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A Systematic Review of the Psychological Effects of Heat Stress on Subjects in Uncooled, Sealed, Environment Suits

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A Systematic Review of the Effects of Heat Stress on Human Psychological Performance in Uncooled Sealed Environment Suits

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A Systematic Review of the Effects of Heat Stress on Human Psychological Performance in Uncooled Sealed Environment Suits

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This review was performed to determine if current literature is sufficient to understand the cognitive effects of heat stress for individuals in uncooled pressure suits and the timeline when these effects would occur. Recent growth in the commercial spaceflight industry has led to renewed interest in environment suits to protect against decompression events. Such suits impair the body's thermoregulatory mechanisms leading to heat stress.[22] Because of this, space suits incorporate cooling mechanisms to offload stored heat.[22,32,44] However, coolant system failures have been a recurrent problem for spacecraft, particularly those affecting the systems in pressure suits.[3,4] Events that force crew members to stay in suits for extended periods of time, such as off nominal landings with a delayed rescue, or coolant failures on orbit could expose crew members to significant heat stress. While the physiological effects are well documented, the cognitive effects of heat stress, which could impair one's ability to perform critical spaceflight tasks, are less well understood.

A systematic review was performed via Ovid, Pubmed, the Defense Technical Information Center, the Institute for Scientific Information Web Of Science, and Google Scholar. The aim was to identify English language studies measuring performance ability, body temperature, and time in individuals wearing uncooled, sealed environment suits and performing limited physical activity under hot environmental conditions. These criteria were used to ensure both space suit based and analogue based studies were detected.

Twenty-eight studies representing data from five hundred fifteen individuals met inclusion criteria. The studies tested multiple variables across a range of conditions. The

results show evidence for increased fatigue, increased depression, increased hostility, decreased cognitive capacity, decreased vigilance, worsened task performance, decreased psychomotor abilities, increased anxiety, decreased perception, and decreased memory.

Application of the results from this review to the spacefaring population are limited because most of the reviewed studies are in analogue populations that do not match current astronauts or expected commercial spaceflight participants. Many factors, such as demographics, suit type, health status of individuals, environmental exposures and activities differ between the conditions in these studies and those expected to be experienced in spaceflight.

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List of Abbreviations

BDU	Battle Dress Uniform
EVA	Extra Vehicular Activity
ISS	International Space Station
NASA	National Aeronautics and Space Administration
NBC	Nuclear Biological Chemical
RH	Relative Humidity
UTMB	University of Texas Medical Branch
WBGT	Wet Bulb Globe Temperature

Chapter 1 Introduction

This review was performed to determine the cognitive effects of heat stress for individuals in uncooled pressure suits and, if possible, a timeline for when these effects could be expected to occur. Recent growth in the commercial spaceflight industry has led to renewed interest in environment suits to protect occupants against a sudden explosive decompression of the cabin. As of this writing, five missions and over 60% of spaceflight deaths involved a decompression event without sufficient protective equipment.[3,60] While wearing a pressure suit can offer such protection,[22,44] these suits present their own physiological challenges. Pressure suits impair human thermoregulatory mechanisms and can cause significant heat stress if an effective cooling mechanism is not built in.[22,32,44,45,48] Many studies document the physiological effects of heat stress both in[10,22,48] and out[7,22] of environment suits, but its effects on human psychology are less well understood. Since impaired cognition can affect one's ability to perform mission critical tasks or handle a spaceflight emergency, it is important to understand these effects and determine the time an individual can function effectively should the cooling system fail and the suited subject be unable to remove the suit.

Human metabolism maintains a core body temperature of 37 ± 1°C.[7,11,22] The mechanisms responsible for this are capable of generating a wide range of energy; from 70W at rest to over 1000W with maximal exertion.[20] If this energy is not offloaded to the environment, it builds up within the body and causes a rapid increase in core body temperature. The endogenous thermoregulatory mechanisms, like sweating, vasodilation, and behavioral changes, are effective at managing stored heat up to a core body temperature of 40°C.[7,20,21] These systems rely on the existence of a large, relatively cool, external environment. The small volume of a pressure suit can rapidly saturate with heat and overwhelm the body's thermoregulatory defenses, which is why a built in cooling mechanism is essential for modern space suits.[20,22,44] Unfortunately, coolant system malfunctions in spaceflight are not uncommon. They have occurred with six different spacecraft, including the International Space Station,[3,4,22,75] and four different pressure suit designs including both of those in use today.[4,60]

In order to determine the level of risk to cognitive performance, we must understand the degree of heat stress a crew might experience and the time they would be exposed. Under normal operations, suited crew members of a commercial spacecraft would be strapped in seats within a small volume capsule or spaceplane.[1,5,22,24,46] Physical effort would likely be limited to operating flight controls or computer consoles, performing anti-g straining maneuvers, placing and removing restraints, and exiting the vehicle after landing. They may have mental tasks such as listening and responding to radio calls, interpreting instrument panels or following instructions from crew members or ground control.[1,5,22,36,46] Thermoregulatory models[21,45,48,49,50] and experiential studies[36,50] have demonstrated that with adequate cooling in place, humans can survive comfortably in this state for at least eight hours without evidence of heat stress. However, if the coolant system fails, significant heat would build up quickly and can reach physiologically dangerous levels.[10,50]

It is also important to understand how long the crew would be expected to endure this heat should the cooling system fail. If the crew member is able to open the seals of the suit or remove it entirely, the heat storage problem is solved. However, circumstances where this is not possible would force the crew member to remain suited for an extended period of time. According to the published flight profiles for suborbital vehicles, the mission durations are often under two hours.[1,2,3,5,75] For orbital vehicles the time from de-orbit burn to landing is between one and three hours[2,3,75]. Under normal operations the vehicles would land near planned sites and recovery of the vehicle and crew would occur rapidly, often within one hour.[1,2,3,5,75] However, due to the altitudes and speeds spacecraft can achieve, an off nominal landing can place a spacecraft far from its intended destination and prolong the time to rescue.[2,3,60,75]

Since an off nominal landing may be precipitated by a crew incapacitating event or may itself expose the crew to cripplingly high g forces[3,60] it is conceivable that crew members would be unable to self extricate from their suits. Furthermore, if the space craft is returning astronauts from extended stays aboard the ISS, de-conditioning may increase the likelihood of crew incapacitation.[22] Like coolant failures, off nominal landings are not uncommon[3,60] and, in some cases, have left crew without assistance for over 24 hours.[2,3]

A second possibility is that cooling could fail on orbit or peri-reentry, as happened aboard STS-111.[50] In this case the crew would not be able remove their pressure suits due to the risk of cabin decompression and would have to remain in uncooled suits for the duration of reentry. Under these conditions the crew would endure rising cabin temperatures as well as trapped metabolic heat, which could impair mental function during critical phases of flight when a clear head is most needed.[50]

Both commercial entities and government programs are planning more launches in coming years.[23] More launches will increase the risk of off nominal landings and coolant system failures. For this reason, it is important to establish how heat stress affects mental function and how long a suited crew member could remain uncooled before being affected.

Chapter 2 Methods

A systematic literature search was conducted in Ovid, Pubmed, the Defense Technical Information Center, the Institute for Scientific Information Web Of Science, and Google Scholar. The aim was to compile all available literature on human studies of cognitive performance and endurance in uncooled environment suits. The search terms included; “TEMPERATURE”, “THERMAL”, “CONVECTION”, “HEAT”, “MICROCLIMATE”, “HYPERTHERMIA”, “COGNITION”, “COGNITIVE”, “PSYCHIATRIC”, “PSYCHIATRY”, “PSYCHOLOGY”, “PSYCHOLOGICAL”, “VIGILANCE”, “MOOD”, “PSYCHOMOTOR”, “PERCEPTION”, “SUIT”, “GARMENT”, “CLOTHING”, “GEAR”, “PRESSURE”, “ENVIRONMENT”, “ACES”, “NBC”, “LES”, “SEES”, “HAPS”, “CSU”, “NUCLEAR BIOLOGICAL CHEMICAL” “ADVANCED CREW ESCAPE” “SHUTTLE EJECTION ESCAPE” LAUNCH ENTRY” “HIGH ALTITUDE PROTECTION” “ MODIFIED ADVANCED CREW ESCAPE” All titles obtained through these keywords were reviewed. Additional references were sought among citations within the articles. Titles published without translation in non-English languages, those where suits were not sealed, and ones that did not measure psychological variables were discarded. Additional inclusion criteria are presented in Table 1. All sections of the remaining papers were then carefully evaluated and incorporated into this review.

Many studies were found that included measures of physiological tolerance to heat stress in suits but no measures of mental function. Others measured psychological variables under heat stress but did not involve suited subjects. The decision not to include these studies was based on the number of reviews on physiological heat tolerance and space suit validation studies already present in the literature.[36,49,50,51] The answers sought here were intentionally narrowed to address the specific question of how and how fast heat stress impacts mental function in suited subjects.

Each included study was assessed for quality and validity according to criteria adapted from the McMaster/Duke EBM appraisal guide.[25,40] These criteria were used to assign each study a quality score out of a maximum of 10 points, one for each section of the appraisal sheet (Table 2). Additionally, each psychological battery and metric used in each study was appraised according to the scale in Table 3 and assigned a score from one to four. The total score for each paper was added together divided by the maximum possible to arrive at a percent validation. Scores under 20% were given a rating of F and coded red, 21-40% were rated D and coded orange, 41-60% were rated C and coded yellow, 61-80% were rated B and coded green, and 81-100% were Rated A and coded blue. These results are presented in Table 5 in Appendix A.

Databases and search criteria;
- Inclusion Criteria;
• Conducted on human subjects or validated mannequins
• English language
• Used sealed environment suit or space suits
• Used physiologic monitoring
• Collected measures of psychological performance

Table 1: Study Inclusion Criteria

Points	**How serious is the risk of bias?**	
3 points	**Aside from the exposure of interest, did the exposed and control groups start and finish with the same risk for the outcome?**	
	Were the patients similar for prognostic factors that are known to be associated with the outcome (or did statistical adjustment level the playing field)?	
	Were the circumstances and methods for detecting the outcome similar?	
	Was the follow-up sufficiently complete?	
2 points	**What are the Results?**	
	How strong is the association between exposure and outcome?	
	How precise is the estimate of risk?	
5 points	**How can I apply the results to my patient care?**	
	Were the study patients similar to patients in my practice?	
	Was follow-up sufficiently long?	
	Is the exposure similar to what might occur in my patient?	
	What is the magnitude of the risk?	
	Were the results analyzed effectively	
Total Points____/10		

Table 2: Harm Cohort Study Critical Appraisal Worksheet [25,40]

Subjective ratings	assessment battery without validation	Assessment battery with some validation studies*	Assessment battery with extensive validation** OR Objective measures of performance quality
1 point	2 points	3 points	4 points
		*1-3 small studies in cohorts not necessarily similar to the study population	**Multiple studies in similar cohorts to study population

Table 3: Psychological battery and metric assessment scale

Chapter 3 Results

Using the methods outlined above, 1,763 references were identified dealing with environment suits and temperature. Of these, 1,349 were not scientific studies, were not conducted on humans, were not in English, or focused primarily on cooling mechanisms. 319 did not assess psychological variables, and 67 were review articles. 28 studies met criteria and are included in this review (Figure 1). A summary of these studies and an assessment of quality is provided in Appendix A in Table 4 and Table 5 respectively.

The studies represent 515 healthy individuals, 18% female/82% male, with a mean age of 21.5 years. Most of these studies compared performance in suited subjects to performance of the same subjects in plain clothes on separate days. Plain clothes included military Battle Dress Uniform (BDU) or athletic clothing. The suits used include hazardous materials gear, firefighter turnout gear, Nuclear-Biological-Chemical (NBC) protective gear, and a launch and reentry suit intended for the Space Shuttle.[36] The settings include human performance laboratories, field studies, and simulators and the measures of psychological variables range from self report surveys to validated assessment batteries to measures of task or flight performance.

Exposure conditions and endurance times varied greatly across the studies. Temperatures ranged from ambient air up to 89C. In most studies, several participants had to be removed early. This occurred for a variety of reasons such as exceeding pre determined heart rate limits, core temperature limits, showing signs of heat shock, or electively terminating their own participation due to discomfort or fatigue.

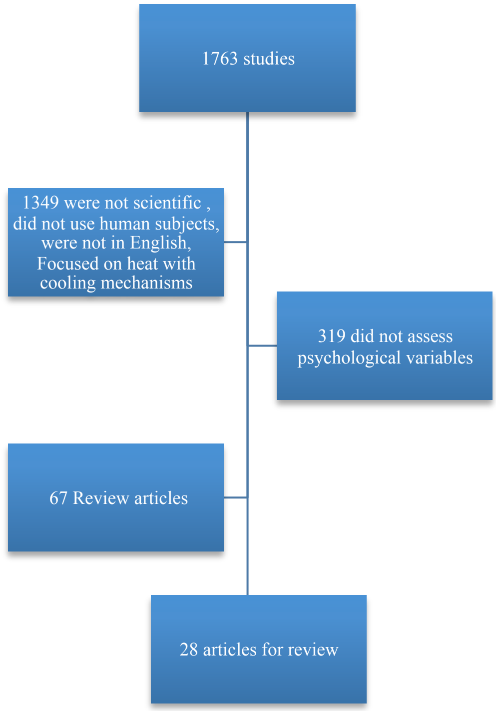


Figure 1: Study Selection

GENERAL FINDINGS

The most commonly tested variables were fatigue, mood, cognitive capacity, vigilance, perceptual ability, and task performance. Other variables included psychomotor abilities, anxiety, and memory. The studies demonstrate that endurance time decreases with hotter external conditions and more vigorous exercise. In those studies where the timing of psychological symptoms was reported, they appeared in less than three hours above 30C external temperature. Below 30C external temperature, participants were often able to complete the trial protocols. The exception to this was a trial lasting more than 24 hours, in which the majority of participants withdrew by 18 hours.[43]

EFFECTS ON FATIGUE

Fatigue is the state of being exhausted[22] seven studies (Hamilton, 1983,[26] Mitchell, 1986,[41] Munro, 1987,[43] Ryman 1988,[57] Smith 2001,[64] Szlyk, 1992,[67] and Thornton 1992[72]) included this as a measure of psychological impact related to heat stress. Five of the seven reported a deficit.[26,41,43,67,72] Feeling fatigued may have an impact on many areas of mental performance including detection of information, processing of information, motivation to perform tasks and endurance.

Symptoms appeared between two and four hours[67,72,43] and were increased relative to plain clothes comparisons for all but one trial lasting for that duration.[57] External temperatures tested ranged from 19C[26] to 40.5C[72] and study durations ranged from 18 minutes[64], with no fatigue reported, to over 24 hours[43], with multiple early terminations due to fatigue. Figure 2 is an overview of the studies including fatigue as a variable and their findings.

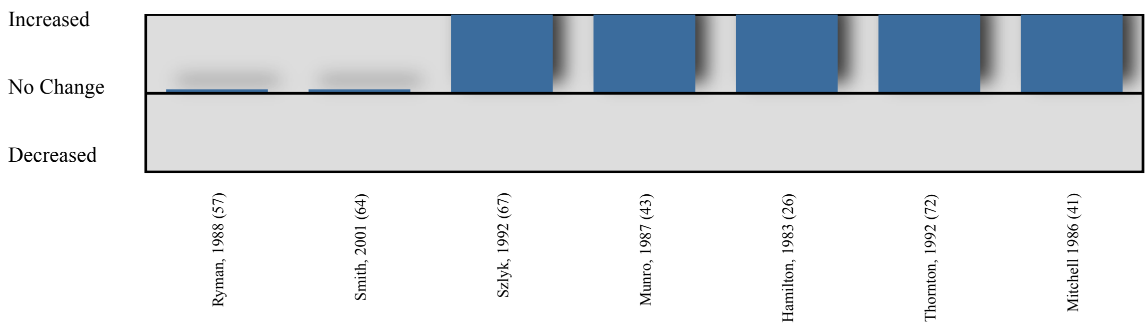


Figure 2: Effect on Fatigue

EFFECTS ON MOOD

Mood is a temporary state of mind that can have significant impact on social interaction, motivation to perform tasks, and self perceptions of capability.[58] Nine studies (Hamilton, 1983,[26] Hamilton, 1982,[27] Mitchell 1986,41 Munro, 1987,[43] Reardon, 1996,[55] Rose, 1987,[56] Ryman, 1988,[57] Smith, 1996[62] and Tharion, 1986[70]) included a measure of participant mood as a function of heat stress. All of them reported that prolonged exposure to heat stress depresses mood and increases hostility.

These symptoms appeared by three hours[43,57] and persisted but did not worsen over time.[43,56] One study found the common pattern of increased depression and hostility among female subjects but, among males, found an increased positive mood and decreased hostility.[26] Figure 3 is an overview of the studies including mood as a variable and their findings.

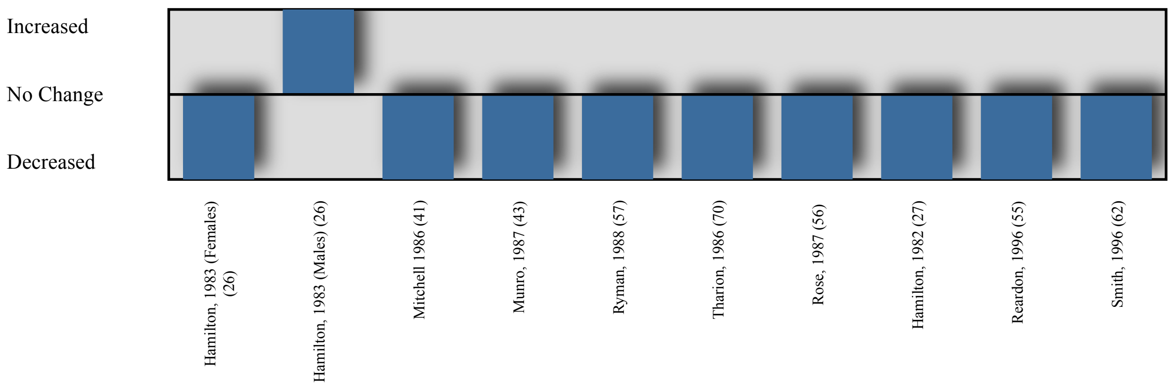


Figure 3: Effect on Mood

Effects on Cognition

Cognition is the act of processing information and is necessary for recognition and effective response to unplanned circumstances.[58] Deficits in cognition may have a severe impact on one's ability to respond to emergencies, interpret flight instruments and radio calls, or perform critical operational tasks. 14 trials (Caldwell, 2012,[14] Fine, 1987,[18] Fine, 1985,[19] Hamilton, 1983,[26] Hamilton, 1982,[27] Kaufman, 1988,[35] Kaufman, 1987,[36] Kelly, 1987,[37] Mitchell 1986,[41] Rauch, 1986,[53] Reardon, 1998,[55] Rose, 1987,[56] Smith, 1998,[61] and Thornton, 1992[72]) included this measure as a function of heat stress. Seven of these trials[14,27,35,36,37,41,55] found no deficit to cognition across durations ranging from 90 minutes[14] to eight hours.[36] Most of these trials were conducted in an external temperature less than 33C. The two hotter trials at 38C[55] and 48C[14] were terminated early for medical reasons and lasted less than two hours. One trial found no difference in cognitive ability between suited and unsuited subjects for short durations at ambient temperatures, but did report a deficit related to mechanical impairment from the gloves and mask equivalent to that found in their suited subjects.[53] The exercise intensity in these trials ranged from minimal to mild.

Among the trials that found a cognitive deficit under heat stress, two were conducted under conditions hotter than 33C for longer than two hours,[56,72] two trials included moderate to heavy levels of exercise,[56,61] and two were conducted at 33C for seven hours.[18,19] One additional trial found cognitive deficits during a four hour helicopter flight under wet bulb globe temperatures (WBGT) temperatures near 24C.[26]

The two longer trials noted normal cognitive ability up to three hours but recorded significant deficits after this point for both male and female subjects.[18,19] However, The authors note that the magnitude of the reported deficits is exaggerated due to the analysis method used.[18,19] Figure 4 is an overview of the studies including cognition as a variable and their findings.

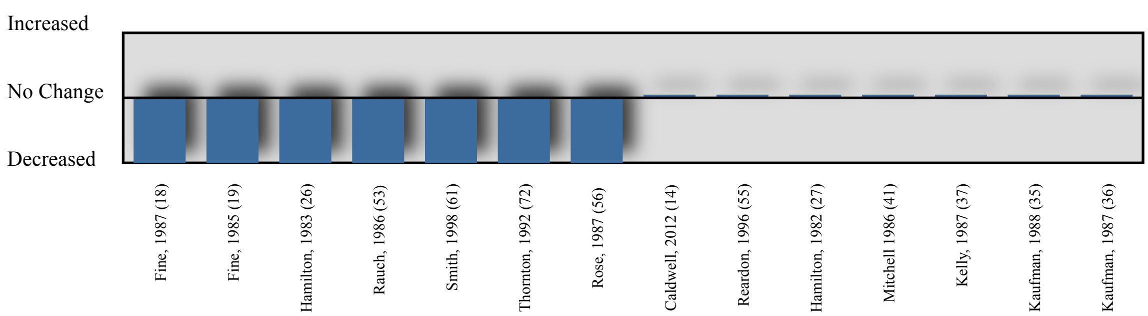


Figure 4: Effect on Cognition

Effects on Vigilance

Vigilance is the ability to maintain attention to detect a signal. Deficits in vigilance may impair the ability of a crew to monitor fight instruments or attend to radio calls and would increase the chance of missing information signaling a change in status or detecting an emergency situation.[58]

Eleven studies (Hamilton, 1983,[26] Hamilton, 1982,[27] Johnson, 1997[33] Kelly, 1987,[37] Mitchell 1986,[41] Munro, 1987,[43] Reardon, 1998,[55] Rose, 1987,[56] Stein, 2010,[65] Thornton, 1992,[72] and Warren, 1988[73]) included measures of vigilance relating to heat stress. Four of these[27,55,65,73] found no deficit to vigilance. These ranged in temperature conditions from 22C[73] to 38C[55] and were conducted for durations from 20 minutes[73] to nearly five hours[72] at exercise intensities ranging from minimal[27,55,72,73] to heavy.[65]

The six trials that did note a deficit to vigilance[26,33,37,41,43,56] tended to be longer, ranging from four hours[26,33] to over 24 hours.[43] They were conducted under similar external temperature conditions (19C-37C),[26,56] but lower levels of exercise intensity (mostly minimal exercise with one study at moderate[56]). One study noted an increase in signal detection with increasing heat but decreased accuracy in responses.[72] Figure 5 is an overview of the studies including vigilance as a variable and their findings.

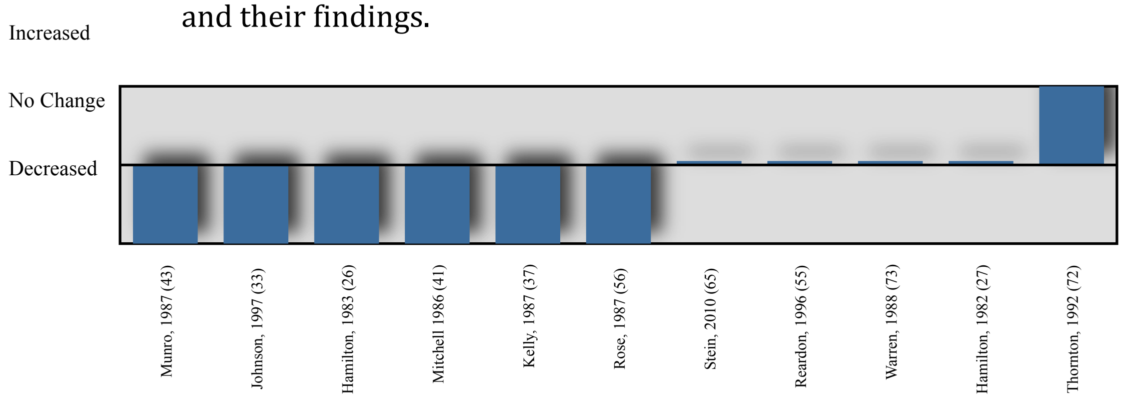


Figure 5: Effect on Vigilance

Effects on Psychomotor Function

Psychomotor function is a measure of how well cognitive processing is translated into physical action.[58] Deficits may lead to poor coordination and impact the performance of delicate tasks like flying a spacecraft or operating non-flight controls.

This literature search identified six studies measuring this variable (Johnson, 1997[33] Kaufman, 1988,[35] Kaufman, 1987,[36] Munro, 1987,[43] Rauch, 1986,[53] Rose, 1987[56]) with significant variation in the results. The two longest studies 12 hours[56] and 24 hour[43] reported deficits to psychomotor ability at 30C and 37C respectively, one study, lasting four hours at 35C reported no change,[33] and two studies, one for eight hours at 27C, and the other for three hours at 33C, reported improved psychomotor function.[35,36] The level of exercise intensity also varied across these studies. The one study conducted at moderate exercise intensity[56] showed psychomotor deficit, while two studies at minimal[35] and low[36] intensity reported enhanced psychomotor performance. Figure 6 is an overview of the studies including psychomotor function as a variable and their findings.

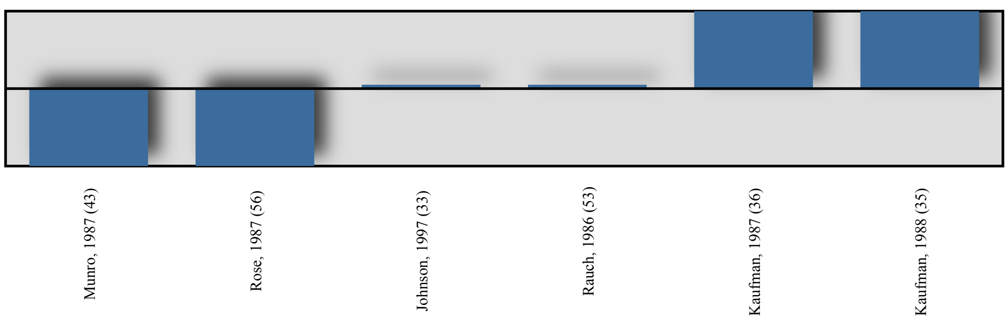


Figure 6: Effect on Psychomotor Function

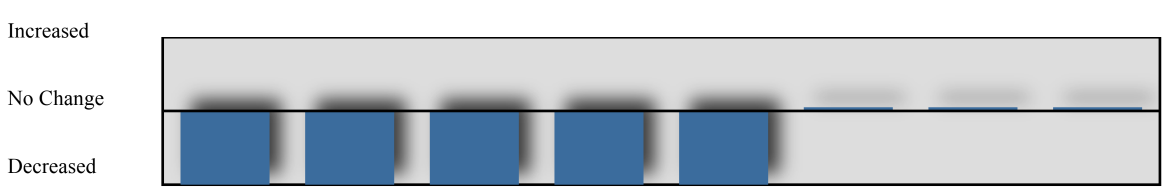
EFFECTS ON TASK AND FLIGHT PERFORMANCE

Task and flight performance are direct measures of complex activities. While they do not focus on any specific aspect of psychology, they can provide insight into global mental performance.[58] Eight studies measured task performance (Fine, 1987,[18] Fine, 1985,[19] Hamilton, 1983,[26] Mitchell 1986,[41] Reardon, 1998,[54] Szlyk, 1992,[67] Thornton, 1992,[72] and Warren, 1988[73]). Five of these reported a deficit in task performance ability under heat stress.[18,19,54,67,72] two studies tested flight performance in helicopter simulators,[54,72] two in actual helicopters,[26,41] two studies measured performance on artillery firing preparation tasks,[18,19] one measured performance firing artillery,[67] and one measured performance crossing a balance beam.[73] One trial was conducted at a moderate exercise intensity, [67] but the other performance trials were all conducted at minimal exercise intensity.

The two simulated helicopter flights took place under 35C-40.5C and 38C in UH-60 simulators.[55,72] The 38C trial, used pilots who were not all qualified to fly UH-60s. It was terminated in under two hours and the authors reported no performance deficits. Several significant events, such as crashes and tail strikes, were recorded in this trial but were reported to not be significantly different between the control group and heat stress group.[54] The second simulated flight trial lasted nearly five hours and did report deficits to flight performance. All pilots in this trial were UH-60 qualified, and in this case the authors noted a significant increase in the number of crashes in the heat stress arm.[72]

The trials conducted during actual helicopter flights did not record deficits in flight performance.[26,41] These trials were conducted under ambient temperature conditions that were 19C-23C in one trial[26] and not reported in the other.[41] Actual duration was not reported in either trial, but the planned duration was reported as four hours over two, two hour flights in Hamilton, 1983,[26] and six hours over four, 90 minute flights in Mitchell, 1986.[41] The authors of the latter study noted that many flights had to be terminated early but did not record reasons or the actual time flown.

The two simulated artillery tasks[18,19] were conducted at 33C and both detected performance deficits after three hours. These deficits were reported most commonly as errors of omission, in which information requiring action was missed, but errors of commission, where mistakes were made during task performance, occurred as well. In the artillery firing trial,[67] conducted at 28C, firing rates were compared between suited and unsuited subjects under both hot and not hot conditions. Preparation tasks were not measured. This trial noted that the time required to fire a round was increased more than four-fold in the suited heat stress arm when compared to crews in BDUs. Additionally, two of the three crews in the suited heat stress arm were unable to complete the trial and stopped midway through their task. Endurance time was not reported. Figure 7 is an overview of the



studies including task performance as a variable and their findings.

Figure 7: Effect on Task Performance

Effects on Anxiety

Anxiety is a heightened state of emotional activation that can lead to panic in its extreme forms.[58] Mild elevations in anxiety may increase performance, but too much anxiety may cause severe deficits in performance such as overreaction to stimuli, inability to respond to stimuli or panic.[12,58] In the confines of a spacecraft, any of these responses can endanger other crew members.[42]

Three studies (Smith, 1997,[63] Tharion, 1986,[70] Warren, 1988,[73]) measured state anxiety relating to heat stress in their participants. All three studies report significantly increased anxiety levels among participants. These studies were conducted over temperatures ranging from 22C[73] to 89C[63], exercise intensities ranging from mild[70] to moderate,[63] and durations from 16 minutes[63] to three hours.[73] Figure 8 is an overview of the studies including anxiety as a variable and their findings.

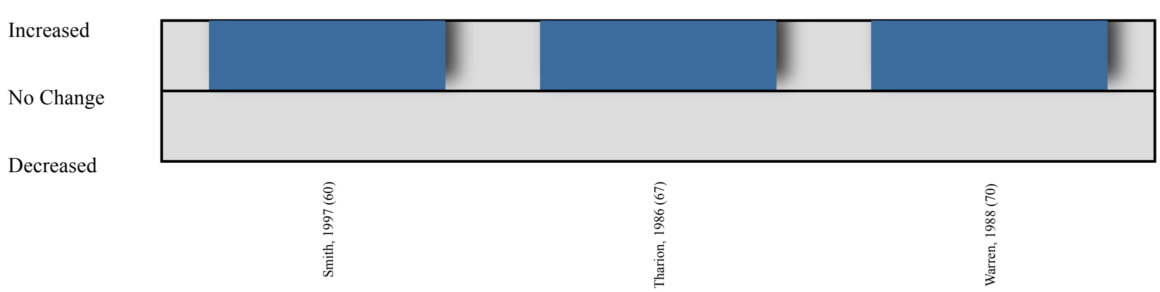


Figure 8: Effect on Anxiety

Effects on Perception

Perception is the ability to accurately identify incoming information.[58] It is related to vigilance and cognition in that vigilance is the maintenance of a state where one can identify that information is present, perception is the ability to sort that information into the appropriate category, and cognition is the ability to process and interpret that information leading to an effective response.[58]

Five studies (Fine, 1987,[18] Fine, 1985,[19] Kobrick, 1985,[39] Thornton, 1992,[72] and Warren, 1988[73]) examined perceptual ability related to heat stress. These studies were conducted at minimal to mild exercise intensity and external temperatures ranging from 22C to 35C. Of the studies that reported endurance time, the longest was eight hours[39] while the others ran between three and five hours. Four of the five studies[18,19,39,672] reported deficits in perceptual ability and one reported no change.[73] The single study reporting no change to perceptual ability was conducted for three hours at 22C and had no premature terminations.[73] Figure 9 is an overview of the studies including perception as a variable and their findings.

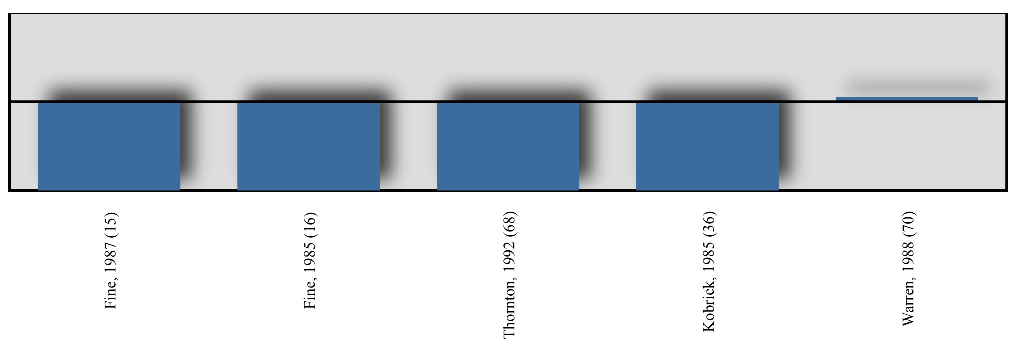


Figure 9: Effect on Perception

EFFECTS ON MEMORY

Memory is the ability to store and retrieve information.[58] Four studies (Caldwell, 2012,[14] Mitchell 1986,[41] Reardon, 1998,[55] and Thornton, 1992,[72]) reported measures of memory relating to heat stress. Subjects performed these trials with minimal exercise intensity under conditions ranging from ambient cockpit temperature[41] to 48C.[14] The duration of these studies lasted from just over 90 minutes[14] to just under five hours.[72] Only one trial, lasting four hours and 45 minutes at 35C, reported a significant memory deficit.[72] Two of the other trials were hotter at 38C[55] and 48C,[14] but lasted less than half as long.

The fourth trial was conducted in a helicopter under ambient cockpit temperatures and consisted of four, 90 minute flights with time for subjects to rest in shaded locations between sorties. Figure nine is an overview of the studies including memory as a variable and their findings.

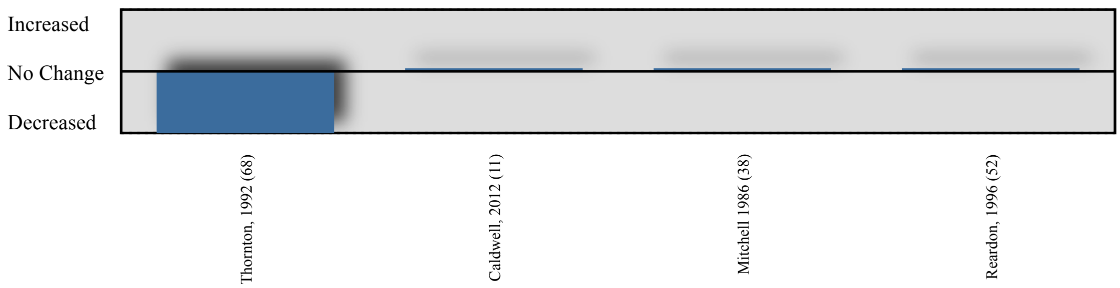


Figure 10: Effect on Memory

Chapter 4 Discussion

While, the literature does not provide sufficient evidence to build a timeline of psychological effects, the evidence supports that subjects at rest in sealed environment suits exposed to ambient temperatures lower than 30C for less than two hours are unlikely to develop significant psychological impairment.

The literature also provides clues as to which aspects of human psychology are affected. Each study in this review used different methods and different metrics, which limits direct comparison of their results. However, since many of the variables overlap, the degree of agreement can be used to illustrate the likely effects of heat stress on these subjects. The strongest story in the literature is that heat stress in suited subjects leads to increased fatigue, increased depression, increased hostility, decreased vigilance, decreased cognitive capacity, and worsened task performance. There is also substantial agreement that it can cause decreases in perceptual ability, and increased anxiety. Perhaps the most concerning piece of evidence is the suggestion from one study that it may increase a pilot's propensity to crash.[72] Given that cooling systems have been known to malfunction on reentry, this is an ominous finding.[50]

Five of the seven trials found fatigue increased in suited subjects. While this is not a revelation for anyone who has spent substantial time in hot environments, it goes along with other findings in this study of decreased vigilance (six of the 11 studies), decreased mood (eight out of eight studies), and perceptual difficulties (four out of five studies). Fatigue can be a marker for one's ability to maintain attention and wakefulness.[58] With increased fatigue, maintaining a state of vigilance, task performance, and the ability to correctly interpret information becomes impaired. Studies that examined tasks like receiving instructional radio calls, filtering out unnecessary information, and responding appropriately found both abilities substantially impaired in heat stressed subjects.[18,19]

The two studies that did not find increases in fatigue do not provide good evidence to the contrary either. One was conducted at ambient temperatures for only 18 minutes[64] and the other was conducted for three hours but had over 25% of its subjects withdraw.[57] With the first trial, it is reasonable to assume that the duration was too short to reveal fatigue symptoms in relatively cool external temperatures. In the second, duration may play a roll as well since most trials reported symptoms starting at the three hour mark and ran for five to 24 hours. Additionally, the reason why 25% of the subjects, in the Ryman, 1988[57] trial withdrew was not recorded and may represent an increase in fatigue symptoms that were missed due to early withdrawal.

In terms of the effect on mood, nine out of nine trials describe increased depressive symptoms and hostility with suited subjects under heat stress. This level of agreement is convincing that the effect of heat stress on mood is likely real. The one unusual finding comes from Hamilton, 1983.[26] This trial found that the same increased depression and hostility among female subjects but among males the opposite effect was detected. While this is intriguing, it does not agree with the other eight trials. Since these trials were predominantly male, the Hamilton, 1983[26] trial appears to be an exception rather than the rule. The authors suggest that their findings may be an effect of temperature rather than sex since temperatures were not controlled and the female subjects were tested at higher average WBGTs (23.5C) than the male subjects were (20.2C).[26] Since higher temperatures seem to be associated with increased psychological symptoms, this explanation is certainly plausible.

The most extensively studied effects are on cognitive performance, and here too there is substantial agreement. Seven of the 14 trials describe a deficit compared to controls while the remaining Eight find no deficits. The most salient difference between these groups is that studies reporting a cognitive deficit were longer and/or hotter than those that did not. Time-wise, the break points seem to be three hours. Most studies with mean endurance times less than this reported no cognitive deficits, while those with longer endurance times demonstrated clear deficits. The exceptions to this were three studies conducted at or below 30C where most subjects were able to complete the protocol and endurance times were five or more hours.[27,36,72]An additional exception is a study conducted on firemen during a live fire drill. In this trial external temperatures ranged between 50C and 78C which is substantially hotter than the temperatures in the other studies.[61] The protocol in this trial lasted less than 30 minutes at high intensity exercise and all subjects completed it but recorded a significant deficit in cognitive performance.

The implication is that at temperatures less than 31C cognition is preserved for up to three hours before deficits are detectable; above this temperature, cognitive endurance time is reduced. However, there are limitations to this conclusion. High loss to follow up in some of the studies may bias results in favor of more resilient individuals. Additionally, two of the studies finding cognitive deficits, Fine, 1985 and Fine, 1987, use an analysis method that inflates the degree of deficit reported.[18,19] Another important point, made by Rauch, 1986,[52,53] is that the protective gear itself impacts performance on cognitive tests. With this in mind, the effect of time on cognition may be related to fatigue rather than prolonged heat stress.

Another variable assessed in the literature is vigilance. Six of the 11 studies assessing vigilance found deficits. This deficit also appears to be a time related effect since all but two of the negative trials lasted less than three hours. These two trials were Hamilton, 1982,[27] and Warren, 1988.[73] Both were conducted at temperatures less than 30C, while most of the studies detecting vigilance deficits were under hotter conditions. The Munro, 1987[43] trial, which found a deficit but was conducted at only 30C lasted far longer than the other trial at over 24 hours. Hamilton, 1983,[26] also found a deficit at lower temperatures, however this trial used WBGT instead of dry air temperature. WBGT generally reports much lower temperatures than dry air,[22] and if dry air temperature were reported this trial would likely be in the above 30C range. This implies that higher temperatures also decrease vigilance in addition to time. As with cognition fatigue may also play a roll in decreasing vigilance since increased fatigue increases lapses in attention.[58] One vigilance trial, Thornton, 1992,[72] reported increased vigilance among subjects but the authors believed this was likely a learning effect since the baseline sequences were done first and scores improved as the test was repeated throughout the protocol.

The variable with the least concurrence between studies is psychomotor function. Six trials assessed psychomotor function with two reporting improvement,[35,36] two reporting no change,[33,53] and two reporting deficits.[43,56] Neither temperature, endurance time, nor exercise intensity reveal a pattern to this disagreement. This implies that there is either considerable individual variation, or that we do not currently have enough evidence to suggest how suited heat stress affects psychomotor capacity.

Perhaps the most relevant variable is that of task performance. Five of eight studies that examined this variable reported a deficit, with the remaining studies showing no change from baseline. The pattern revealed is similar to other variables in that longer studies, those hotter than 30C, and those with higher exercise intensities showed deficits. Notably, the three trials that show no deficit include two testing actual flight performance on standard maneuvers. In one of these, Mitchell, 1986,[41] nearly all flights without cooling mechanisms had to be terminated early for "medical reasons." This may have biased the results by selecting for more resilient individuals. In the second, Hamilton, 1982,[27] subjects were allowed to rest in shaded areas between each two hour flight, which may have allowed some time for recovery. While, temperature conditions were not controlled in this trial, the authors report that flight performance did appear worse in hotter temperatures relative to cooler ones. The negative results in these two trials may be an artifact of the conservative measures required when operating actual aircraft under conditions believed to cause psychological impairment. The third negative study, Warren, 1988,[73] measured performance crossing a balance beam. This is more a measure of balance than of task performance, and this study was also conducted at lower temperatures, 22C for a shorter duration, three hours, than the positive studies.

Of the studies that reported a deficit, four were conducted for longer than three hours between 33C and 35C. The remaining two had more subjects removed, but were conducted at a hotter temperature, 38C in Reardon, 1998,[51] or with higher exercise intensity, Szlyk, 1992.[64] Which again supports the theory that increased time, hotter temperatures, and increased metabolic heat generation decrease mental reserve.

The implication from the four trials conducted under actual or simulated flight conditions is that heat stress may severely impair flight performance in pilots starting somewhere between 90 and 280 minutes. Both simulator studies reported that heat stress significantly impaired flight performance, and one of these trials, Thornton, 1992,[72] found the rate of crashes was significantly higher in the suited arms compared to the non-suited arms. The study had a mean endurance time of four hours and 45 minutes before symptoms appeared and all subjects were qualified UH-60 helicopter pilots. The authors noted that most crashes occurred during low level flights and that four occurred in the "cool" arm (22C) and two in the "hot" arm (35-40C). The authors believe this may be an effect of the suit restricting vision rather than of heat stress, but it does raise concern about the ability of heat stressed space craft occupants to perform critical flight tasks.

The other simulator trial was done at 38C. High drop out rates gave it an average endurance time less than two hours, and no significant differences were found for crash rates among suited and/or heat stressed subjects. However, in this trial many of the pilots were not UH-60 qualified pilots.[54] Since not being familiar with the aircraft type is likely to increase accident rates, this cannot be used as evidence against heat stress impacting flight performance. It is worth further study to examine the potential for suited heat stress to increase crash rates.

The design of the two studies in actual helicopters limited the flights to two hours or less with breaks between flights. Neither reported a deficit in flight performance, but in the Mitchell, 1986[51] trial many of the flights were terminated in less than 90 minutes for "medical reasons relating to equipment."[51,72] This suggests that at least some pilots may have experienced heat stress related performance decrements that were not recorded.

Another variable with high concurrence between studies is anxiety. While only three studies measured state anxiety, they did so over a wide range of temperatures, times and activity levels; and all three reported it be increased. There is also evidence suggesting increased baseline anxiety from the protective clothing itself.[12,40] This is attributed to individual claustrophobia, increased heart rate from exertion, and the effects of restricted breathing through the mask assembly.[12,40,53] Since spaceflight itself is likely to increase feelings of anxiety,[42] there is significant concern for adding additional anxiety provoking stimuli as this may to increase the risk of panic responses.[58] Further research could focus on the effect that adequate cooling, or its absence, has on anxiety levels in suited subjects.

A cooling system failure would by definition be an off nominal event, arguably one that threatens crew health. Conditions like that tend to be anxiety provoking in and of themselves. Since the ability to predict individual anxiety response to spaceflight is currently beyond our capabilities,[42] and anxiety responses can pose a significant danger to others,[42,58] any intervention that can reduce the chances of adding to that anxiety should be strongly considered.

Perception is another area of mental processing that appears to be adversely affected by heat stress. Four of the five trials investigating this variable found a deficit. Failures in perception represent a failure to adequately interpret data perceived by the senses.[58] This can lead to missed emergency signals, incorrect control inputs, and any number of potentially dangerous circumstances in flight. The studies finding a deficit were all longer than three hours in duration and were conducted between 33 and 35C. The one study that did not find a perceptual deficit, Warren, 1988,[73] was conducted at the cooler temperature of 22C and lasted for only three hours. This duration is similar to that found with the other variables, and is likely part of the same pattern.

The final cognitive variable assessed in this literature is memory. Four studies evaluated it, and only 1 reported a deficit. This study, Thornton, 1992,[72] lasted nearly five hours at 35C and is, in practice, the longest of the trials evaluating memory. While, Mitchell, 1986,[41] lasted six hours on paper, the study protocol included only 90 minutes of flight time before a break to a cooler, less mentally taxing environment was permitted. A single study is not enough data to draw a conclusion, but many of the other variables appear to show deficits only after an extended period of time, or with extreme temperatures. It is reasonable to assume memory would follow this pattern as well and further studies could evaluate this possibility.

Based on these findings, it appears that most significant psychological deficits appear after exposure to temperatures greater than 30C for between two and three hours. At present most planned suborbital flights are expected to be less than two hours total, and less than 20 minutes from rocket start to landing.[1,2,3,5,75] Similarly, most orbital flights are on the ground less than two hours after the de-orbit burn.[2,3,75] While, it is tempting to apply the data from this review directly and conclude that there is minimal risk to crew should the cooling systems fail; there are significant pitfalls in this approach.

First, the cited articles are nearly all analogues. Only one study directly measured cognitive impairment in suits meant for spaceflight.[36] Analogues are useful but are, by definition, a substitute for the real thing, and results are not often exact. Additionally, nearly all of these studies had high numbers of subjects withdraw early but did not record detailed reasons for these withdrawals. This may introduce bias by missing significant deficits or artificially delaying the time of onset for those deficits that were detected. Since spacecraft occupants cannot withdraw from the flight should they become overheated, this represents a significant limitation.

Another limitation is that the subjects in these studies were mostly healthy, fit, young, and male. They were mostly drawn from military or firefighter populations, had a mean age under 22 years, and less than 18% of the study participants were female. These demographics are not reflective of the current astronaut corps.[74] let alone those expected fly commercially.[24,46] Both populations are older, may have higher proportions of female participants, and often live with some degree of medical pathology. The commercial population is especially likely to be less physically fit, more prone to anxiety, and sicker.[24,42,46] Previous literature has established that older age, poor physical fitness, and certain chronic illnesses can decrease one's ability to tolerate temperature extremes,[7,22] so the tolerance times in the space fairing population may be considerably shorter.

Another factor that should be accounted for is the mission profile. While suborbital participants are not likely to be significantly de-conditioned or dehydrated, future orbital participants might, which is also likely to decrease heat tolerance.[22] Additionally, many of the studies included in this review employed some form of heat acclimatization to prepare their subjects. This could certainly be added to the preflight regimen for future spaceflight participants, but the values reported in these studies are likely to be longer than the psychological tolerance times of non-acclimatized individuals.

Another profile specific concern for orbital missions is that passing through the atmosphere generates enormous heat. This could significantly increase cabin temperatures in the setting of a malfunction in the coolant system.[3,50] The studies in this review suggest that extreme temperatures shorten physical and psychological endurance times. If the cabin or suit is not well cooled, the heat of reentry puts spacecraft occupants at increased risk.[50] Especially since some of the risks suggested by this review may include aircraft crashes.[72]

Finally, these values do not take into account contingency operations. An off nominal landing may prolong rescue,[3] and de-orbit burns must be precisely timed which may extend the duration a spacecraft occupant must tolerate an uncooled suit. With reentry times as long as two hours,[75] any delay would put passengers and crew uncomfortably close to the deficit line for an orbital mission. The same could be said for an off nominal landing site in a suborbital vehicle, though this is admittedly less likely to leave occupants without rescue for more than a few hours.

There is too much variance between the studies in this review to build a useful timeline of psychological impairment. However, the studies do suggest a threshold value. Most studies did not find impairment in subjects exposed for less than 2 hours or to less than 30C dry air temperature. Perhaps the best way to use this information is as an upper limit of tolerance in the best case scenario subject. Outside of the limits outlined above, significant impairments to cognitive capacity, task performance, vigilance, perceptual ability, anxiety, mood and fatigue become increasingly likely with increased time, temperature, or exercise intensity. Given the youth and health of the subjects studied in this literature, temperature limits for populations that are not healthy, fit individuals, in their early 20s should be set more conservatively.

Future research should focus on directly assessing relevant cognitive variables under sealed pressure suit conditions similar to those expected in orbital and suborbital spaceflight. This research should aim to recruit older individuals with varied fitness levels, those with chronic medical conditions, and varied genders. It should expose these individuals to the static conditions associated with awaiting rescue, and the dynamic conditions associated with the g-forces and cabin environments of reentry. It would also be useful to measure the reentry cabin temperatures of human-rated vehicles without functioning cooling systems to learn the expected temperature range. Subjects could then be exposed to these ranges and asked to perform tasks associated with spaceflight to measure performance ability.