Human Fatigue Modeling in Wargaming Simulations

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ABSTRACT

Wargaming is a valuable tool for military planning and leadership strategic thinking and tactics training. However, wargaming simulation software has critical limitations that need addressed to increase the realism and efficacy of the scenarios. One limitation is that human factors are often absent in scenarios, with personnel treated as high functioning, uniform units. In reality, human factors have critical effects on personnel readiness and performance. Of particular interest in the current effort is the effects of human fatigue on simulated personnel entities and how this can inform wargaming participant decision making.

We developed an application that integrates human fatigue modeling with a wargaming logistics simulation software to inform the effects of fatigue on aircrew and maintainer mission readiness and performance. The fatigue modeling application was developed using the R programming language Shiny package and implements the Sleep, Activity, Fatigue, and Task Effectiveness (SAFTE) biomathematical fatigue model. The SAFTE model produces performance effectiveness curves (i.e., fatigue) based on sleep input, homeostatic regulation, circadian rhythm, and sleep inertia. As a use case, the application intakes Air Tasking Order (ATO) information from the Integrated Sustainment Wargaming and Analysis Toolkit (iSWAT), which provides logistic resource information on aircrew and maintenance personnel, and other resources pertinent to wargaming scenarios. Sleep schedules for personnel were generated in the fatigue modeling application based on ATO information, general scheduling practices from the literature, and subject matter expert input. The current effort examines fatigue estimates based on a realistic, mock-up wargaming scenario.

Resulting fatigue estimates suggested that a subset of aircrews and maintainers were commonly fatigued during the wargame scenario, likely degrading performance and increasing safety risk. This has important implications for wargaming participant decision making as they will need to shift mission sets and use alternative resourcing to ensure peak mission readiness and performance.

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INTRODUCTION AND BACKGROUND

As military operations tempo increases and continues to expand globally with new threats emerging, it is critical to develop effective software to help plan and evaluate wartime mission scenarios. Wargaming software allows leaders to plan out military maneuvers and processes, as well as, train strategic thinking and tactics. Although these exercises are beneficial, they often lack realism in terms of the personnel involved in the missions. Personnel are often characterized as mission ready, available commodities. Whereas, in reality several human factors come into play, affecting mission performance and success. One critical human factor of interest in the current effort is fatigue. The following paper will detail an effort that integrates human fatigue modeling with an Air Force wargaming logistics scenario tool and discuss the implications of this modeling for scenario development and decision making.

Integrated Sustainment Wargaming and Analysis Toolkit

Logistics information is a critical aspect of military planning as thousands of assets are deployed during wartime. As a result, realistic logistics simulations are needed to enhance wargaming play. In the current effort, we focus on a recent wargaming logistics software, the Integrated Sustainment Wargaming and Analysis Toolkit (iSWAT). iSWAT allows for military operation planners to grasp a more realistic assessment of potential maintenance and logistics situations while in combat. The software was developed by Frontier Technology Inc. to address the shortfall of a "reality" gap from a recent lack of research and development of wargaming technologies (Air Force SBIR/STTR Program, 2018). iSWAT is composed of two major components, the configuration tool and web application.

The configuration tool is used to initialize a wargame, and allows the facilitator to establish an area of responsibility (AOR), initial pool of resources, and baseline flying schedule/mission plan. In the mission plan, the facilitator can specify: the weapons system (including aircraft), weapons expenditure factors, weapons loadout, flight frequency, and takeoff/landing locations. Attacks and other factors (e.g., weather) can be implemented in the scenario by using the game control or adjudication cell as well (Frontier Technology Inc., 2018). An Air Tasking Order (ATO) is able to be imported through an external file, as well as merged with existing entries in the iSWAT database. The ATO includes mission types, definitions, loadouts, and flying schedules.

The web application visualizes past, current, and projected air and sustainment operations as well as the availability and usage of logistics resources. It also gives subject matter experts (SME) and facilitators insight to more detailed levels to be able to identify inadequacies and execute changes to the mission plan and resource logistics. The iSWAT web application provides a geospatial visualization of resource status, limiting factors, and locations to inform travel time, ranges, and health status. The application also supports post-wargame analyses that offer an event summary– including background information and graphical and numeric table displays of key parameters (Frontier Technology Inc., 2018).

Although iSWAT simulates valuable wargaming logistics information, it has limitations regarding aircrew and maintenance personnel readiness in the logistics chain. These resources are treated as constant entities and assumed to be fit for mission execution. In reality, and especially during wartime operations, this is not the case. Several factors affect personnel readiness and this should be accounted for within the wargaming simulation as it has important implications for logistics strategy. Given the 24-hour tempo of operations and the need to travel great distances to support efforts, fatigue becomes a critical issue for these personnel given circadian desynchrony and sleep restriction.

Human Fatigue Modeling

Fatigue is a critical and costly human factor within the Air Force (Caldwell, 2005; Gaines et al., 2020). In order to assess and predict fatigue, organizations often use biomathematical fatigue models that incorporate homeostatic regulation and circadian rhythm processes, as well as other factors, to produce estimates (Mallis et al., 2004). The Department of Defense sponsored the development of the Sleep, Activity, Fatigue, and Task Effectiveness (SAFTE; Hursh, Redmond, et al., 2004) model. This model uses homeostatic regulation, circadian rhythm, and sleep inertia processes to provide performance effectiveness assessments on a scale of 0 to 100%. Performance effectiveness is a general cognitive effectiveness. The lower the performance effectiveness, the more fatigued an individual is. The typical performance effectiveness bands for output are: Green (77.5 - 100%; low fatigue), Yellow (70 - 77.5%; medium fatigue; caution, potentially perform mitigation strategies), and Red (0 - 70%; high fatigue; warning, immediately perform mitigation strategies). Research suggests that SAFTE performs well in predicting subjective fatigue ratings and objective performance (Hursh, Balkin, et al., 2004; Hursh et al., 2006; Hursh, Redmond, et al., 2004; Mallis et al., 2004).

Current Effort

In the current effort, we develop an application that takes ATO inputs from iSWAT and produces fatigue estimates for aircrew and maintenance personnel based on generated sleep schedules run through the SAFTE algorithm. Specifically, we developed algorithms to generate realistic aircrew sleep and maintainer work and sleep schedules based on the ATO flying schedule as well as general scheduling practices and duty assumptions. These schedules were then run through SAFTE to generate performance effectiveness estimates across the wargaming scenario. Additional features were added to the application to manipulate sleep parameter information and allow for what-if scenarios based on different work and sleep schedules. The remainder of the paper describes the development of this application and an analysis of fatigue given a realistic, mock-up wargaming scenario and optimal versus more realistic sleep schedules. We then discuss implications of this fatigue analysis for wargaming simulation scenario development and decision making.

METHOD

Developing Wargaming Scenario Fatigue Modeling Application

The Fatigue Modeling in Wargaming Application was developed using the R programming language with the Shiny package, along with shinyjs (Attali, 2021) and shinyBS (Bailey, 2022) libraries. We used R Shiny to create the application because it provides a reactive platform to build a graphical user interface (GUI) application with a statistical language back-end. We also have an implementation of SAFTE written in R which lent itself nicely to being incorporated into this application.

Figure 1. Screenshot of the Fatigue Modeling in Wargaming Application. The red highlighted area (Figure 1a) shows the tab panel, where the user is able to change settings. The blue highlighted area (Figure 1b) shows the graphing panel, where the resulting graphs are displayed.

The application is divided into two components: the tab panel (Figure 1a) which allows the user to switch between various settings, and the graphing panel (Figure 1b) which graphs both flight crew schedules and maintenance crew schedules. Since R Shiny is a reactive application, changes that the user makes in the tab panel updates the output graphs in the graph panel.

The tab panel (Figure 1a) has several tabs which allow the user to explore the effects of different sleep schedules on performance effectiveness during shift times. The "Intro" tab describes general use information as well as specifying various assumptions for the creation of both flight crew and maintenance personnel sleep schedules given shift start/end input either in the "Interactive" tab or by loading a file in the "File Load" tab.

The "Interactive" tab provides the user with a way to specify the "Work Shift Start" and "Work Shift End" times, the number of days of sleep schedule, and specifying the amount and whether there is a limit to how many shift hours the flight crew is allowed to have during the specified number of days. The user can also specify the first date of the schedule and the base location which is necessary to calculate any circadian shifts due to non-standard sleep schedules and time zone changes. When the user enters new values into any of the text boxes, the graphs in the graph panel are automatically updated by first recalculating the automatically generated sleep schedules (assumptions of how these sleep schedules are created will be discussed below), and then graphing the corresponding output after the sleep schedules are run through the SAFTE algorithm.

The "File Load" tab allows the user to load a pre-existing ATO with shift schedules. The file must be in .CSV file format with the following columns: depart, arrive, type, squadron, loc (see Table 1 for description of columns and valid entries). All times input in the ATO are assumed to be in Zulu time. After the user loads the file, they can select the base location and squadron to see the available mission shift times for the corresponding location. This will result in a list of checkboxes being displayed with available mission shift times. The user then needs to select one (or more - though not recommended as it makes the graph difficult to read) checkbox(es) and press the "Plot" button. The application will calculate the sleep schedule based on the mission shift times and output the appropriate flight crew and maintenance crew graphs.

Table 1. Input Column Descriptions for Loading an ATO into Application

Column Name	Description	Valid values/type
depart	Flight departure time (shift start)	values 0-23 (military time)
arrive	Flight arrival time (shift end)	values 0-23 (military time)
type	Aircraft type	string (ie. F15, C130, F22, etc.)
squadron	Squadron number at base location	1 or 2
loc	Base Location	string description (ie. Mildenhall, Bitburg, etc.)

The “Settings” tab allows the user to modify how the automatically generated schedule is created and controls the graph output. In generating the automatic sleep schedules, the application needs to know 1) how many hours before the work shift the crewmember needs to wake up (set using the “Lag” text input box), 2) the typical sleep length expected, and 3) if variability to the sleep length should be included (allows for more realistic noisy sleep durations - variability defined in hours; 0.25 is adding sleep duration variability of 15 minutes around the sleep length defined previously). The display settings allow the user to modify what information is output in the graphs. If the checkboxes for “Show work shift line” and “Show sleep line” are selected, the graphs will indicate (by color coding) the portion of the lines which fall within work shift and sleep times, respectively. If “Show work shift duration” and/or “Show sleep duration” are checked, then there will be a small number at the bottom of the graph listing the duration of the corresponding region shown above in the graph (red for sleep duration, blue for work duration). Finally, the user can specify which flight crew and which maintenance personnel to display which will toggle the maintenance graphs as appropriate and display the calculated schedule specific to the flight crew number.

The “Output” tab allows the user to download three different levels of data regarding the output of the sleep schedule SAFTE calculations. In this tab, it is also possible to view the automatically created sleep schedule and download it as a comma separated value (.CSV) file. At the lowest level, raw minute by minute data is output with performance effectiveness values and the color band it falls within for each minute of the schedule, along with whether that minute falls within a sleep period, flight leg/work shift period, or neither. At the middle level, the proportion of minutes each hour in each day falling within each color band is output. At the high level, the proportion of minutes spent in each band during each day is output. The same aggregation technique is used in both the flight crew and maintenance crew output.

Lastly, the “About” tab lists references for the SAFTE model used in the application. Note, in Figure 1 there is a tab for “Add Caffeine.” This tab is not currently functional, but will be added in a future version of the application (see the Future Directions section for more details).

Developing Aircrew and Maintenance Personnel Sleep Schedules

Flight crew sleep schedules are automatically generated by taking the mission start time and augmenting it to include 2.5 hours of lead time prior and 2 hours after to generate the work shift window (to simulate travel time and briefing/debriefing time). A sleep period is then created to end 2 hours prior to work shift start time (this can be modified using the “Lag” input in the “Settings” tab). This sleep period has a duration as specified by the “Sleep Length” and “Variability” inputs in the “Settings” tab. Following the work shift, another sleep period is scheduled 24 hours after the one that occurred prior to the work shift. The maintenance personnel schedules were automatically generated from the work shift start/end times specified by the user or input from the loaded files. The key assumptions were that the entire 24-hour period must be covered by at least one maintenance person and that each work shift for a maintenance person is 10 hours long. There is also a half hour overlap between consecutive maintenance personnel. There is also the assumption that a maintenance person can not have back-to-back days with work shifts. These assumptions were developed based on general scheduling practices from Air Force Instruction (AFI 21-101, AFI 21-150, and AFMAN 21-113) and subject matter expert input.

Optimal and Realistic Sleep Schedules

To examine the effects of fatigue in the wargaming scenario, we observe performance effectiveness levels based on two scenarios. The first scenario includes an optimal sleep schedule for all aircrew and maintenance personnel where they receive 8 hours of uninterrupted sleep. The second scenario reflects more realistic sleep schedules during wartime. Specifically, we use an average of 6 hours of sleep and add variation in the sleep start and end times by 15 minutes. As a result, sleep periods for crews will randomly be between 6 hours and 30 mins and 5 hours and 30 mins. In other words, we are adding variability to the sleep periods given potential environmental stressors (e.g., construction near the hotel) that affect the length and quality of sleep crew and maintainers receive. We provide descriptive statistics regarding performance effectiveness levels and categorization into performance effectiveness bands for these two scenarios for both aircrew and maintenance crews.

RESULTS

Wargaming Scenario Fatigue Analysis

The mock-up wargaming scenario included 23 bases with 172 missions. This resulted in 2,360 flight legs across the 30-day period. Additionally, there were 5 sets of maintenance crew rotations for each base, resulting in 15,274 shifts across the 30-day period. The following sections examine performance effectiveness (fatigue) during the missions and shifts given an optimal sleep schedule versus a more realistic sleep schedule.

Scenario with Optimal Sleep

The optimal 8 hour sleep schedules based on the scenario had an average performance effectiveness of 92.40 and an average minimum performance effectiveness of 88.94, with 93.84%, 5.92%, and 0.25% of time in the Green, Yellow, and Red bands, respectively across the 2,360 flights. Additionally, the optimal scenario resulted in 44 legs (~2%) where performance effectiveness fell into the Red band. Readers should note that this subset consisted of 6 mission sets from RQ-4 and E-3 crews, which tended to be longer in duration compared to other types of missions. Table 2 highlights a few examples of these legs, showing low performance effectiveness (e.g., 57.67) and portions of the flight leg in the Red band (e.g., 20.98%). These 44 legs had an average performance effectiveness of 84.16 and an average minimum of 63.65, with 73.08%, 13.69%, and 13.22% of time in the Green, Yellow, and Red bands, respectively.

Table 2. Sample of Mission Legs with Performance Effectiveness in Red Band - Optimal Sleep

Type	Leg	Time	Mean Effectiveness	Min.	Max.	Green %	Yellow %	Red %
RQ-4	1	1200-0600	86.28	67.16	96.91	70.65	8.38	20.98
RQ-4	5	1300-0700	86.69	67.14	96.92	72.20	8.30	19.50
RQ-4	10	0000-1800	83.58	60.43	90.93	78.43	6.30	15.27
RQ-4	4	0100-1900	79.02	57.67	84.25	82.65	6.45	10.90
E-3	3	1700-0500	86.74	69.24	98.77	69.36	16.28	14.36

Note. Type = Aircrew type. Leg = Flight number across the 30-day period. Time = Local time of mission. Min. and Max. are minimum and maximum effectiveness values within the mission leg. Green, Yellow, and Red % is the percentage of mission time that fell within the Green, Yellow, or Red band.

Maintenance personnel with optimal sleep schedules had an average performance effectiveness of 93.57 and an average minimum of 90.21, with 96.92%, 3.08%, and 0% of time in the Green, Yellow, and Red bands, respectively.

Scenario with Realistic Sleep

The realistic sleep schedule (6 hours with variability) based on the scenario had an average performance effectiveness of 87.93 and an average minimum of 84.50, with 87.27%, 8.93%, and 3.81% of time in the Green, Yellow, and Red bands, respectively (see Figure 2 for proportions of flight legs falling into band categories based on start time of flight leg). Additionally, the realistic scenario resulted in 266 legs (~ 11%) where performance effectiveness fell into the Red band. Readers should note that this subset consisted of 74 mission sets from B-2, B-52, C-130, E-3, F-16, F-15C, F-15E, F-22, F-35, KC-46, KC-135, and RQ-4 crews. Table 3 highlights a few examples of these legs, showing low performance effectiveness (e.g., 54.03) and portions of the flight leg in the Red band (e.g., 73.73). These 266 legs had an average performance effectiveness of 75.31 and an average minimum of 66.79, with 29.81%, 36.43%, and 33.76% of time in the Green, Yellow, and Red bands, respectively.

Table 3. Sample of Mission Legs with Performance Effectiveness in Red Band - Realistic Sleep

Type	Leg	Time	Mean Effectiveness	Min.	Max.	Green %	Yellow %	Red %
F-16	2	0200-0700	70.66	67.76	77.99	1.41	54.83	43.76
F-15C	3	0130-0630	69.39	66.80	74.31	0	45.17	54.83
KC-46	2	0200-0600	70.38	67.62	77.97	1.18	48.33	50.49
F-15E	2	2305-2530	69.30	66.74	77.07	0	26.27	73.73
F-16	6	2100-2600	71.40	68.83	76.84	0	69.6	30.40
RQ-4	6	0100-1900	77.21	54.03	83.27	78.28	6.67	15.05

Note. Type = Aircrew type. Leg = Flight number across the 30-day period. Time = Local time of mission. Min. and Max. are minimum and maximum effectiveness values within the mission leg. Green, Yellow, and Red % is the percentage of mission time that fell within the Green, Yellow, or Red band.

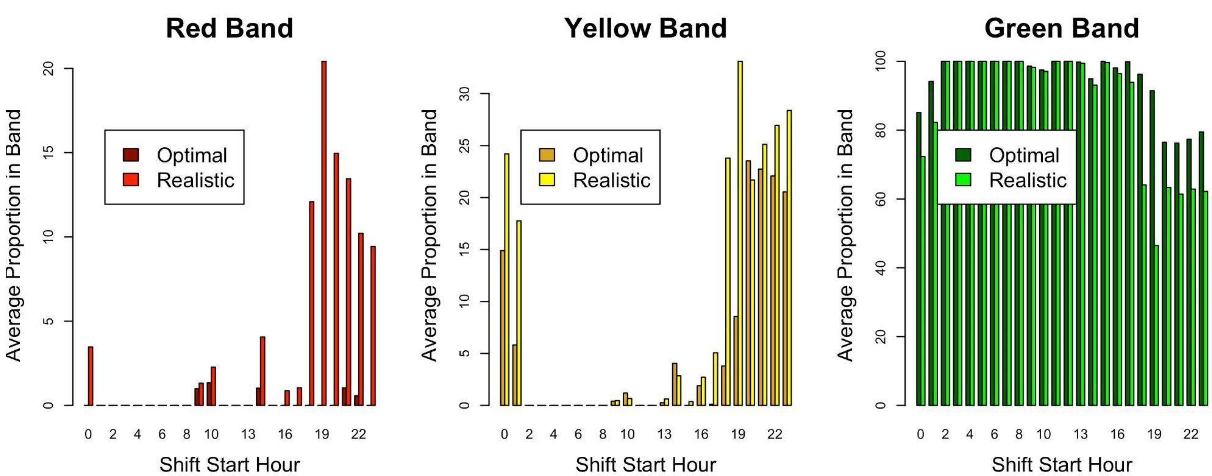

Figure 2. Aircrew schedules. Average proportion of time during flight legs falling within each band based on the starting hour of the leg. Optimal = 8 hours of sleep, Realistic = 6 hours of sleep with variability

Maintenance personnel with more realistic sleep schedules had an average performance effectiveness of 90.63 and an average minimum of 88.18, with 97.17%, 2.45%, and 0.38% in Green, Yellow, and Red bands, respectively (see Figure 3 for proportions of shifts falling into band categories). Additionally, the realistic sleep scenario resulted in

264 shifts where performance effectiveness fell into the Red band. Readers should note that this consisted of all five potential maintenance personnel shift schedules. Table 4 highlights a few examples of these shifts, showing low performance effectiveness (e.g., 66.28) and time of shifts in the Red band (e.g., 51.59). These 264 shifts had an average performance effectiveness of 79.03 and an average minimum of 68.28, with 43.71%, 34.30%, and 21.99% of time in the Green, Yellow, and Red bands, respectively.

Table 4. Sample of Mission Legs with Performance Effectiveness in Red Band - Realistic Sleep

Shift	Time	Mean Effectiveness	Min.	Max.	Green %	Yellow %	Red %
1	2000-2300	72.12	67.06	86.53	18.53	33.89	47.58
2	1150-1300	72.20	68.27	83.43	12.83	52.67	34.50
3	0100-0700	74.04	66.83	91.51	29.38	20.70	49.92
4	1330-1830	74.23	66.28	92.14	31.72	16.70	51.59
5	0700-1300	71.15	66.85	83.57	12.86	37.40	49.75

Note. Time = Local time of mission. Min. and Max. are minimum and maximum effectiveness values within the shift. Green, Yellow, and Red % is the percentage of shift time that fell within the Green, Yellow, or Red band.

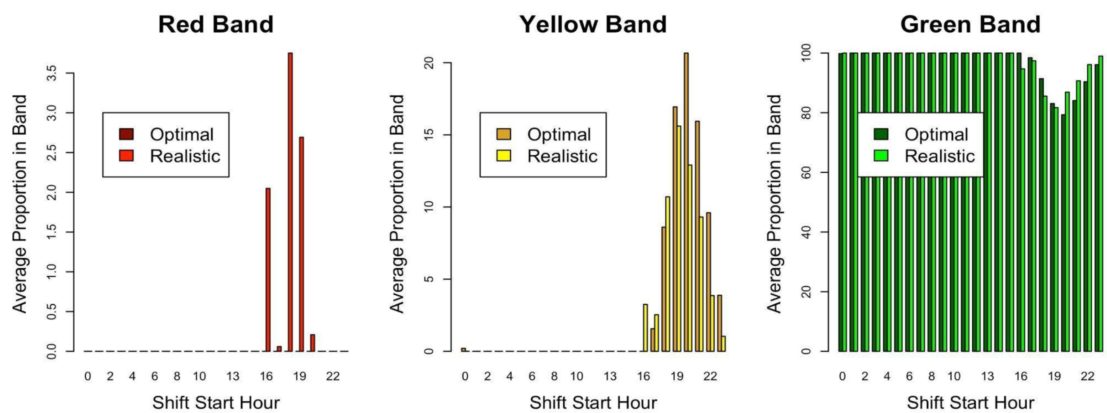

Figure 3. Maintainer schedules. Average proportion of time during shifts falling within each band based on the starting hour of the shift. Optimal = 8 hours of sleep, Realistic = 6 hours of sleep with variability

DISCUSSION

We have developed a prototype application for fatigue modeling for logistics wargaming scenarios that takes in ATO information and generates fatigue predictions for aircrew and maintenance personnel. The application also allows for what-if scenarios if users are interested in changing schedule and sleep information for the crews. Inputting a realistic mock-up scenario into the application with optimal sleep (8 hours each period), we found that some aircrews, especially RQ-4 and E-3 crews, experienced high levels of fatigue during some of the flights throughout the 30-day period. Even with optimal sleep, fatigue will lead to safety risks for some crews with long missions that result in circadian desynchrony. This creates an environment for mishaps to occur, which can be costly in terms of resources and life. Fatigue has important implications for human performance and associated logistics planning as it is unlikely that aircrews and maintenance personnel will be able to get a full 8 hours of sleep before each mission/shift and perform during normal hours in wartime, and it is extremely important that Warfighters are performing at acceptable levels to ensure mission success. Making the sleep periods more realistic (6 hours of sleep with 15 minutes of variability in start and end times) resulted in significantly increased fatigue for an array of aircrews, as well as all maintenance personnel shifts. This suggests that leadership needs to take into account crew fatigue during these scenarios. Either new strategies must be applied to replenish or replace the fatigued crews, or leadership are willing to accept high safety risk that could render missions unsuccessful.

Limitations

The following effort has some limitations that should be considered. We utilized a mock-up of a wargaming scenario in this use case. So although it is not a real scenario, it is a realistic scenario that should provide reasonable fatigue outcome comparisons to a real scenario. We developed algorithms to compute aircrew sleep schedules and maintenance work and sleep schedules based on the ATO information, AFIs, and SME expertise. These provide general schedules that do not perfectly reflect the real schedules that would occur during wartime, but are realistic and provide abstracted information that is useful in this context. We implemented the SAFTE model that is publicly available through the Hursh et al. (2004) paper. As a result, output from this implementation is not exactly the same as the commercially available SAFTE-FAST tool, but does coincide with other research SAFTE implementations (Cleator et al., 2021).

Future Directions

Given the operations tempo during wartime and the stakes, it might not be feasible or desirable to replace crews or cancel certain sorties to avoid fatigue-related risks. As a result, countermeasures will need to be implemented to combat fatigue. Future work will include adding a caffeine modeling capability to the application, allowing users to examine how caffeine can be utilized to help mitigate fatigue during these scenarios. In conjunction with modeling countermeasures into the application, it would be beneficial to incorporate the effects of common dietary ingestants that might contribute to fatigue. In addition to caffeine being a mitigation tool, it can also result in fatigue if ingestion is not timed appropriately, negatively affecting the quality of sleep (i.e., sleep interruption) (Drake et al., 2013). Similarly, alcohol can also have negative impacts on sleep quality (Ebrahim et al., 2013). Caffeine and alcohol tend to be common ingestants in most individuals' normal diets, so it is important to incorporate these effects on fatigue predictions. We also have plans to develop a plug-in or representational state transfer (REST) application programming interface (API) for this initial application that can be integrated with different wargaming software.

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