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Diagnostic Monitoring Of Vigilance Decrement Using EEG Workload Indices

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The resource model of vigilance (Warm, Parasuraman, & Matthews, 2008) suggests that EEG-based indices of workload might be used to monitor the operator's fitness to sustain signal detection. 92 participants performed a 40 minute vigilance task believed to be sensitive to resource availability. Half performed in a cued condition, half without cues. Findings confirmed that cueing reduces workload and enhances vigilance. EEG was recorded throughout performance. Of the various EEG indices analyzed, lower frequency alpha and the Task Load Index (TLI) corresponded most closely to changes in signal detection rates. Other indices, the Engagement Index (EI) and frontal theta, did not show systematic decrement but discriminated cued and uncued conditions towards the end of the task. Implications of the findings for using EEG to drive adaptive automation are discussed.

INTRODUCTION

Vigilance is among the cognitive functions that are most vulnerable to impairment in operational settings. Declines in signal detection performance over time – the 'vigilance decrement' – are known from a variety of domains, including military surveillance, industrial inspection and transportation (Warm, Parasuraman & Matthews, 2008). The operational importance of maintaining vigilance is also indicated by the increasing automation of technology, requiring operators to monitor displays for potential problems. Thus, maintaining vigilance may be an important focus for augmented cognition. Specifically, continuous psychophysiological monitoring for loss of alertness may be used to trigger technological support to maintain performance, i.e., adaptive automation (Berka et al., 2007; Freeman, Mikulka, Scerbo & Scott, 2004).

The resource theory of vigilance decrement (Warm et al., 2008) may provide a framework for diagnostic monitoring of operator status. It states that during performance of high-workload signal detection tasks, resources become depleted, leading to decrements in perceptual sensitivity. Thus, a psychophysiological index that was specifically diagnostic of resource utilization would be ideal for monitoring operator status. Recent research, reviewed by Warm, Tripp, Matthews and Helton (2012), has identified one such index: cerebral bloodflow velocity (CBFV), as measured by Transcranial Doppler ultrasonography (TCD). Declines in right-hemisphere CBFV tend to parallel the temporal performance decrement, and appear to be controlled by the same workload factors. Right hemisphere CBFV is especially diagnostic, consistent with brain-imaging data suggesting that vigilance is controlled by right-hemisphere circuits.

Recent studies have shown that, as an emergent construct that is likely linked to multiple brain areas, 'resources' should be indexed through multiple indicators (Matthews et al., 2010). These authors found that CBFV and subjective task engagement made independent contributions to the prediction of vigilance. Task engagement is a subjective state linked to alertness, which includes energetic arousal, task motivation, and concentration. Such observations suggest the need to explore additional psychophysiological indices that may be combined within a multivariate predictive model.

A promising technique for this purpose is electroencephalography (EEG). Traditionally, vigilance research has identified performance decrement especially with increased slow wave activity (delta and theta waves: e.g., Craig & Tran, 2012). However, it is unclear the extent to which traditional EEG power measures relate specifically to loss of resources. More recent studies of brain responses to cognitive load delineate a variety of indices that may relate more directly to resource utilization than classic arousal measures.

More refined measures of traditional EEG spectral power indices have been used. Increased workload in a range of tasks corresponds to increased theta activity at frontal sites, perhaps indexing mental effort (Gevins & Smith, 2003; Garcia et al., 2010; Lei & Roetting, 2011). Klimesch (1999) proposed that alpha should be split into upper and lower frequency bands. Upper alpha (alpha-1) is suppressed by information-processing requiring semantic memory, whereas lower alpha (alpha-2) corresponds better to the traditional notion of alpha suppression indexing. Multiple power indices may be combined to measure constructs related to workload and resource utilization. Gevins and Smith's (2003) task load index (TLI) is defined by increased frontal theta and reduced parietal alpha during demanding task performance, i.e., the ratio of theta activity at frontal midline sites to alpha at parietal sites. Another index labeled the Engagement Index (EI: Freeman et al., 2004; Pope, Bogart, & Bartolome, 1995) accommodates the association between beta power and cognitive activity, and is defined by the formula beta/(alpha + theta). By contrast with the TLI, the EI assumes that lower theta corresponds to greater alertness.

Each of the indices discussed has some validity as an index of attentional functioning (e.g., Hockey, Nickel, Roberts & Roberts, 2009), but it is unclear which index is maximally sensitive to changes in resource utilization during vigilance. The aim of the current study was to perform a comparative evaluation of the validity of the indices as indicators of the vigilance decrement in performance. For this purpose, we used a sensory vigilance task that has provided performance-based and psychophysiological evidence supportive of resource theory in previous studies (Hitchcock et al., 2003; Matthews et al., 2010). The task requires participants to detect briefly-presented critical signals in a display resembling an air traffic control display. Hitchcock et al. (2003) showed that providing a cue that a critical signal (target) was imminent reduced vigilance decrement and increased subjective task engagement. Furthermore, cue effects on performance were mirrored by changes in right-hemisphere CBFV. Matthews et al. (2010) showed that both subjective engagement and in CBFV response predicted perceptual sensitivity on the task.

The present study aimed to examine temporal change in EEG responses during cued and uncued versions of the Hitchcock et al. (2003) task. It was assumed that cueing reduces demands for attentional resources, allowing participants to sustain resource availability and avoid substantial vigilance decrement. Therefore, EEG-based indices should be sensitive to cueing and time on task effects, as CBFV is. Broadly, we can relate reduced alpha-1 power (Klimesch, 1999) and EI (Freeman et al., 2004) to loss of alertness. It was predicted that these indices would show temporal declines that were greater in the uncued condition. The resource theory of vigilance predicts that mental workload is liable to increase over time as resources become depleted (Warm et al., 2008). Thus, effort-based indices such as frontal theta and TLI (Gevins & Smith, 2003) should show the opposite pattern of an increase over time, especially in the uncued condition.

METHOD

Participants

The participants were 92 students from Kazakh National University aged 18 to 29 years old (50% female). Participants were required to be free of psychiatric and medical diseases at the time of the study. All were right handed, with normal or corrected-to-normal vision, and were native Russian speakers.

Materials and apparatus

Participants performed a slightly modified version of the Hitchcock et al. (2003) task, programmed with SuperLab 2.0 software, for 40 minutes. On-screen instructions were in Russian. The target represented two aircraft aligned on a potential collision course. There were 400 stimuli presented in each 10 minute block of trials, of which 380 were nontarget stimuli, 10 were target stimuli and 10 were the cue word 'LOOK' (in Russian). In the uncued condition, participants were instructed to ignore the word 'LOOK'. In the cued condition, participants were told that it was likely that a target would follow the cue in the next five stimuli. In fact, this was true for 9/10 cue presentations. There was also one target that was not preceded by the cue word. (In the uncued condition, occurrence of the cue word was unrelated to occurrence of the target). Each stimulus was presented for 80 ms, followed by a bank screen. In a practice version of the task, correct detections, missed targets and false positives were followed by spoken feedback. No feedback was given in the main task.

Subjective task engagement was measured by the Russian version of the Dundee Stress State Questionnaire (DSSQ; Matthews et al., 2002). The DSSQ measures 11 dimensions of subjective state expressed in mood, in task motivation and in cognitive responses. In this article, we report data only for the three scales most closely associated with task engagement: energetic arousal, intrinsic motivation and concentration. All scales of Russian DSSQ showed adequate Cronbach alphas, ranging from 0.694 to 0.925. The post-task DSSQ includes an embedded version of the NASA Task Load Index (NASA-TLX: Hart & Staveland, 1988). Participants rated six aspects of workload on 0-10 scales, and an unweighted mean was computed to represent overall workload.

A "Neuron-Spectrum-1" electroencephalograph was used to record EEG from F1, F2, F3, F4, Fz, C3, C4, Cz, P3, P4, Pz, O1, O2, T3, T4 sites using Ag-AgCl electrodes, with referent ears electrodes, according to the International 10-20% system. Sampling rate was 256 HZ; impedance quality was checked automatically. Filters were used: high-pass – 0.05 Hz, low-pass – 35 Hz. Artifacts were excluded both automatically and manually with visual inspection. The Spectral Power Density of EEG bands was computed with a Fast Fourier transformation. Data analyzed in seven bands: Delta (0.5-3.9 Hz), Theta (4-7.9 Hz), Alpha-1 (8-10.9 Hz), Alpha-2 (11-13.9 Hz), Beta-1 (14-19.9 Hz), Beta-2 (20-29.9 Hz), Gamma (30-35 Hz). EEG indices were calculated according to published methods: 1) *TLI*: Ratio of theta Fz to alpha Pz (Gevins & Smith, 2003; Hockey et al., 2009); 2) *EI*: Ratio of beta to (alpha+theta) for central-parietal sites (Cz, P3, Pz, P4); 3) f*rontal theta* effort index, averaged across F1, F2, F3, F4 (Gevins et al., 1997); 4) *alpha-1* and *alpha-2,* averaged across all sites recorded (Klimesch, 1999).

Procedure

Participants signed a consent form. Following attachment of electrodes, participants completed a pre-test form of the DSSQ. Next, they practiced the vigilance task. Then, a baseline EEG measure was taken with closed and open eyes, lasting four minutes in total. Then, they performed the vigilance task for 40 minutes, analyzed as four consecutive task periods of the vigilance task, followed by a post-test version of the DSSQ, and the NASA-TLX. 46 participants were allocated to the no cue condition, and 46 to the cue condition.

RESULTS

In this section, we report, first, effects of task period and cueing on performance and subjective task engagement. These analyses tested whether key findings of past vigilance studies – vigilance decrement, substantial workload, and loss of engagement – replicated in the Kazakh sample. Then, we tested effects of task performance on the four EEG indices related to resource utilization described previously.

Task performance

Effects of task parameters on three performance indices – correct detections, false positives, mean RT for correct detections – were analyzed using 2 x 4 (cue x task period) mixed-model ANOVAs, with repeated measures on task period. False positive percentages were log-transformed to correct positive skew. Box's correction was used in applying *F* tests, where appropriate, because of violations of the sphericity assumption. For correct detections, the main effects of cue, $F(1.90) = 9.47$, $p<.01$, partial $\eta^2 = 0.095$, and period, $F(2.479, 223{,}124) = 11.27$, $p<0.01$, partial $\eta^2 = 0.111$, were significant, but the interaction between these factors was not. The only significant effect for false positives was the main effect of cue, $F(1,90) = 8.31$, $p<0.01$, partial $\eta^2 = 0.870$. False positives were higher in the no cue condition (8.46%) than in the cued condition (3.66%). The analysis of mean RT showed a significant cue x period interaction, $F(2.841, 252.889) = 2.92$, $p<0.05$, partial $\eta^2 = 0.032$, but no main effects.

A vigilance decrement in correct detections was evident (see Figure 1); across periods, detection rate tended to decline in both participant groups. Correct detections were higher in the cued condition but a trend towards greater performance decrement in the no cue condition was non-significant. RT was fairly stable across time in the cued condition, but increased monotonically in the no cue condition (see Figure 2).

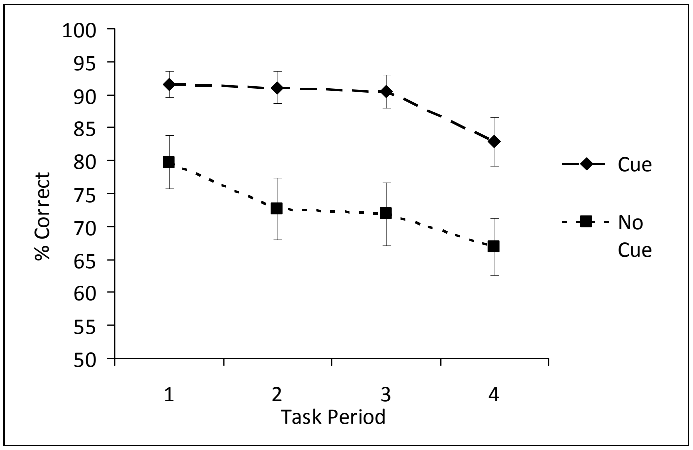

Figure 1. Task parameter effects on correct detections. (All error bars are standard errors).

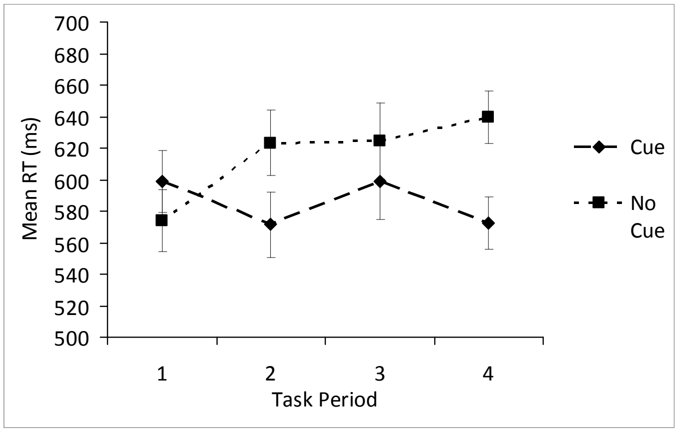

Figure 2. Task parameter effects on mean RT.

Subjective state and workload

The two groups were matched initially for pre-task subjective state. Next, we conducted a series of 2 x 2 (cue x pre- vs. post-task) ANOVAs to test for effects of task performance on subjective state, for the three DSSQ scales associated with task engagement. For each scale, the effect of pre- vs. post-task was significant at $p<0.01$. F values (df = 1,90) were 36.94 (energetic arousal), 68.20 (intrinsic motivation), 10.95 (success motivation), and 22.23 (concentration). The corresponding partial η^2 values were .291, .431, .108 and .198. No significant main effect of cue was obtained, but a significant cue x pre- vs. post-task interactions was found for energetic arousal ($F(1,90) = 5.64$, $p<0.05$), partial $\eta^2 = .059$. Surprisingly, a larger drop in energetic arousal was seen in the cued group. Mean (and SD) for overall workload was 5.67 (1.63) in the uncued condition, and 4.89 (1.31) in the cued condition. These means differed significantly $t(92) = 2.52$, $p<.05$.

EEG indices

A series of 2 x 4 (cue x task period) mixed-model ANOVAs were run to assess effects of task parameters. There were no significant effects of the task factors on alpha-2. For the remaining indices, the main effect of period was significant for TLI, $F(2.517, 226.496) = 3.29$, $p<0.05$, partial $\eta^2 = 0.035$, for alpha-1, $F(2.116, 190.483) = 16.91$, $p<0.01$, partial $\eta^2 = 0.158$, and for frontal theta, $F(2.814, 253.256) = 3.16$, $p<0.05$, partial $\eta^2 = 0.034$, but not for EI. The effect of cue was significant for TLI, $F(1, 90) = 4.18$, $p<0.05$, partial $\eta^2 = 0.044$ and alpha-1, $F(1, 90) = 4.40$, $p<0.05$, partial $\eta^2 = 0.047$, but not for the other indices. The period x cue interaction was significant (or nearly so) for EI, $F(2.175, 195.745) = 2.92$, $p = 0.052$, partial $\eta^2 = 0.031$ and for frontal theta, $F(2.814, 253.256) = 3.05$, $p<0.05$, partial $\eta^2 = 0.033$, but not for other indices.

Thus, different EEG indices showed different patterns of response to the task parameters (see Figures 3-6). Lower alpha-1 and TLI showed complementary responses. Time-on-task decreased TLI and increased alpha power, whereas providing the cue elevated TLI and lowered alpha. By contrast, effects of task parameters on frontal theta and EI were interactive, not additive. In the final period of work, EI was higher but frontal theta was lower in the cue group.

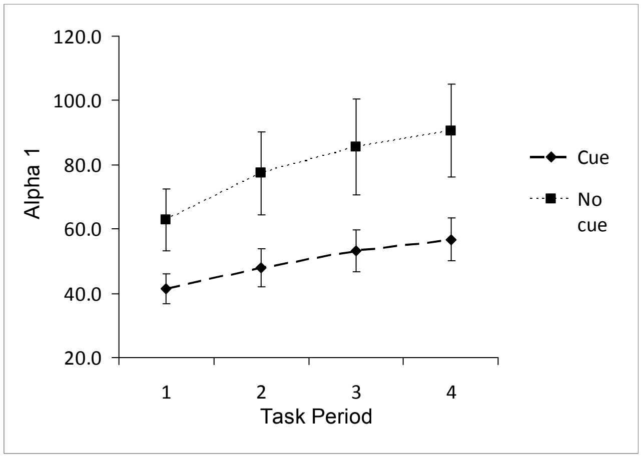

Fig. 3 Task parameter effects on alpha-1 index.

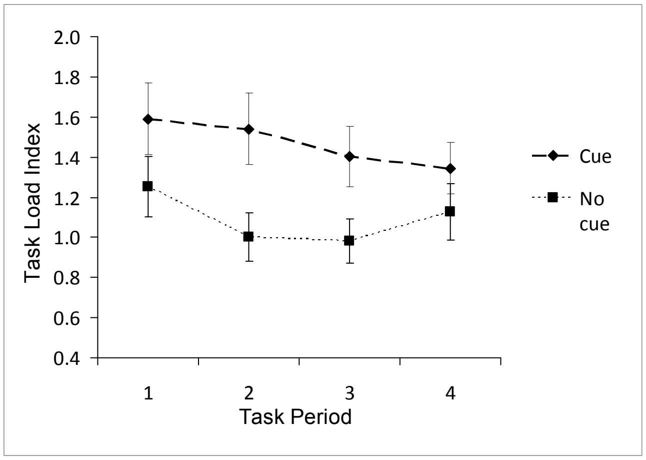

Fig. 4 Task parameter effects on TLI.

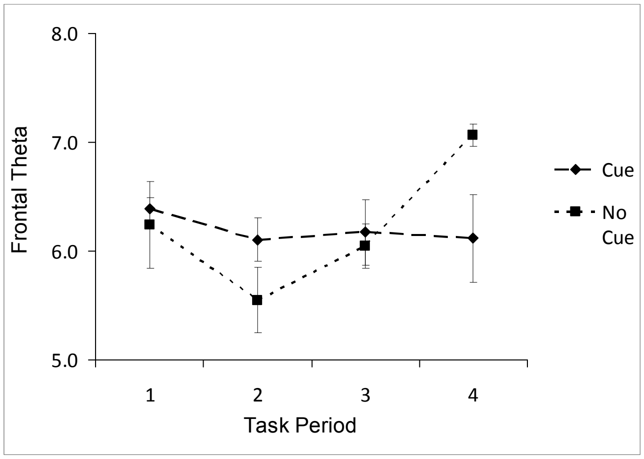

Fig. 5 Task parameter effects on frontal theta.

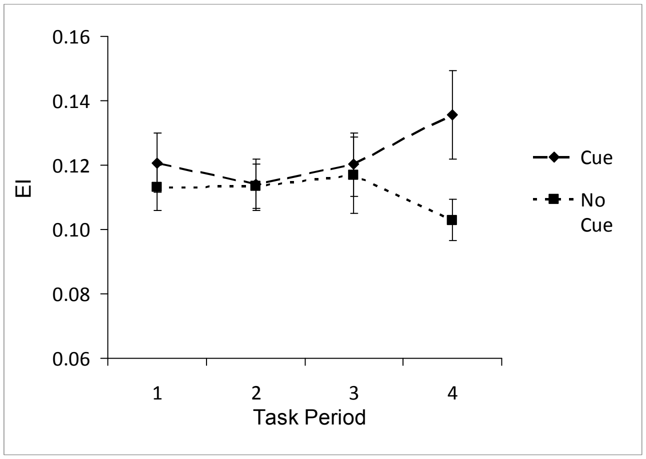

Fig. 6 Task parameter effects on EI.

DISCUSSION

The study was successful in producing vigilance decrement in performance, as well as loss of subjective task engagement. As in previous studies (Hitchcock et al., 2003; Matthews et al., 2010), a pronounced decline in correct detections across the four task periods was observed, and providing a cue elevated detection rate. Cueing also reduced the incidence of false positives. However, no differential decrement in detections was seen across the two conditions. Possibly, signal detection deteriorated faster in the uncued than in the cued condition within the first 10 minutes, with no differential decrement subsequently. By contrast, a differential decrement was seen in the RT data. Mean RTs were matched in the first task period, thereafter increasing progressively over time in the uncued, but not the cued condition. NASA-TLX workload was higher in the uncued than in the cued condition, consistent with the assumption that cueing reduces demands for attentional resources. Thus, data are broadly consistent with the resource model (Warm et al., 2008), except the hypothesized greater loss of resources in the uncued condition may be more evident in RT data than in correct detections.

We hypothesized that EEG indices associated with alertness – alpha-1 and EI – would show temporal decline, especially in the uncued condition. The hypothesis was largely confirmed for alpha-1. Increasing power in alpha-1 over time corresponded fairly closely to declining correct detections. Alpha-1 was higher for the no-cue condition, corresponding to the main effect of cueing on performance. The lack of any effects on alpha-2 is consistent with Klimesch's (1999) identification of this frequency band with semantic processing, given that the task required only a sensory discrimination, with no requirement to retrieve information from semantic memory. As with performance, there was no differential decrement across conditions. The prediction of temporal decline in EI was not confirmed, although there was a cue x task period effect that approximately corresponded to the interaction seen in the RT data. By the fourth period, EI was lower in the no cue than in the cue group.

Although alpha-1 seems promising as a diagnostic index of vigilance, it may not correspond exactly to the CBFV indices of resource depletion discussed in the introduction (Matthews et al., 2010; Warm et al., 2012). Specifically, the task parameter effects shown in Figure 1 were similar in both hemispheres (space limitations precluded reporting of these data above). By contrast, right-hemisphere CBFV appears to be especially diagnostic in vigilance studies (Warm et al., 2012). Given right-hemisphere control of vigilance, CBFV responses may be more proximal than alpha-1 to the processing mechanisms controlling vigilance.

We identified frontal theta and TLI (Gevins & Smith, 2003) with effort, which was expected to be higher for the uncued task (consistent with the NASA-TLX data), and as time progressed. However, there were no main effects of either task period or cueing on frontal theta. Instead, as with EI, the two factors interacted such that the index differentiated cued and uncued conditions only in period 4. (The inverse patterns of the two indices may reflect the place of frontal theta in the denominator of the formula for EI). There were main effects of cueing and task period for TLI, but opposite to those expected. TLI was higher when the task was less demanding: in the earlier task periods, and in the cued condition.

Thus, the different indices show different patterns of temporal change. Broadly, TLI and alpha-1 were most diagnostic of loss of vigilance, corresponding fairly closely to the correct detection data. These indices may be diagnostic of attentional resource insufficiency. The equation of high alpha-1 with attentional impairment is consistent with previous findings (Craig & Tran, 2012; Klimesch, 1999). The present findings contrast strongly with previous studies showing that TLI increases with task demands. However, these studies (e.g., Gevins & Smith, 2003; Hockey et al., 2009) have typically used complex, multi-component tasks requiring working memory that differ considerably in their processing demands from vigilance. The significance of TLI may depend on the nature of task demands.

Frontal theta and EI did not decline systematically across the first three task periods. The two indices did differentiate the two task conditions in period four, but frontal theta data suggest higher workload/effort in the uncued condition, whereas EI data imply reduced engagement with no cue. As with TLI and alpha-1, these indices may provide different diagnostic information for vigilance than for other types of task. However, a recent study (Garcia et al., 2011) showed temporal increases in frontal midline theta during a 40-min vigilance task consistent with the effort hypothesis, so further work on this index is needed.

Turning to applications, the present findings provide reasons for both hope and caution in using EEG to drive adaptive user support for vigilance (Freeman et al., 2004). On the positive side, alpha-1 and TLI may both be diagnostic of loss of attention, and could be used to monitor operator functional state. The effect size for temporal change in alpha-1 was substantially larger than that in TLI, and so the former may be the preferred index. The discrepancies between the current findings on TLI, EI and frontal theta and those from previous studies (e.g, Gevins & Smith, 2003; Hockey et al., 2009) suggest caution in extrapolating findings from other task paradigms to vigilance. Use of EEG indices in augmented cognition may require an appreciation of the moderator effects of task demands. Indeed, relevant task demands may vary across different vigilance tasks. The Hitchcock et al. (2003) task is a simultaneous task, requiring comparison of stimulus elements presented within the same display. Other vigilance tasks are successive, requiring working memory to integrate information across multiple displays. The diagnosticity of the various indices may be different for simultaneous and successive tasks. TLI is sensitive to working memory load (Berka et al., 2007), and so might perform differently with a successive vigilance task.

Some limitations should be noted. First, there was no significant differential decrement in correct detections across conditions. TCD is diagnostic of differential decrement (Hitchcock et al., 2003), but it remains open whether EEG is equally effective. Second, task duration was relatively short compared to many operational tasks. Using an air traffic control simulation, Crowe et al. (2010) observed marked changes in EEG only after 70 minutes or so continuous performance. Third, in keeping with the applied focus of the study, we analyzed broad indices of EEG response as defined in previous studies. More fine-grained analyses, including analysis of response at individual electrode sites, may also add to understanding of vigilance. Fourth, to our knowledge this is the first study of vigilance using contemporary methods in a Kazakh sample. Although performance-based, subjective state and workload responses resembled those reliably seen in Western samples (Warm et al., 2008), there may be subtle cross-cultural differences in regulation of performance that influence EEG. Fifth, constructs such as ‘resources’ and ‘effort’ are often loosely defined (Matthews et al., 2010). Stronger theoretical accounts of these constructs are needed to support diagnostic monitoring using multiple indicators of cognitive-energetic state.

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