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WORKLOAD EVALUATION OF THE C-27J HEADS-UP DISPLAY

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1. SUMMARY

This report describes work conducted by the Air Force Research Laboratory (AFRL), Applied Neuroscience Branch in support of the C-27J System Program Office. The requirement was for an assessment of the workload and situation awareness (SA) impacts of the original Heads-up Display (HUD) as compared to a proposed modification to enhance usability, while also assessing cockpit, display, and aircrew procedural workload and SA as part of Airworthiness certification. AFRL personnel completed this evaluation with pilots and aircraft from the 179th Airlift Wing, Ohio Air National Guard (ANG). Subjective ratings and physiological workload data were collected from eleven training sorties flown by thirteen different Ohio ANG pilots. The results indicate that pilot workload was unacceptably high during particular maneuvers even in these training sorties. The location and arrangement of the primary (Heads Down Display, HDD) flight display suite was found to be acceptable during maneuvers that could be accomplished solely by reference to the HDD. However, under flight profiles requiring heads-up, the baseline HUD system incurred excessive workload. The pilots were able to monitor and control the system flight path management, navigation, caution, warning, advisory, communications, identification, propulsion, and mission and utilities subsystems at an acceptable level of workload and SA for the HDD only, and not for the baseline HUD. Limited data was collected regarding a modified HUD; the results suggest but do not confirm that workload was reduced by the HUD modification. We therefore recommended immediate implementation of the HUD modification, as well as procedural changes designed to reduce pilot workload to more acceptable levels.

2. INTRODUCTION

The Air Force Research Laboratory, Applied Neuroscience Branch was requested to perform a workload and situation awareness study by Mr. Kevin Kemper, Chief Engineer of the C-27J program office. Mr. Kemper's request (dated 1 Jun 11) stated that: "HQ AMC and the Air National Guard Bureau have requested that the C-27J SPO perform the workload (WL) and situation awareness (SA) study. We have had multiple HUD issues with the aircraft and continue to have them: 1) HUD misalignment (fixed) and now 2) HUD Eye Motion Box (EMB) and Cockpit Design Eye Point (DEP) mismatch (not fixed)." This study was deemed time-critical due to imminent aircraft deployment.

Separate but related efforts were undertaken by AFRL to respond to this requirement. The position and visibility of the HUD were assessed and have been reported in Harbour, Hudson, and Zehner (2012). The findings from that technical report for the baseline system (which includes the baseline HUD) are as follows:

- Current C-27J HUD
 - Cockpit Design Eye Point (DEP) & HUD Eye Motion Box (EMB) do not match (variance of 1.6 to 3.25 inches), on average 2 inches
 - Reduces visible HUD symbology a minimum of a 25% to as much as a 100% loss depending on pilot perception of DEP
 - Restricts AF pilot population
 - Increases Work Load (WL)

- Decreases Situation Awareness (SA)
- May create an unsafe flight condition
- Reduces mission capability & effectiveness

The Applied Neuroscience Branch designed and implemented an operational evaluation of WL and SA; the first data collection took place one month after the initial request. At that time, the only operational unit flying C-27Js was the 179th Airlift Wing, Air National Guard, Mansfield, Ohio; consequently all data collection was accomplished with 179 AW pilots and aircraft. This resulted in a very realistic evaluation of operational workload with current ANG pilots of varying experience and skill levels.

The critical issue for this WL and SA assessment was the impact of poor HUD visibility in various maneuvers. As evaluated, the HUD symbology was not visible without raising the seat height to a level that caused excessive interference with the flight controls. During maneuvers that require frequent visual reference to outside terrain, such as low-level flight and assault landings, pilots variously reported not using the HUD (flying via crosscheck with the HDD), using what HUD symbology was visible (dividing attention between HUD and HDD to obtain all critical flight data), or elevating their seats to obtain full HUD symbology and attempting to cope with the resulting control interference. All of these situations could result in a significant increase in WL and decrease in SA, due to either divided attention or the distraction of control interference. In flight operations, increasing workload will cause decreased pilot SA, leading the way to mishaps such as controlled flight into terrain (CFIT) (Wickens & McCarley, 2008). Consequently, workload assessment and management is a critical and ongoing issue for the Air Force generally and the C-27J specifically.

Measuring pilot WL and SA in a flight context presents unique challenges. Individual differences in expertise, experience, and tolerance for stressful tasks can result in significant variance in any measure of WL and SA; consequently all such assessments must be performed with a reasonable number of individuals who are representative of the population that will be flying the aircraft in actual operations. While not an absolute threshold, researchers in human factors have arrived at 8 individuals as a minimum number for test validity, based on having at least an 80% chance of detecting a difference of 20% or more in a particular measure. Subjective self-report (survey) measures have traditionally been used to assess cockpit WL and SA post-flight (AFFSA, 2007). The time delay and intervening tasks between flight and assessment can degrade recollection accuracy; in addition, the authors have observed that military pilots may underreport their workload due to perceived pressure to fully handle all challenges and avoid triggering additional follow-up or scrutiny. Subjective workload data is consequently useful but limited in assessing overall workload.

Therefore, heart-rate based assessment was used in addition to subjective workload. AFRL has utilized heart rate assessment in similar studies over the past 20 years (Hankins & Wilson, 1998; Wilson, Fullenkamp, & Davis, 1994; Wilson, O'Donnell, & Wilson, 1982); these results have indicated that heart assessment may be more sensitive to the actual demands of flight than subjective measures (Wilson, 2002).

One shortcoming of heart-rate based assessment is the difficulty in defining a threshold for excessive workload. Heart measures vary considerably from one individual to another; even averaging together

multiple individuals may not be sufficient to produce a reliable result. However, when analyzing heart rate variability (which decreases with increasing stress and workload), we may use a clinical diagnostic threshold as a proxy of excessive workload; when variability falls to a level indicative of cardiac pathology, we will conclude that stress/ workload is excessive (Malik, 1998). This same issue of variance between individuals has been observed in subjective workload assessment. Specific to the one-dimensional Bedford workload scale, a “redline” of a 4 or greater (out of 9 points total, with higher indicating higher workload; see Appendix A for the scale) has been established (Colle & Reid, 2005). We will consequently define Bedford ratings of 4 or greater as excessive workload.

While there are many other subjective and objective measures that could have been included, the high time pressure for the assessment and need to accomplish data collection during routine training on a non-interference basis dictated the selection of these measures.

3. METHODS

The methods were chosen to be minimally intrusive to both the pilot and the mission. The instruments used have been well-established in previous research; this research was not intended to develop new measures but instead to establish a workload assessment protocol and collect real-world data. Subjective (survey) instruments included the Bedford Workload Scale (Roscoe, 1984; Roscoe & Ellis, 1990) and China Lake Situation Awareness Scale (Adams, 1998; instruments in Appendix A). These were administered to the pilots post flight. In addition electrocardiography (ECG) was measured with the use of three-lead ECG (Hankins & Wilson, 1998; Nickel & Nachreiner, 2003)

The objective measures obtained from ECG included heart rate (HR) and heart rate variability (HRV). Both measures have been extensively studied, and in this study are taken to be broadly reflective of stress experienced by the pilot. To maximize the ecological validity of this study, all data collection was accomplished with actual flight operations. To avoid disrupting training activities, experimenters could not direct the flight profile for each sortie; relevant segments were extracted post hoc. Consequently this study is a quasi-experimental design.

3.1 Participants. Thirteen participants were recruited from the Ohio ANG population and ranged in ages from 25 to 46. All of the participants had flying experience and were qualified in the aircraft. Participants flew using either the HDD or both the HDD and HUD. The experimental protocol was reviewed and approved by the Air Force Research Laboratory’s Institutional Review Board and the Aeronautical Systems Center’s Flight Safety Review Board. Participation was voluntary.

3.2 Flight Maneuvers. Aircrew (both pilot and copilot) flew routine training missions that included some combination of normal takeoffs and landings, instrument approaches, cruise flight, low level flight, airdrops, and assault/tactical landings.

3.3 Equipment. The C-27Js had an L-3 Communications HDD and a Rockwell Collins Flight Guidance Systems HUD. The ECG data was collected using a Vitaport 2 physiological recording system (Temec Instruments B.V., Kerkrade, Netherlands), which is a small, portable pilot-worn physiological data collection system with onboard digital data storage. The three leads were placed on left and right clavicles and sternum; impedances were verified at or below 40 kOhms, and signal

quality was checked prior to the beginning of data collection for each training mission. The sampling rate was 256 Hz, and the data were bandpass filtered from 0.7 to 30 Hz as part of the data acquisition.

3.4 Procedures. After completing written informed consent, pilots were instrumented for ECG. An AFRL evaluator accompanied all flights, and used dedicated marker channels along with written notes to time stamp and categorize flight segments and events of interest. A typical sortie was approximately three hours in duration, with changes in pilot flying and maneuvers being practiced. Post-flight, pilots were asked to complete a set of subjective measures for each segment.

3.5 Analysis. All analysis for this study took place post-hoc. ECG data were processed using previously developed methodologies (Allen, 2002; Allen, Chambers, & Towers, 2007) for the extraction of heart rate data (as derived from the R-waves of the ECG signal; also known as the inter-beat interval, or IBI, time series) and associated measures of HRV. For this work, the specific measure of HRV utilized for analysis was the standard deviation of the IBI time series (Murray et al., 1975). HR and HRV were both calculated over 5-minute segments per the recommendation of the Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology (1996) for each training mission segment of interest.

4. RESULTS

Due to the quasi-experimental nature of this study, there are different numbers of pilots represented in each comparison; this will be noted where appropriate. Due to the unequal numbers and multiple comparisons, omnibus statistics have not been generated. Multiple sorties or repeated maneuvers were averaged together for each pilot and maneuver type; the plotted means and standard errors reflect a single value from each pilot. All data presented here are drawn from the pilot flying.

4.1 HDD vs HUD. The first comparison involved 3 pilots, each of whom completed 2 sorties utilizing both the HDD and original HUD configuration to conduct multiple non-precision instrument approaches, uncoupled from the autopilot (Fig. 1). Note that the lower rail is set at 40 ms; this is a clinical diagnostic threshold for cardiac dysfunction (Malik, 1998).

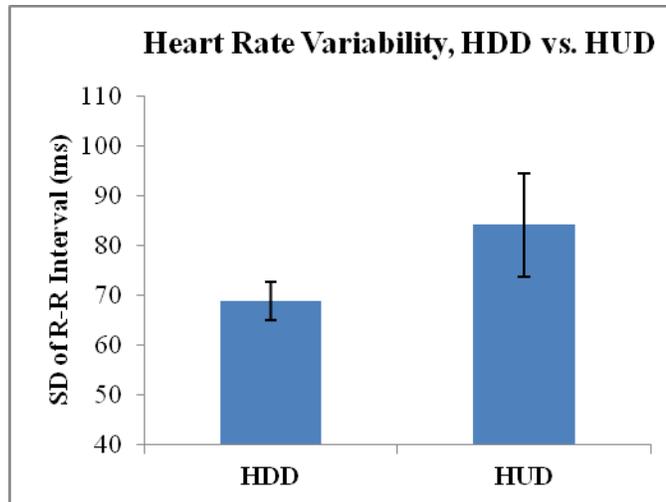


Figure 1. Average SDNN for instrument approaches conducted solely heads down (HDD) and with the heads-up display available (HUD). Bar height represents the mean, and error bars are one standard error of the mean. Note that higher values are associated with decreased stress and workload.

Based on Figure 1, the use of the HUD lowers workload during instrument approaches. This was also reflected to some degree in the self-report surveys of workload and SA (Figs. 2 and 3). However, note that the self-report measures exhibit compression and floor effects – self-rated workload is very low and SA very high in both cases. All of the subjective workload results for non-precision, uncoupled approaches were below redline.

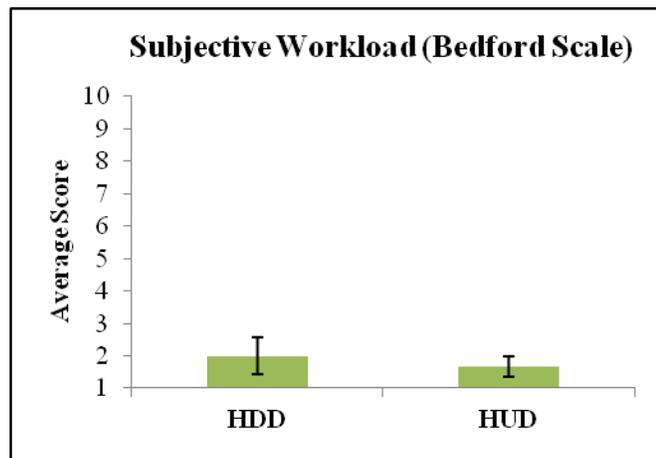


Figure 2. Average subjective workload ratings, on the Bedford 1 to 10 scale. Higher values correspond to higher workload.

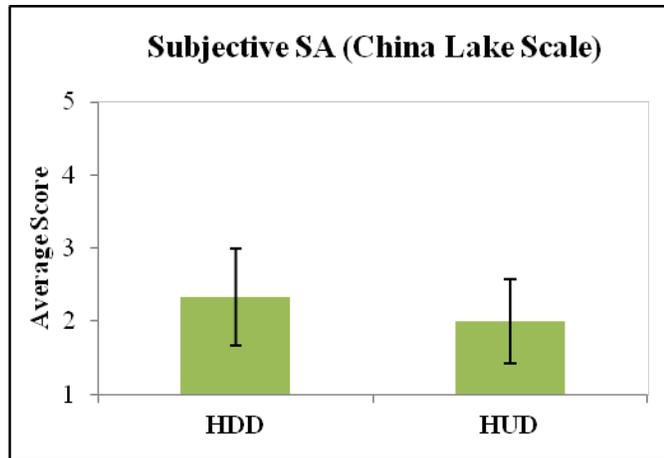


Figure 3. Average subjective situation awareness (SA) ratings, on the China Lake 1 to 5 scale. Higher values correspond to lower SA.

4.2 Air drops. A second comparison was drawn from low-level air drop maneuvers. 5 minute segments were generated by counting back from the release point; the comparison for reference was drawn from data during circling back to begin another air drop. A new set of 3 pilots conducted air drops, with each contributing one average value based on 3 to 4 repetitions of the maneuver (Figs. 4-6).

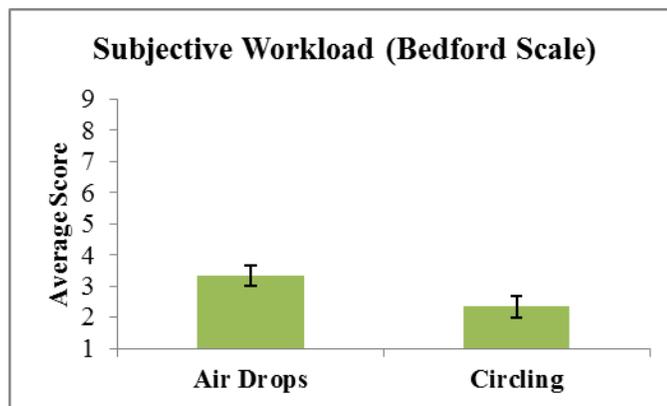


Figure 4. Subjective workload (Bedford scale) during air drops and circling. Higher values correspond to higher workload.

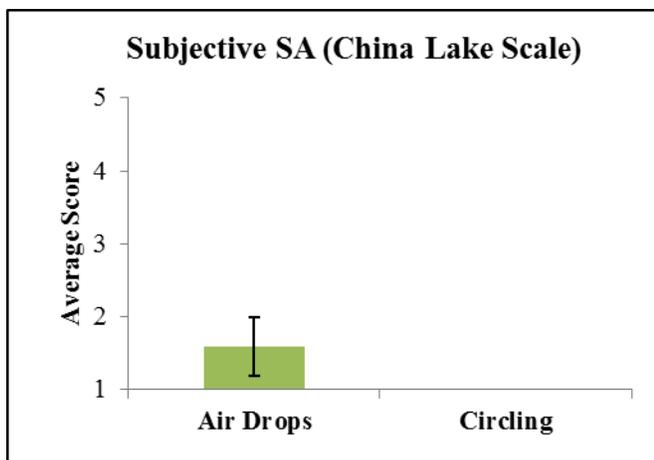


Figure 5. Subjective situation awareness (China Lake scale) during air drops and circling. Lower values correspond to better SA. Note that all pilots rated SA during circling back for a subsequent approach a 1, consequently there is no variability or bar visible for that measure.

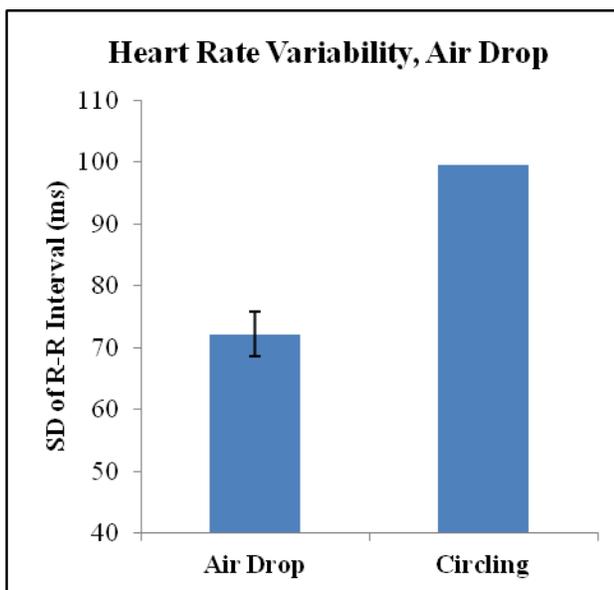


Figure 6. Average SDNN for low-level air drops as compared with circling back to conduct another drop. Variance was negligible during circling, hence the missing error bar. Higher values correspond to decreased stress/workload.

In examining Figure 4, we note that the redline value of 4 is within one standard error of the mean. This indicates that for the average pilot in our sample, workload is at redline and is therefore excessive during low-level air drops. We noted that these airdrops were hand flown due to a then current limitation on autopilot use during air drops; we recommended via the Cockpit Working Group that this limitation be reexamined for removal, which took place in the Fall of 2011.

4.3 Assault landings. Assault landings (steep, high-speed approach) resulted in the highest average subjective workload and lowest HRV measures (Figs. 7-8) of all the maneuvers tested. Due to the low pitch attitude and frequent visual reference to the runway required during the approach, the HUD

is particularly critical during this maneuver. Six pilots completed at least one assault landing each. SA was still rated acceptable at 2.4 out of 5. The average workload rating of 4.2 out of 10 exceeds the redline of 4. The HRV confirms this result, with values approaching the clinical diagnostic threshold of 40.

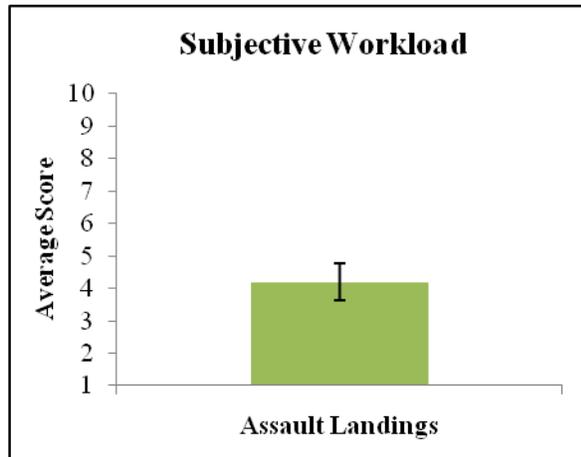


Figure 7. Subjective workload (Bedford scale) during assault landings. Higher values correspond to higher workload.

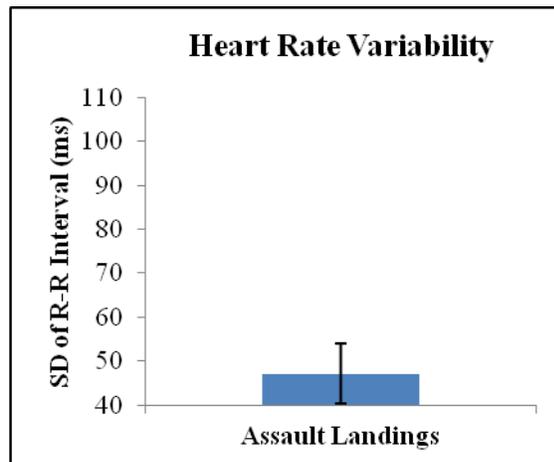


Figure 8. HRV during assault landings. Lower values correspond to higher stress/workload.

Figure 9 compares the HRV results from all the measured maneuvers. This was shared with instructor pilots from the 179 AW; they confirmed that the relative ordering of maneuver types matches their own perceptions of the workload involved.

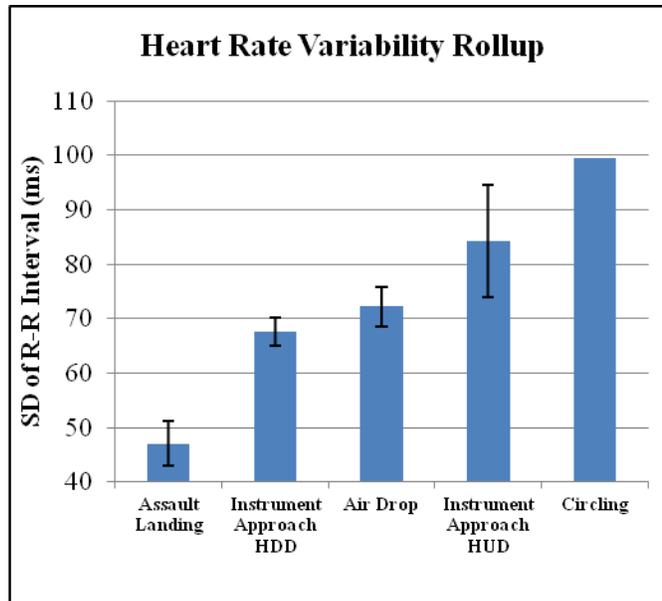


Figure 9. Average HRV for all the maneuvers analyzed to date. Higher values correspond to decreased stress/workload.

4.4 T1 modification to HUD. Very limited data was collected on the T1 modification the HUD (displacing the combiner 2 inches down). The T1 mod evaluation flights conducted during the study period precluded heart rate assessment. Subjective data was obtained from the two flights flown by highly proficient instructor pilots; this subjective data all indicated minimal WL and maximal SA. Written comments indicated that the pilots found the modified HUD was “much easier to see and found myself using it more”, “much better”, and “much better in terms of not having to move my head around to see full view of the HUD”. This data is insufficient to draw firm conclusions regarding the efficacy of the HUD; however the comments are some evidence that the modification is subjectively effective.

5. DISCUSSION

The results of this assessment indicate that pilot WL during routine training flights is generally acceptable; however certain maneuvers result in excessive demand. In the instrument approach data we observed that even the original HUD is an improvement over not using or having a HUD at all. However, the assault landing and air drop data indicate that the original installed HUD results in excessive WL during these maneuvers. Based on both heart-based measures of WL and subjective ratings, assault landings, air drops, and instrument approaches flown without a HUD were identified as areas of significant concern. SA was not found to be problematic, though SA theory suggests that prolonged excessive workload would result in a breakdown of SA.

As would be expected based on Wilson (2002), we observed that heart-based measures were more sensitive to changes in WL than the Bedford subjective scale. The instrument approach data demonstrated a significant difference in HRV as a function of HUD vs. HDD. The Bedford WL scores trended in the same direction, but were not significantly different. This illustrates the utility of multimodal workload assessment in evaluations of this type.

The following recommendations were made via the Cockpit Working Group:

Recommendation I: Workload during low-level airdrops was found to be high. Autopilot usage could significantly reduce workload. The USAF has already implemented this recommendation.

Recommendation II: For assault landings, instrument approaches, and low-level flight an effective HUD, particularly a certified primary flight display HUD is strongly recommended.

The authors who are rated pilots noted that their own observations of pilot workload in flight were not always consistent with the subjective ratings. For example, several pilots rated hand-flying a low level air drop as 3 out of 10 on the Bedford scale; the anchor text is “Enough spare capacity for all desirable additional tasks”. We observed channelized attention focused on minimizing lateral deviations, with consequent mistaken radio calls and lack of attention to secondary displays. Our observations were more consistent with 6 or perhaps 7 on this scale. While there may be perceived pressure to underrate workload despite assurances of no negative repercussions, we also feel that pilots may misperceive their workload in the absence of a highly visible error. If this is indeed a systematic feature of subjective ratings taken from this type of population and task, it further underlines the importance of integrating multiple measurement types in conducting these workload studies.

6. CONCLUSIONS

Low-level flight, assault landings, and air drops are frequent operational tasks. Our findings indicate that the C-27J with baseline HUD produces excessive pilot workload during these maneuvers; as a result we assess overall pilot workload as unacceptable. Insufficient data was collected on the previous T1 modification to draw firm conclusions; however comments suggest the modification is an improvement. Further improvement is recommended to reduce workload to consistently acceptable levels.

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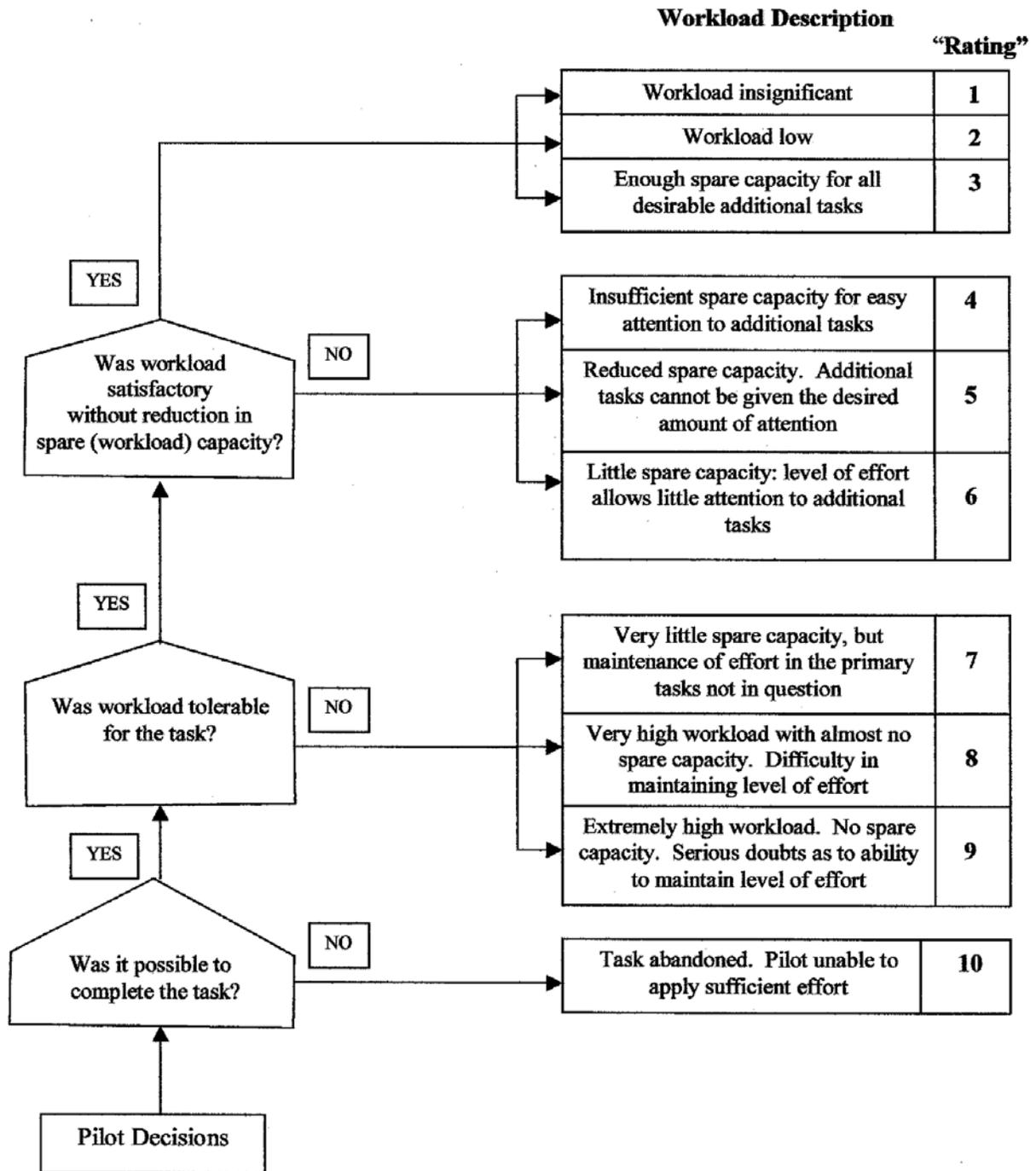
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9.0 APPENDIX A

Bedford Workload Scale



China Lake Situation Awareness Scale

Instructions: circle the number that best matches your situational awareness.

Situation Awareness Scale Value	Content
Very Good – 1	<ul style="list-style-type: none"> • Full knowledge of A/C energy state / tactical environment / mission • Full ability to anticipate / accommodate trends
Good – 2	<ul style="list-style-type: none"> • Full knowledge of A/C energy state / tactical environment / mission • Partial ability to anticipate / accommodate trends
Adequate – 3	<ul style="list-style-type: none"> • Full knowledge of A/C energy state / tactical environment / mission • Saturated ability to anticipate / accommodate trends • Some shedding of minor tasks
Poor – 4	<ul style="list-style-type: none"> • Fair knowledge of A/C energy state / tactical environment / mission • Saturated ability to anticipate / accommodate trends • Shedding of all minor tasks as well as many not essential to flight safety / mission effectiveness
Very Poor – 5	<ul style="list-style-type: none"> • Minimal knowledge of A/C energy state / tactical environment / mission • Oversaturated ability to anticipate / accommodate trends • Shedding of all tasks not absolutely essential to flight safety / mission effectiveness

Note: A/C – aircraft

LIST OF ABBREVIATIONS AND ACRONYMS

AF	Air Force
AMC	Air Mobility Command
ANG	Air National Guard
AW	Airlift Wing
CFIT	controlled flight into terrain
ECG	electrocardiography
DEP	design eye point
EMB	eye motion box
HDD	heads-down display
HR	heart rate
HRV	heart rate variability
HUD	heads-up display
Hz	Hertz
kOhms	Kilo Ohms
SA	situation awareness
WL	workload