. The team had nearly 20 work functions, including flight strategy, cognitive assessment, and weather monitoring.

DATA COLLECTION

The Two Eagles mission provided a unique opportunity to assess cognitive function in an extreme environment in which two pilots were confined to an unpressurized box the size of a king-size bed flying at high altitudes. Data were collected to better understand the relation between cognitive ability and the stressors in this extreme environment and to monitor the cognitive health of the pilots in real-time (or near real-time) to identify periods in which decision making should be turned over to mission control on the ground. It was important not to interfere with the pilots' mission-relevant tasks or sleep. Each pilot was prompted every 12 hours through the flight automation system to take a brief survey (taskwork/teamwork load, situation awareness, etc.) (Figure 3) and two cognitive tests- (Sternberg's Short Term Memory Task (Sternberg, 1969) and a -Mental Rotation Task (Shepard & Metzler, 1971)). Both the survey and the cognitive tests were presented on a laptop. The prompt requested that the pilot complete the survey and tests at his earliest convenience. Baseline data were also gathered prior to launch on January 24, 2015 (UTC). During the Two Eagles mission, data results were immediately sent by satellite to mission control and were then forwarded to the research team for analysis and monitoring. Completing the survey and cognitive tests took about five minutes to complete.

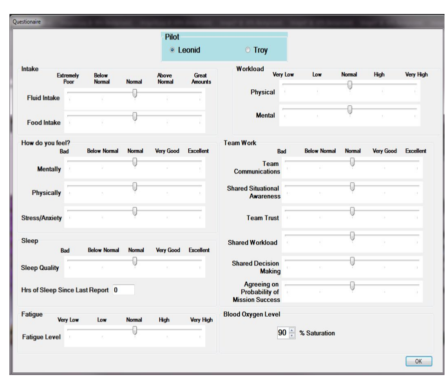

Figure 3. Pilot Survey

The pilots were only able to take the tests once a day at most. Therefore, the data are limited and in particular, the data represent periods during which the pilots were experiencing the least stress and workload (and therefore had the time to take the test). Optimally, as noted in the lessons learned, it would have been beneficial to be able to collect this data during periods of high workload and stress. We provide a general overview of the results here (technology failures resulted in incomplete data on January 25).

The survey data indicated that one pilot experienced maximum stressors (e.g., poor sleep, high workload) on January 26 and 29 (see Table 1 & Figure 4) and on these same days, this pilot's mental rotation performance, and to a lesser extent the Sternberg performance was negatively impacted. On the other hand, the second pilot experienced maximum stressors on January 24 and 26, but experienced the greatest decline in performance on both cognitive tests on January 27. Aggregating the results from the two tests and the survey, the days that were most problematic for the pilots seemed to be January 26 and January 27. It turns out that on January 26 the pilots were miles from the coast of Japan over the Pacific Ocean, but still in Japanese airspace. They were receiving satellite calls from Japanese Air Traffic Control every five minutes, creating a tremendous workload. Eventually, this was mitigated by having the calls redirected to mission control. The first couple of days of the flight were also stressful for other reasons, such as equipment problems, ballast consumption, communication problems, and decisions about trajectories.

Date	Stress	Sleep Quality	Sleep Hours	Fatigue	Workload Physical	Workload Mental
1/24/2015	3	2	4	4	3	3
1/26/2015	3	1	3	4	4	2
1/27/2015	1	4	8	2	3	4
1/28/2015	2	2	6	3	2	3
1/29/2015	4	1	2	4	4	4
1/30/2015	4	3	6	3	3	3

Table 1. Partial Survey results with extreme stressors highlighted for one pilot (standard 5 pt. likert scale).

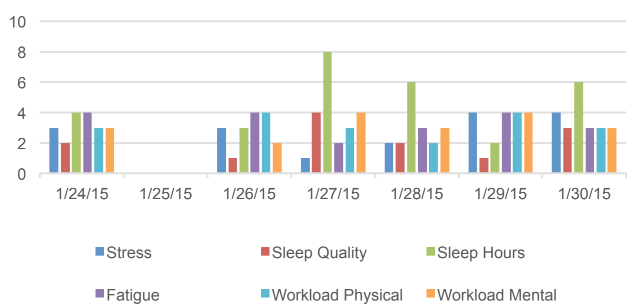

Figure 4. One Pilot's Survey Data

LESSONS LEARNED FROM THE TWO EAGLES DATA COLLECTION

Although the data that we managed to collect were sparse, the lessons learned along the way were quite valuable. We highlight lessons learned in Table 2.

Lesson 1: Use Unobtrusive Measures that are Integrated with Real Work

Collecting data in a routine and structured manner was one of the most challenging aspects of this study. We initially planned to have the pilots complete the survey and participate in the tasks twice a day (they were prompted on their computers every 12 hours), but due to the challenging conditions of the environment, the pilots usually only had time to complete them once a day. Often, the pilots were too busy with their work or too fatigued to complete the measurements when they were prompted. The prompt could be and was ignored when the pilots were dealing with something more important or simply sleeping (sleep cycles were extremely sporadic). When capturing this type of data, it is incredibly important that it is captured during both high/low periods of fatigue/stress/workload. In fact, failures are more likely to occur during high periods, so it is critical that data is captured then. That being said, it is complicated to collect data during these periods as evident in this study.

In response to these challenges, we have several recommendations for ensuring that data collection can regularly occur within an extreme environment. First, measurements should not interfere with the work (or sleep) that takes precedence. One approach is to integrate measures within real work. For example, collecting and analyzing the communication that occurs during actual work allows for insights into cognition, without negatively interfering with any real work. Analyzing communication of team members has previously been utilized in other contexts to develop insights into multiple teamwork behaviors (Cooke, Gorman, Myers, & Duran, 2013). In addition to not being obtrusive, the measures are also directly associated with the work and likely to be more valid. Another approach that can be easily utilized and not require any extra time (from the pilot) is to capture physiological measurements (example: Plarre et al., 2011). This allows for autonomous continuous measurement that takes place in the background of both work and sleep.

Lesson 2: Provide for Real Time Automatic Transmission and Analysis of Data

One of the aims of the data collected in this project was to provide meaningful feedback to mission control on the pilots' cognitive function. If any declines or alarming trends in the data were apparent, mission control could intervene and take over certain aspects of the project. The data transmission plan relied on having the pilots' data sent to the researchers to analyze. Although the data were transmitted, there were multiple challenges that made it difficult to analyze and provide feedback to mission control in real time. Specifically, there was a significant lag in the pilots' sending the data and the researchers receiving it. This is due in part to the data being sent to mission control, who then had to forward it to the researchers. In some cases, the data that the researchers received was up to 12 hours old. This makes it extremely hard to provide timely feedback. There was a specific instance when the researchers alerted mission control to a drop in hours of sleep and sleep quality, but due to the time lag, they were already aware of the issue. In addition to a lag between receiving the pilots' data, there was also a lag from when the researchers initially received the data and when they were able to analyze it. At times, the data would come in at the middle of the night when the researchers were sleeping and they were not able to analyze it in a timely manner.

Due to these challenges, we suggest that data be automatically and directly transmitted to the researchers. There should be minimal lag between data entry by the pilots and receipt by the researchers. In addition to having to wait for mission control to send the data to the research team, there were also hardware malfunctions that resulted in substantial lags. This means that back-up plans must be developed for data transmission. In general, there should be safeguards to ensure for continued data collection and transmission in the event of a system failure.

In addition, we highly recommend that the analysis of data be conducted automatically. With cutoff regions set for certain measures, researchers could be immediately notified if there is a notable change for a specific measure. Not only does this allow for immediate feedback, but it also provides continuity when the researcher is unable to get to the data.

Lesson 3: Pre-test *All* Aspects of Data Collection and the Analysis Plan

In order for data collection and analysis to go as planned in this context, planning and organization are critical. This might seem like a straightforward recommendation, but based on our experience, the extreme environment adds complexities that require additional planning and testing. Even with a substantial amount of planning and testing, we experienced unanticipated consequences due to the environment itself. For example, while we had a plan in place for data collection and it was vetted across all relevant parties, external forces often led to inconsistent and limited data collection. Extremely detailed plans on how the data is being collected, when it is being collected, how is it being analyzed, and who is analyzing it must be developed to account for the project's entire length of time. Testing and training of these plans is also critical to ensuring success. Before data collection begins, pilot data should be collected and analyzed. The research team should practice the data analysis procedures. In this context, researchers often only get one shot, so they must ensure that is done correctly.

Lesson 4: Take a Human Systems Integration Perspective

The single most important lesson that we learned from this project is the importance of taking a human systems perspective (Pew & Mavor, 2007). The Two Eagles project was dependent on many people making correct decisions and effectively working together within a larger system. The attention was rightfully on the pilots, but the overall project's success was due to contributions from multiple people. In retrospect, it would have been wise to collect data from the mission control team, the launch team, family members, and a variety of other decision-makers. These are all people who were critical to the performance and success of the overall mission and make up the larger integrated system.

Although the pilots were under a great deal of pressure and stress, others on the Two Eagles team felt similar pressures. For example, in this project, the mission control team was directly responsible for making many of the critical decisions. For instance, the balloon was headed toward Vancouver, Canada and mission control had all details in place for a Canadian landing including air traffic clearance, news media, and recovery personnel. Suddenly, and unexpectedly, the meteorology team's model predicted a complete change in the balloon's trajectory such that it would now be heading south for Mexico. Mission control had to scramble to divert resources from Canada to Mexico. These mission control activities were essential for the success of the larger team.

Yet, much like the pilots, members of the mission control team were not getting much sleep. All critical decision makers need to be monitored within an extreme environment. One small mistake by one member of the overall team can drastically affect overall mission performance. Simply understanding and monitoring the cognition of all critical Two Eagles team members would have been valuable in providing meaningful feedback.

In addition, it is important to understand the relations between these sub teams and how decisions made by one unit can affect the task of another. Focusing on the pilots and monitoring their decision making may miss some critical events taking place in other parts of the system.

Lesson Learned	Specific Recommendations
1. *Use Unobtrusive Measures that are Integrated with Real Work*	• Cognitive measurements should closely align with real work to ensure that they do not get in the way of work, yet are relevant to work • Use communication analysis for insights into cognition • Capture physiological measurements relevant to cognition
2. *Provide for Real Time Automatic Transmission and Analysis of Data*	• Data need to be immediately and directly transmitted to researchers on a regular schedule • Establish backup plans for data transmission protocol • Provide safeguards for failures in data transmission technologies • Automate the analysis of data
3. *Pre-test All Aspects of Data Collection and Analysis Plan*	• Specific plans should be developed in collaboration with the participants for every stage of data collection and analysis • Pilot tests and training prior to the data collection should be conducted with the research team and real world participants
4. *Take a Human Systems Integration Perspective*	• Collect data from all key players relevant to the task and the environment • Look for interactions of system components and possible unintended consequences

5. *Establish a Plan for Declines in Cognitive Function*	• Develop a plan for how to address a decline in cognition- Operationally define a decline in cognitive function • Automatically alert when there is a decline • Test plan with research team and participants

Table 2. Lessons Learned for Conducting Research in an Extreme Environment

Lesson 5: Establish a Plan for Declines in Cognitive Function

Finally, it is fundamental to develop a plan for cases of declining cognitive function. One of our main goals was to ensure that the pilots' cognition was stable and did not drop below a certain threshold. Yet, what is considered stable cognition and what constitutes a significant drop in cognition? These are matters that must be articulated and addressed before data collection. Identifying what constitutes a decline in cognitive function during the mission wastes valuable time and could end in a negative result.

In addition, the researchers, along with mission control and the pilots, must develop and understand how to implement a specific protocol if cognitive function declines. It is important that this is developed in collaboration with everyone on the team because when the time comes to implement it, everyone must be on the same page. Testing the protocol is integral to ensuring that it is feasible and that each team member understands his or her role during the protocol. Monitoring cognition in an extreme environment should be done for the safety of the people within the environment, and it is not enough to simply monitor it, there must be a plan of action in place.

CONCLUSION

The Two Eagles project provided a natural laboratory in which to study cognitive function in an extreme environment. The mission was happily a success. Records were broken and everyone involved was safe. Although we were able to collect data, the process was not perfect and many challenges arose. These challenges provided a number of lessons learned which we will implement in our next opportunity to study cognitive function in an extreme environment.

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