Accounting for Fatigue in Systems Design and Operations: Issues and Opportunities

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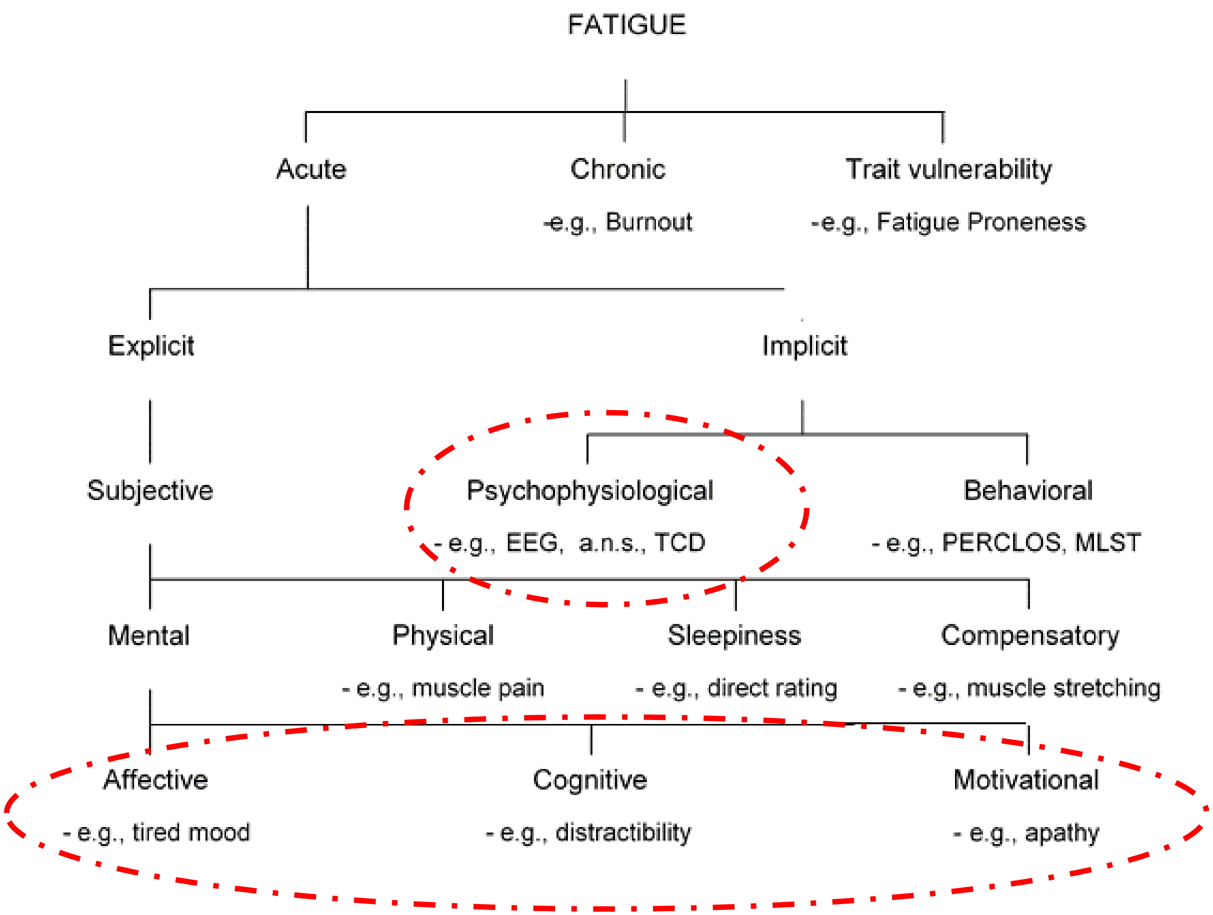
Overview

- Rationale for multivariate assessment strategy
  - Fatigue, workload and stress all have multiple components
- Components of acute subjective stress and fatigue
  - 3-D model of task stress (Matthews et al., 2002)
  - Application to performance prediction in UAV simulation
- Combining psychophysiology and subjective assessment
  - Multiple facets of workload response
  - Physiological and subjective predictors of performance in UGV simulation
- Implications

Facets of Fatigue

- Taxonomy of dimensions of fatigue (Matthews et al., 2012)
- Focus on acute, task-induced fatigue and individual differences in performance



Stress and Fatigue in Autonomous Vehicle Operation

- Task factors
  - Overload and underload
  - Poor interface design
  - Temporal: prolonged monitoring during ISR operations (vigilance)
- Increasing autonomy
  - Vehicle as ‘team-mate’
  - Automation monitoring as a major operator function

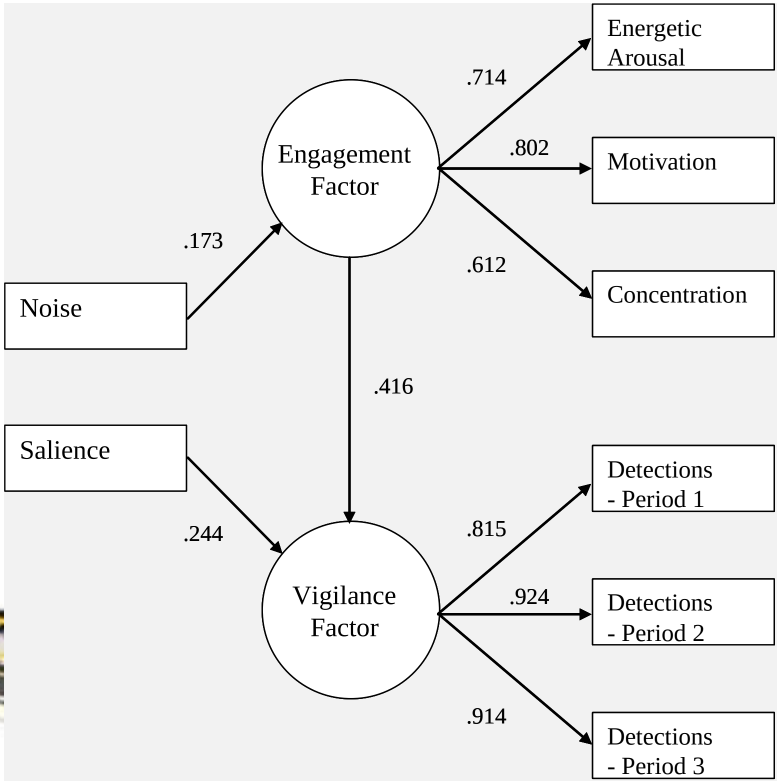
Subjective Stress: Three Factor Model
(Matthews et al., 2002; Matthews, 2016)

	Task Engagement	Distress	Worry
Principal scales	Energetic arousal Motivation (Intrinsic) Motivation (Success) Concentration	Tense arousal Low hedonic tone Low confidence	Self-consciousness Low self-esteem Cog. Interference (task-related) Cog. Interference (personal)

- General framework for understanding stress and fatigue in performance contexts
- Measurement with Dundee Stress State Questionnaire (DSSQ)
- Fatigue as low task engagement: tiredness, apathy, distractibility
- Only partial overlap with physiological metrics

Fatigue as Task Disengagement

- Task engagement predicts performance of demanding visual attentional tasks in multiple studies (e.g., Shaw et al., 2010)
  – e.g., vigilance, visual search, change detection, facial processing
  – Task engagement as a marker for attentional resource availability
  – Predicts across fatiguing and non-fatiguing tasks
- Engagement as a mediator of stressor effects
  - Effects of jet engine noise on vigilance (Helton et al., 2009)
  – Effects of cold infection on vigilance Matthews et al. (2016)



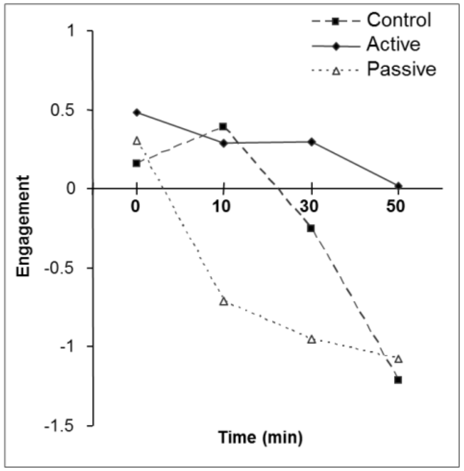
Workload Assessment: Subjective vs. Physio

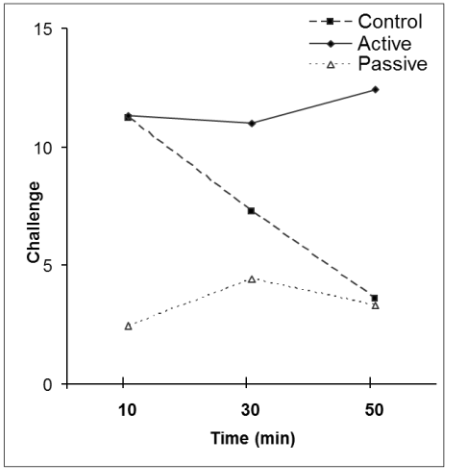
- Workload is expressed by complex patterns of physiological response
- Dissociated from subjective workload

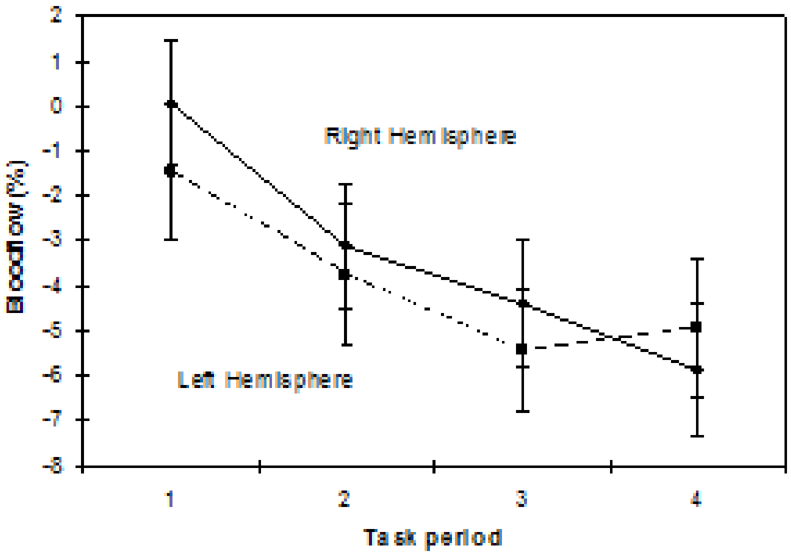
Study	Task or Manipulation	NASA-TLX effect (points)	Metrics for elevated workload (expected)	Metrics for reduced workload (unexpected)
UGV simulation	Change detection (vs. threat detection)	16.1	Lower HRV, higher rSO_2 (fNIR), higher frontal theta, higher ICA	
UGV simulation	Dual-task (vs. single task)	10.0	Shorter fixation duration	
NPP simulation	Detection (vs. other tasks)	4.9	Higher rSO_2 (fNIR)	Lower beta, gamma Lower heart rate Higher alpha
UAV simulation	Cognitive load (vs. low cog. load)	16.7	Higher beta Higher gamma	Higher HRV

Multiple Levels of Driver Fatigue

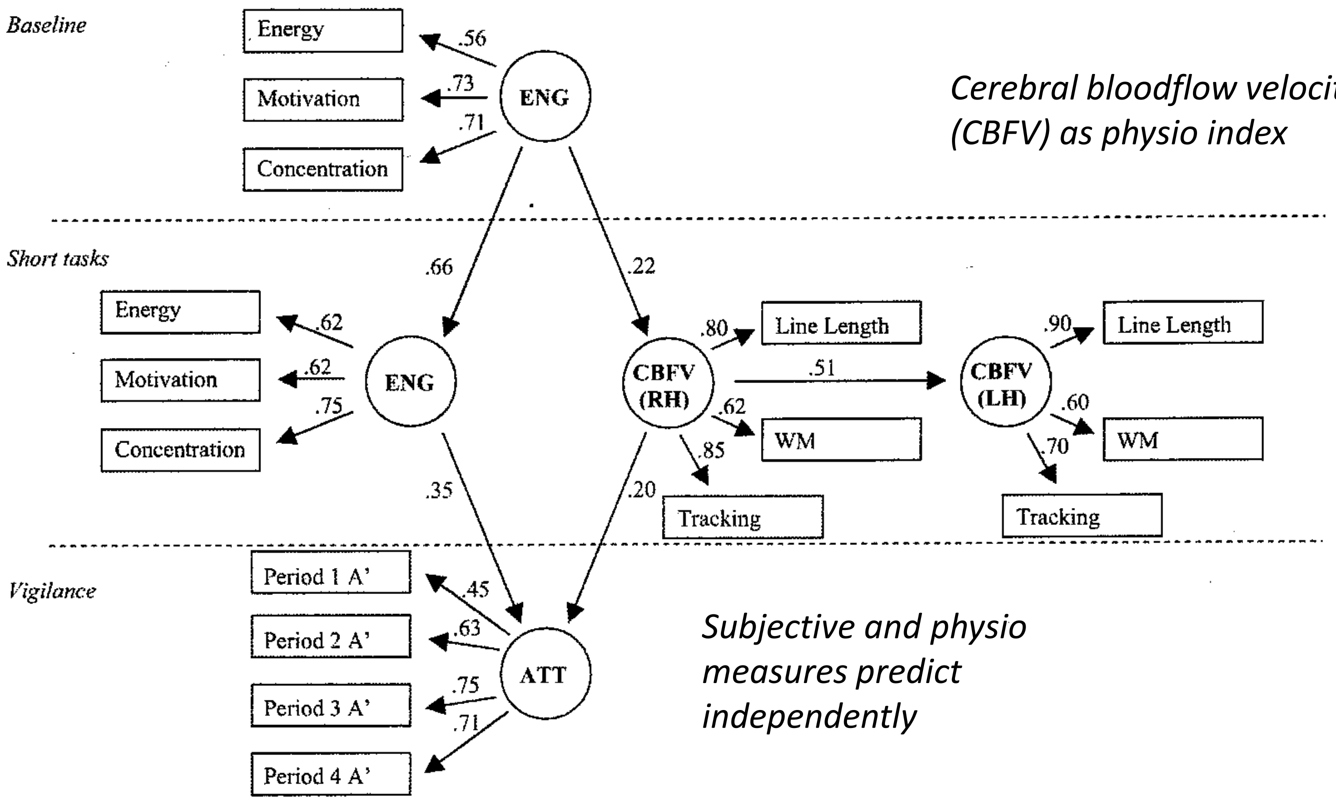
- Loss of task engagement is accompanied by:
  - Declining cerebral bloodflow velocity (CBFV)
  - Changes in cognitive processing (appraisal and coping)
  - Loss of performance
  - Example data from driving (Saxby et al., 2013; Reinerman et al., 2008)







Performance Prediction: Latent Factor Model
(Matthews et al., 2010)



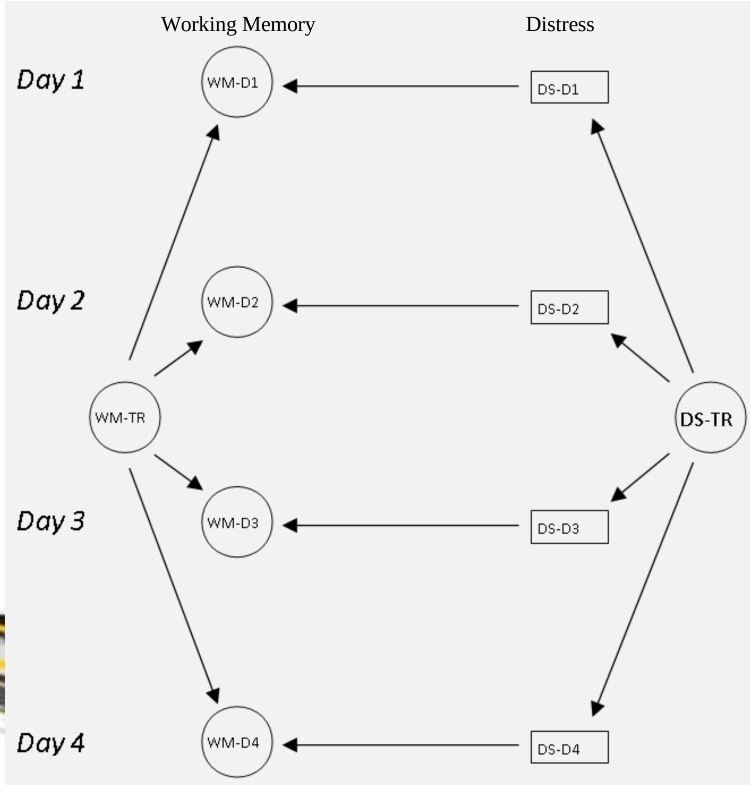
Cerebral bloodflow velocity (CBFV) as physio index

Subjective and physio measures predict independently

Figure 4. Latent factor model fitted to data from the sensory vigilance task. Eng = Engagement; Att = Sustained Attention; WM = Working Memory.

Distress as a Response to Fatigue

- High workload tasks reliably induce distress
  - Response to vigilance typically combines low task engagement and high distress
  - Distress correlates at ~.5 with NASA TLX workload
- Distress correlates negatively with performance requiring multi-tasking and divided attention
  - e.g., working memory (OSPAN)
- Multivariate modeling of distress (Matthews & Campbell, 2010)
  - State variation matches working memory variation



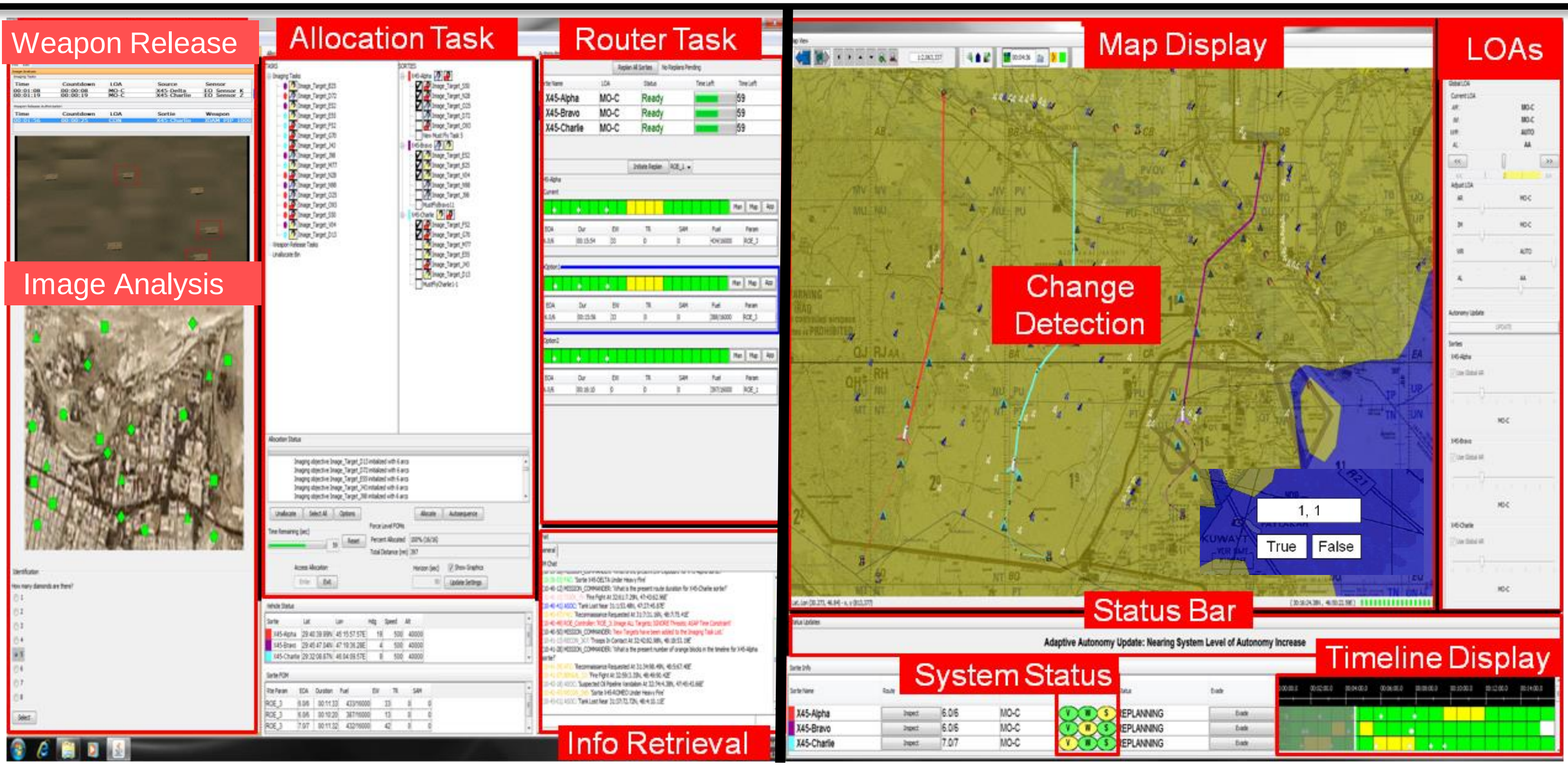
Multi-UAV Simulation: Adaptive Levels of Autonomy (Lin et al., 2015)

- Collaboration with AFRL (Gloria Calhoun, Greg Funke)
- UCF funding from AFOSR Trust and Influence program
- Aims
  - Investigate impact of task load on performance, subjective stress, and reliance on automation
  - Investigate impact of automation characteristics (LOA, reliability)
  - Investigate predictors of performance
  - Manipulations of task load

Method

- Participants
  - 101 UCF students (43 men, 58 women); mean age = 18.95 years
- Design
  - Manipulations of task load (and level of automation)
- Procedure
  - Pre-test questionnaires, including stress state
  - Training (about 30 min)
  - Main task (60 min)
  - Post-task workload and stress

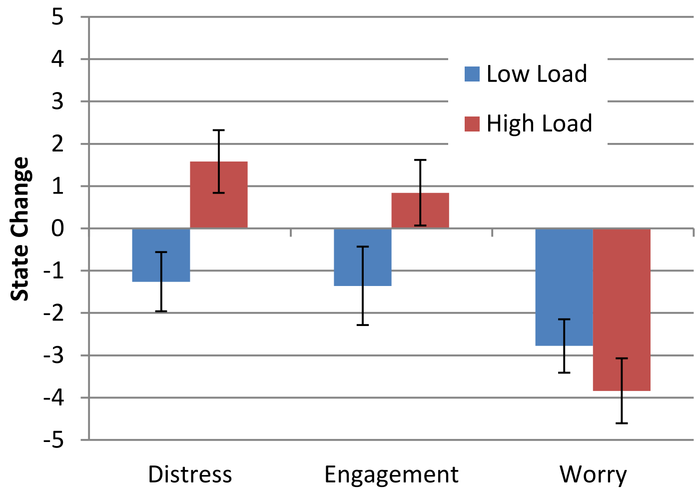
Adaptive Levels of Autonomy (ALOA) Simulation



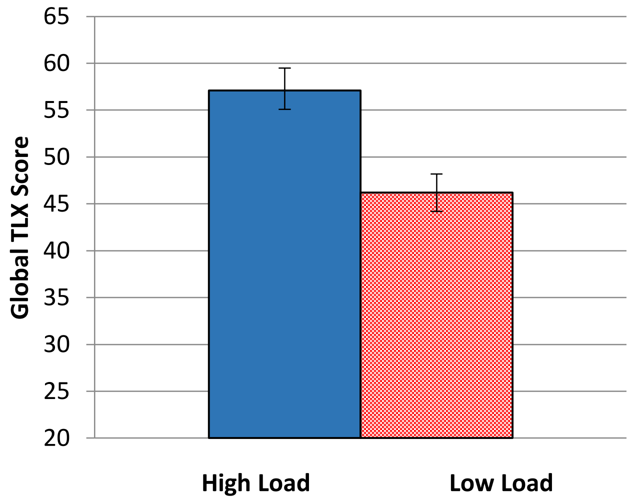
- Multiple sub-tasks on two displays (Calhoun et al., 2011)
- ISR (signal detection) tasks embedded for primary performance assessment
- Automation manipulated for signal detection (weapon release, image analysis)
- Selected tasks used to manipulate workload

Results: Task Load and Stress

- Higher distress and workload (TLX) under high task load
  - Manipulation working as intended



N.B. Post-task – pre-task scores



Stress State and WR/IM Performance - In High Task Load Condition

	Image Analysis				Weapon Release		
	Distress	Engagement	Worry		Distress	Engagement	Worry
Accuracy	-.33*	.14	-.29*		-.41**	.20	-.17
Reliance	-.16	.04	-.24		-.09	-.01	-.20
Neglect	.33*	-.41**	.25		.41**	-.31*	.18
*P<.05, **P<.01							

- Distress most damaging element of state
  - Due to multi-tasking requirement
- Low task engagement (fatigue) associated with neglect

Stress and Workload in UGVs
(Matthews et al., 2015; in press)

- MIX Sim: Remote operation of UGV for ISR
- Physio: Measurement of multiple workload responses
- Aims
  - Is there a unitary physiological workload/stress response?
  - How does stress response correlate with attention and performance?

UGV: MIX Simulation

- MIX testbed: Simulation of OCU of UGV (Taylor et al., 2013)

Task type:
- Change Detection (CD) is higher workload than Threat Detection (TD)

Dual-tasking:
- Dual vs. single task performance

Event rate:
- Calibrated for each task

Method

- Participants: 85 M, 66 F. Mean age = 19.57
- Design
  - Within-subjects: completion of four task scenarios varying in workload
  - Three event rates, varied within scenario

Scenario 1	Scenario 2	Scenario 3	Scenario 4
Change Detection	Change Detection + Threat Detection at constant rate	Threat Detection	Threat Detection + Change Detection at constant rate

  - Psychophysiology: 5 min baseline + continuous monitoring
  - Workload: NASA-TLX after each task condition (x12)
  - Stress state: DSSQ after each task condition (x12)

Physio: Workload Metrics

- Simultaneous recording of multiple metrics

Response system	Metrics
Electrocardiogram (ECG: Mulder, 1992)	Mean heart rate (HR)
	Heart rate variability (HRV)
Electroencephalogram (EEG: Borghini et al., 2012; Gevins & Smith, 2003)	Frontal theta
	Alpha
	Beta
Transcranial Doppler Sonography (TCD: Warm, Tripp, Matthews & Helton, 2012)	Cerebral bloodflow velocity (CBFV) in medial cerebral arteries (bilateral)
Functional Near Infra-Red (fNIR: Warm et al., 2012)	Regional cerebral oxygen saturation (rSO_2) in prefrontal cortex (bilateral)
Oculometric indices (Jacob & Karn, 2003; Marshall, 2002)	Duration of fixations
	Pupillometric Index of cognitive activity (ICA)
Subjective (Hart & Staveland, 1988)	NASA-TLX overall score

Results: Metric Correlations

	ECG IBI	ECG HRV	EEG Theta	EEG Alpha	EEG Beta	CBFV Left	CBFV Right	rSO_2 Left	rSO_2 Right	Eye Fix. Duration	Eye ICA	NASA-TLX
ECG IBI	-	.53**	-.29**	-.14	-.24**	.01	-.15	-.01	.01	.10	.06	-.02
ECG HRV		-	-.09	-.16	.12	.01	-.09	-.02	-.01	-.06	.05	.11
EEG Theta			-	.68**	.65**	.14	.16	-.13	-.13	.05	-.02	.14
EEG Alpha				-	.36**	.18*	.21*	-.10	-.11	-.01	-.04	.19*
EEG Beta					-	.17	.15	-.03	-.06	.06	.09	.05
CBFV Left						-	.61**	-.10	.00	-.02	.02	-.01
CBFV Right							-	.03	-.01	.01	.00	-.08
rSO_2 Left								-	.68**	.06	-.08	-.06
rSO_2 Right									-	.02	.03	-.01
Eye Fix. Duration										-	-.34**	-.02
Eye ICA											-	.03
p < .05, **p < .01.												

Results: Metric Correlations

- Correlations across sensor systems mostly zero
  - ECG IBI vs. EEG theta (r = -.29, p < .01) and beta (r = -.24, p < .01)
  - EEG alpha vs. left (r = .18, p < .05) and right (r = .21, p < .05) CBFV.
- Five factors defined by sensor system:

	Factor				
	1 (EEG)	2 (fNIR)	3 (TCD)	4 (Eye)	5 (ECG)
ECG IBI	-.20	.02	.02	.06	**.80**
ECG HRV	.14	-.02	-.03	-.08	**.91**
EEG Theta	**.90**	-.06	-.03	.04	-.10
EEG Alpha	**.83**	-.02	.05	.05	.23
EEG Beta	**.73**	.08	.03	-.08	-.18
CBFV Left	-.01	-.04	**.91**	-.03	.05
CBFV Right	.02	.03	**.89**	.03	-.07
rSO_2 Left	.01	**.90**	-.03	.07	-.02
rSO_2 Right	-.01	**.91**	.02	-.06	.03
Eye Fixation Duration	.06	.04	-.01	**.81**	.04
Eye ICA	.04	.03	-.01	**-.82**	.06

Correlates of Performance

- All measures averaged across condition
- ECG, EEG and eye fixation duration as physio correlates
- Low distress and worry, high engagement as DSSQ correlates
- Regression models: Physio and subjective state predict independently

	ECG	EEG		Eye	DSSQ		
	HRV	Alpha	Beta	Fix. Dur.	Dist.	Eng.	Worry
Change Detection	$-.258^{**}$	-.149	$-.259^{**}$	$.262^{**}$	$-.392^{**}$	$.451^{**}$	$-.302^{**}$
Threat Detection	-.074	$-.172^{*}$	-.154	.161	$-.214^{**}$	$.280^{**}$	$-.247^{**}$
Workload (TLX)	.112	.144	$.190^{**}$	-.024	$.611^{**}$	$-.167^{*}$	.080

Note: *p < .05, **p < .01

UGV Study: Conclusions

- No unitary physio response
- Physio and subjective responses dissociate
- No single metric adequately captures response
- Multiple predictors of performance
  - Subjective state and physio independently predictive
- Multivariate assessment needed for system evaluation

Implications

- Evaluating system design requires multiple metrics for workload, stress and fatigue
- Physio and subjective assessments are both diagnostic of performance issues
  - Neither easily substitutes for the other
  - Dimensions critical for performance vary across domains and vary with cognitive demands
- Physio analogues for task engagement critical for operator diagnostic monitoring
- Evaluation of operator response pattern may guide selection and training